A System Dynamics Study of Ideation in R&D

by

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ABSTRACT

The R&D (Research and Development) division of manufacturing firm A considers that technical innovation is critical to ensure the firm's long-term growth through new products. However, R&D senior management has been concerned with the low quantity of ideas that show promises for new platforms and products. R&D started an initiative (Idea Management Process or IMP) to formally manage ideas and to enable everybody to contribute ideas especially in what is called the Fuzzy Front End phase of the Product Development Process. The present work is intended to better understand some of the structures behind the ideation process and to help management assess and improve policies around its initiative.

A group of R&D employees of Company A were interviewed about the IMP initiative and associated concerns. Following a standard system dynamics process, the interviews aimed at eliciting the key variables of concern and at graphing their behavior over time. Questions emphasized the fears and hope for the future. Causal diagrams captured the mental models or dynamic hypotheses of why such behaviors could occur. Feedback from the interviewees led to the selection of a central hypothesis called "ideas fuel growth." This hypothesis became the focus of the study and the basis for developing a computer model. A fundamental equation relating key parameters to the success of the R&D initiative was derived from the model. Both the analysis of the fundamental equation and simulations showed that the "ideas fuel growth" hypothesis alone could generate the hoped-for as well as the feared behaviors. Two types of parameters emerged from the model: one that can lead the company to growth or decline, and the other that brings the company to an equilibrium state. The model revealed insights such as the importance of the notion of idea lifetime. Analysis of model parameters provided guidance for policy recommendations. Recommendations included a more efficient management of intra and extra R&D interactions such as project knowledge sharing and joint marketing-R&D activities. Reflections about system dynamics were presented. Finally, the study suggested further areas of research.

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TABLE OF CONTENTS

LIST OF FIGURES

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INTRODUCTION

Company A manufactures and sells photographic equipment including film and imaging systems. Company A is several decades old and has experienced flat revenues for the past decade. Upper management has emphasized developing new products as a critical ingredient for growth. Some growth did occur recently, particularly thanks to a couple of successful new product accompanied by efficient marketing and advertising. While this is encouraging, there exists a concern about long-term sustainable growth. This thesis focuses on the perspective of the Research and Development (R&D) organization of Company A and its role, opportunities and barriers as they relate to the concern for long-term growth.

The present work employs a system dynamics approach to understand and analyze some of the underlying structures of R&D's concerns and to propose policies for improvement. Interviews with about twenty persons including a Vice President, Senior Managers, engineers, scientists, and Program Managers provided the data for analysis. Interviews ranged from several group meetings to one-on-one meetings to phone discussions. The cumulative length of the interviews varied from three to twelve hours per person.

Chapter 1 describes the concerns as perceived by R&D. Chapter 2 presents several dynamic hypotheses that were proposed to explain the concerns brought up in Chapter 1. Chapter 3 focuses on a key dynamic hypothesis. The chapter develops a computer model and a corresponding fundamental equation. The chapter analyzes the model's possible behaviors and the important associated parameters. An eigenvalue analysis deepens the understanding about the relationship between the model's behavior and the model's structure. Chapter 4 explores the managerial and policy implications stemming from Chapter 3. Chapter 5 reflects on the system dynamics process, its strengths and challenges. Chapter 6 presents a summary of the study and proposes areas for further work.

Chapter 1

THE CONCERN IN R&D

The concern: reference modes

The R&D organization wishes to increase its role in the sustainable growth of Company A through new products and chemistry-based platforms. Chemistry-based platforms exhibit the advantage that several products can be derived from them, and that they constitute consumables that are essential to increase revenues and profits. They also represent key competencies of Company A and are fully aligned with the current business and technology strategies. On the other hand they usually involve complex technologies and require a relatively long time to be brought to technical feasibility level.

Ultimate commercial success of a product is difficult to predict. One important objective for R&D is to be more efficient in the earliest phase of the Product Development Process commonly called "ideation" or "Fuzzy Front End". There is a concern that not enough quality ideas are being gathered, documented, and ready to be presented for potential funding to the Business Units. This in turn jeopardizes future technical innovation and long-term growth. This could lead to a shrinking of the R&D population and an even lesser level of innovation thereby feeding into a death spiral.

At the beginning of the system dynamics process, we (the interviewer and interviewees) list as many variables as we can think of that are related to our concerns (Appendix A). A *variable* is an entity that, over time, can decrease, increase, or remain the same. This is a simple yet powerful characterization. For example, the *definition* of a term would not qualify as a variable. Once we have listed the variables, we select a few of them for their prime relevance and plot them over time. The fact that we are not plotting the other ones does not mean that they are not important, but rather that they may be redundant or too complex to deal with right now. Also, graphing a small number of variables enables us to focus on the problem at hand and not try to attack everything at the same time; moreover, the essence of a concern can most of the time be captured with just a few key variables. The plots are called "reference modes." Reference modes illustrate the concern by graphically describing key variables' behaviors over time. We plot the variables' hoped-for as well as the feared behavior(s).

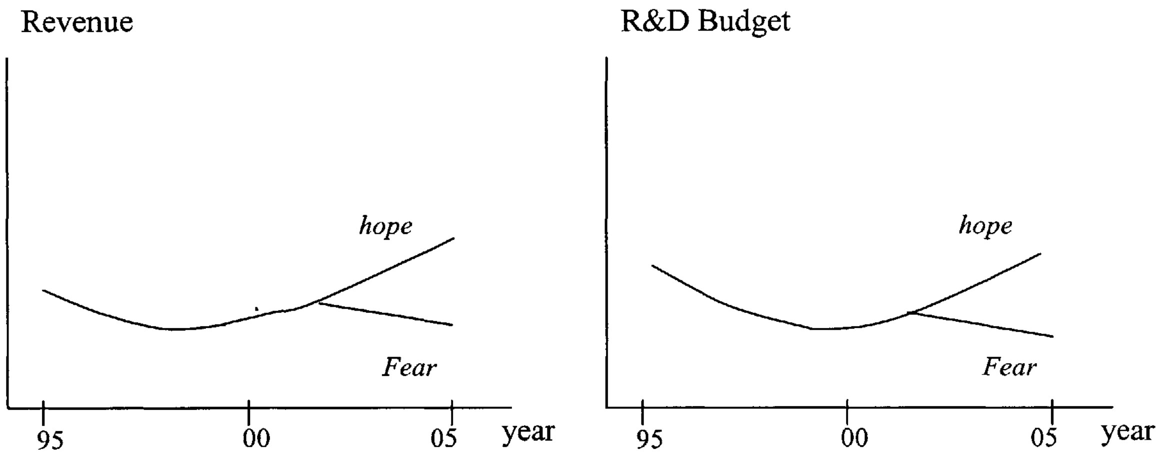


Figure 1-1: Reference Modes for Revenue and R&D Budget

Figure 1-1 shows R&D's concern that Company A's revenue will start declining in a couple of years. The hope is to pursue the very recent turn around revenue growth. From R&D's perspective, a decline in revenue would most likely lead to a reduction in the R&D budget.

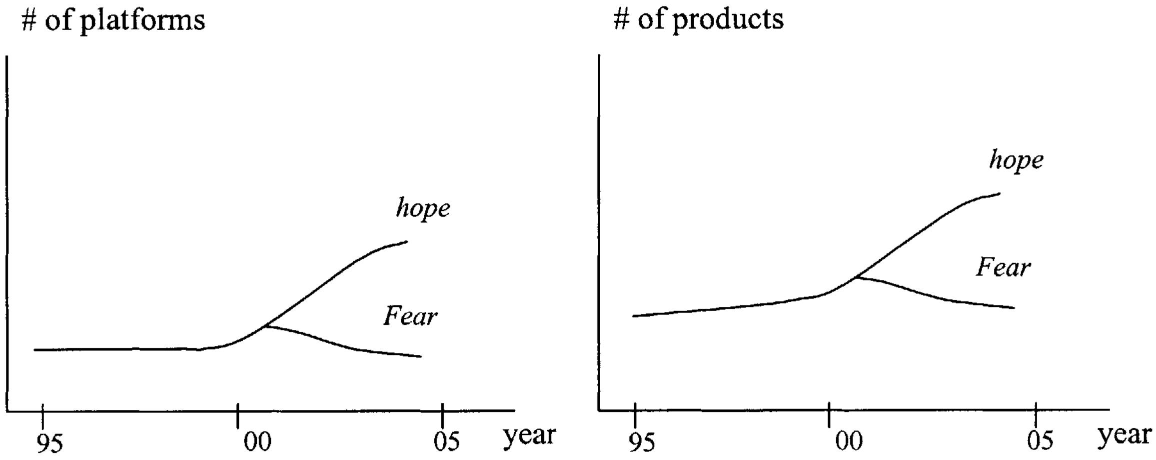


Figure 1-2: Reference Modes for Number of Platforms and Products

R&D hopes to increase the number of platforms and products developed per year (Figure 1-2).

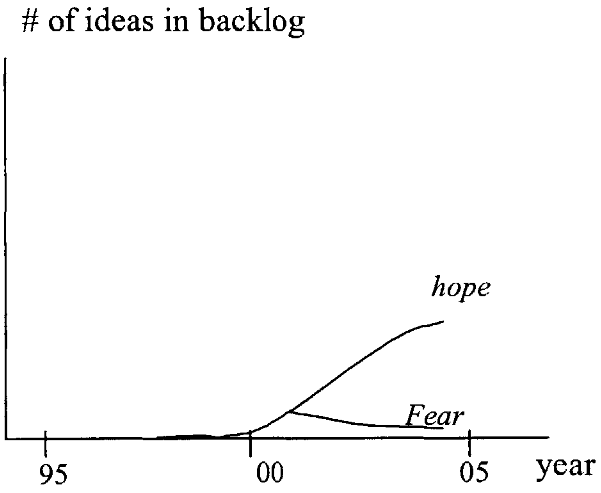


Figure 1-3: Reference Modes for Number of Ideas in Backlog

In the past several months an effort started in R&D to collect and review ideas coming from R&D employees. Let us call this process IMP (for "Idea Management Process"). The intention is to have a backlog of many high-quality ideas that can be presented to the Business Units. A backlogged idea for a new platform could be funded right away or later depending on its attractiveness to the Business Units. A backlogged idea is an idea that for a minimal amount of effort put into it promises to be technically feasible and to add value to the customer. Senior management is concerned that too few ideas have gone through the IMP to arrive into the backlog and hopes that this number will rise (Figure 1-3).

The concern: momentum policies

Momentum policies are policies that we would consider implementing now (at this *moment*) if we had to make decisions today. These policies may already be partially or fully in place or may not exist as of today. Proposed momentum policies to increase the backlog of good ideas include:

- Institute a clear and convenient process to manage ideas (IMP) from submittal to backlog
- Communicate the existence and importance of the IMP (idea management process) to all R&D employees
- Reward the usage of the IMP process
- Accept more ideas at first screening of IMP
- Review ideas faster

- Increase the contacts between R&D and the Business Units
- Increase the contacts between R&D and customers
- Increase other external idea triggering events (attend conferences, etc...)
- Use knowledge management systems
- Increase knowledge of competition
- Develop brainstorming sessions to unleash creativity
- Provide "free thinking" time
- Encourage risk taking
- Reward collaboration as well as individual contribution
- Hire highly creative people

Chapter 2

DYNAMIC HYPOTHESES

At this point of the system dynamics process, we start investigating what may underlie the reference modes presented in Chapter 1. In other words: what structure is driving those behaviors?

Complex problems often exhibit feedback properties (closed loops) linking (possibly in a non-linear fashion) many of the variables under consideration. Oftentimes, dynamics (changes over time) are also present. The human brain has difficulties dealing with many interrelated variables. When non-linearity and dynamics enter the picture, humans are overwhelmed and often show poor judgment. System dynamics provides not only powerful tools to *describe* feedbacks, but also a powerful framework to *surface* those feedback structures. Interviewing the people involved in the issue at hand allows the surfacing of the structures. It is important to employ appropriate interviewing techniques that enable the embedded mental models to emerge. The interviewer must also be careful not to "bias" the client's mental model by offering or imposing his/her own views [Schein 99].

In this chapter we capture the dynamic hypotheses that the interviewees are offering in order to explain the different reference modes presented in Chapter 1. We express the hypotheses in words and find it useful and powerful to illustrate them with causal diagrams [Sterman 2000], [Senge 90]. Generally, a dynamic hypothesis corresponds to a structure that involves a loop or a set of loops. Some of our captured hypotheses do not correspond to loops but just to straight causal links. Each following section corresponds to a specific dynamic hypothesis.

Ideas fuel growth

As more technical ideas are generated, submitted, and reviewed, more quality ideas are funded. This leads to an increase in successful products, revenue, and R&D budget. The increase in R&D budget translates into an increase in R&D workforce through hiring. A bigger workforce generates and submits more ideas. The positive or self-reinforcing loop of Figure 2-1 illustrates this dynamic hypothesis which in turn would explain the reference modes of all of our key variables (ideas in backlog, number of platforms and products, R&D budget, revenue). Indeed, this positive loop gives us a structure for explaining the "hope" behaviors shown in our reference modes.

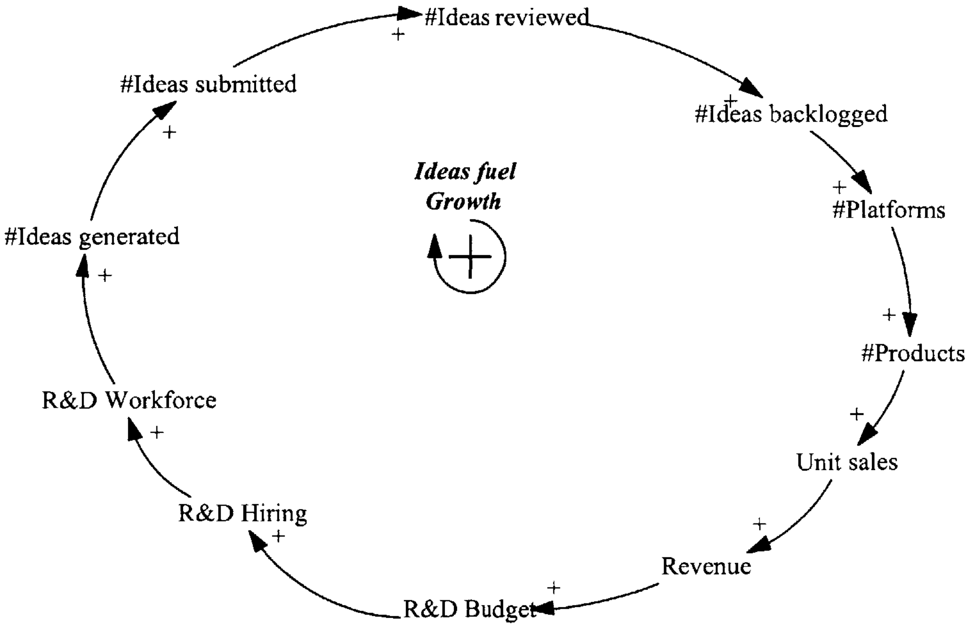


Figure 2-1: Ideas Fuel Growth

Awareness of IMP (Idea Management Process)

Ideas are generated in people's heads first. They may be articulated or not; they may be written down or not. The IMP (see Chapter 1) provides a way to submit ideas in a database using a standard form requesting basic technical and business information. As more people use the IMP's database, they mention it to colleagues and hence raise awareness of the database (Figure 2-2).

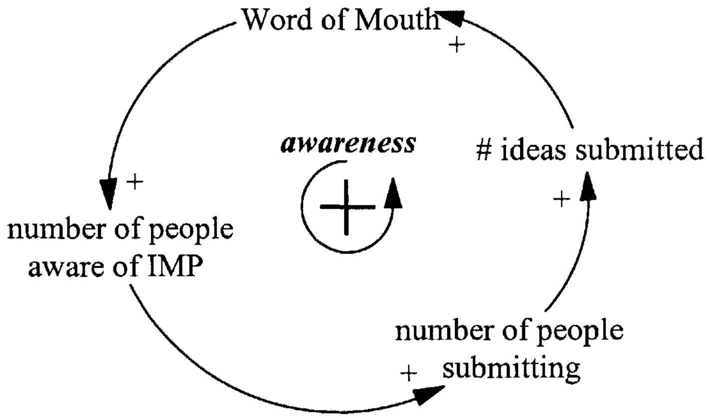


Figure 2-2: Awareness of IMP

This hypothesis explains the hoped-for reference mode for the number of ideas in backlog. The link is indirect but present since more ideas submitted eventually lead to more ideas in backlog (see hypothesis "Ideas fuel growth").

The time issue for submitters of ideas

As more platforms/products are developed, there is more schedule pressure on current projects and less time to submit new ideas leading to less ideas in backlog and hence less platforms (Figure 2-3). This negative or balancing loop would contribute to the feared reference modes.

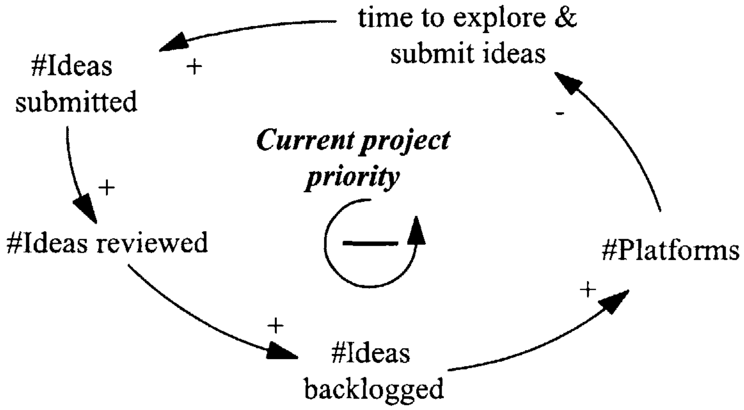


Figure 2-3: Time Issue for Submitters

The review bottleneck

Due to schedule pressure on current tasks, there is no time for reviewers to review new ideas. As more platforms/products are worked on, they become priority tasks, leaving less time for reviewers to review the submitted ideas. One effect relates to the fear reference mode of the backlogged ideas. The fear is that the number of good ideas (i.e. the number of backlogged ideas) depletes to zero over time. The review bottleneck negative loop illustrates this hypothesis (Figure 2-4).

The other small negative loop linking the "number of ideas reviewed" to the "number of ideas submitted" expresses the following fact: as more ideas are reviewed, all else kept equal, the number of ideas in the pool of "ideas submitted" goes down leading eventually to the feared decline shown in the reference mode of the "number of ideas in backlog."

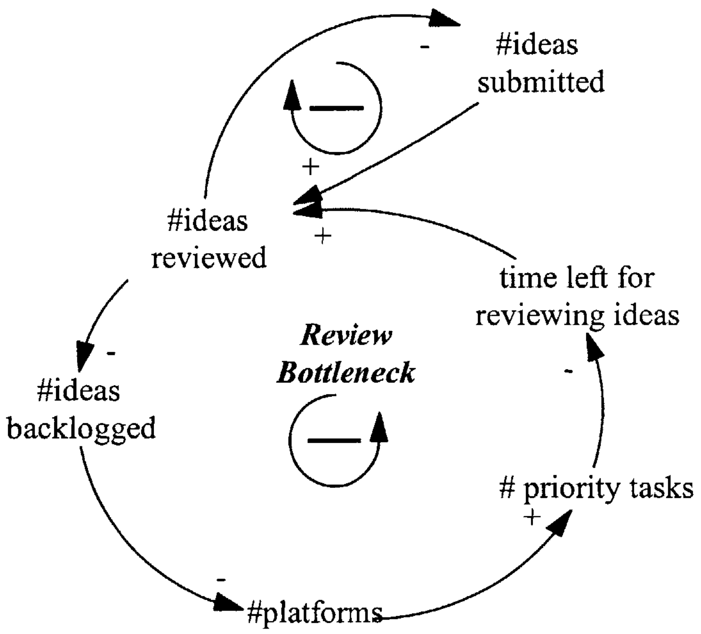


Figure 2-4: Review Bottleneck

Effect of review responsiveness on idea submittal

As people submit more ideas, the ideas pile up in the reviewers' computer, the reviewers take longer to get to reviewing them, leading to more unresponded to or sloppily reviewed ideas, leading to more frustration on the part of submitters and less interest in submitting ideas.

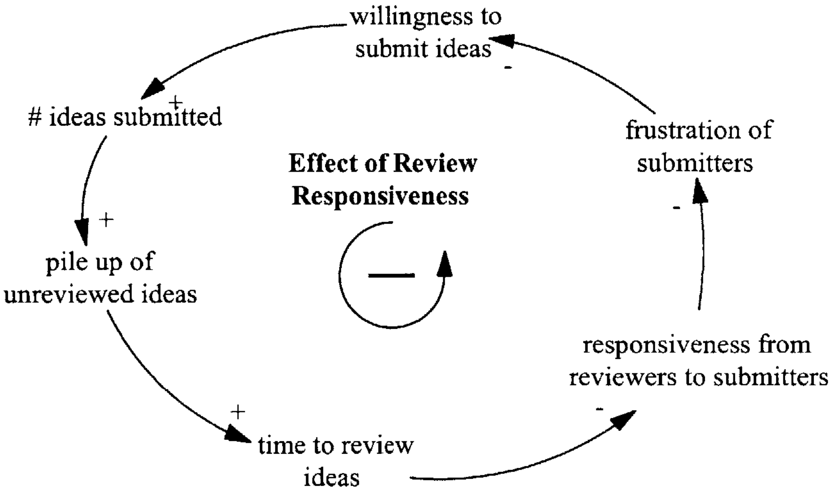


Figure 2-5: Review Responsiveness

This hypothesis illustrated by the above negative loop would contribute to the reference mode of the number of ideas in backlog. Indeed, the slow down in submitting ideas will ultimately lead to a decline in backlogged ideas (feared behavior).

The morale effect

As revenue stays flat or decreases, the morale goes down and talented creative people leave. If they do not leave, they may think of leaving and stop disclosing ideas. Fewer ideas lead to fewer platforms and products leading to less revenue and even worse morale and workforce reduction. These two effects of morale level are illustrated below. The two positive loops which illustrate those effects can explain the feared behaviors described in the reference modes of our key variables (revenue, #products, #ideas in backlog).

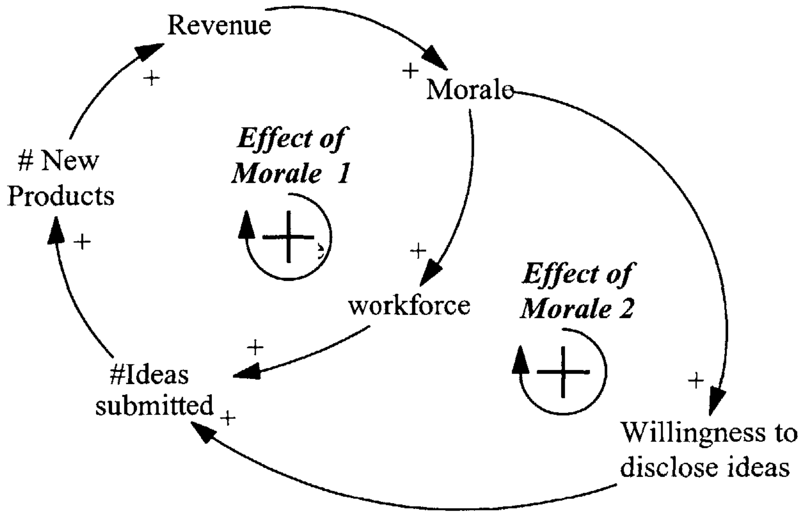


Figure 2-6: Morale Effects

Incentives

Appropriate reward systems would increase the number and possibly the quality of ideas submitted.

The R&D – Business Units link as an idea generator

An increase in communication between Business Units and R&D would lead to more ideas, leading to more new products, then to higher perceived value of R&D (by the Business Units) leading to greater communication.

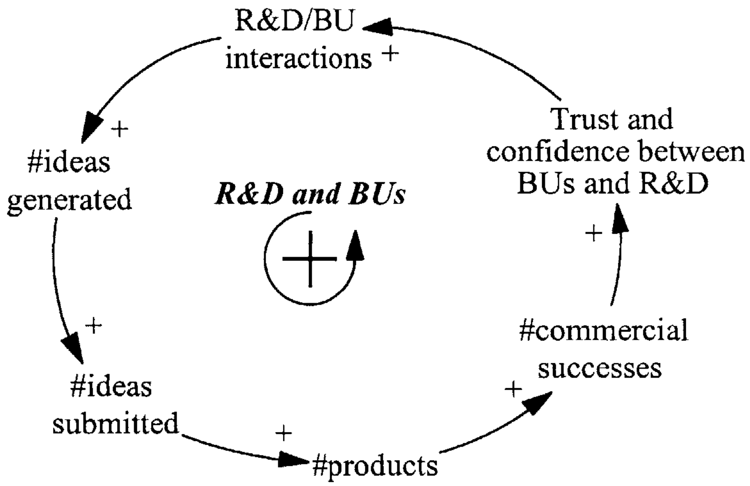


Figure 2-7: R&D and Business Units

Diversity spurs idea generation

If more projects are on-going, and contacts exist between projects, more ideas are generated.

Challenging project spurs idea generation

The more demanding a project is, the more likely it is to require inventions or innovations, the higher the probability that new ideas will be generated for other potential new platforms or products.

Strategy scope as an idea killer

As corporate strategy is more focused, more ideas are rejected early as "not aligned with strategy". Submitters become frustrated and decide to submit fewer ideas or even to stop submitting any idea. Here, there is the possibility of a "closing-loop-link" whereby the reduction in idea diversity leads to a narrowing of the strategy's scope.

Strategy scope as an idea generator

As corporate strategy is more focused, people can focus their thoughts and generate more "on-strategy" ideas, leading to more ideas in backlog, leading to more platform and/or products.

Strategy and attractiveness of R&D

If the scope of the strategy becomes narrower, talented R&D employees will leave for more attractive opportunities.

Chapter 3

THE FUNDAMENTAL EQUATION

In this chapter, we focus on our first dynamic hypothesis evoked in Chapter 2 namely "ideas fuel growth." We develop a computer model progressively. We then analyze the model's structure and behavior with the objective of drawing useful insights. We use Vensim® [Ventana 2000] as our modeling and simulation software.

Building the model

The first step in the IMP (Idea Management Process) is to input ideas in a database that was specifically designed for this task. How do we represent these submitted ideas in a model? Where do these ideas come from? What are the key drivers contributing to submitting an idea?

First of all, we can think of the submitted ideas as a stock. A rectangular box (Figure 3-1) represents that stock. In system dynamics, the term stock (also referred to as a "level") corresponds to an accumulated entity that can be measured at any moment. Mathematically, a stock is an integral. At first, this may seem abstract, but the world is full of stocks! The water in a bathtub is a typical example of a stock. Money in a bank account, inventory in a warehouse, and engineers in a company are all stocks.

In our case, the R&D workforce is also a stock (R&D Workforce). Ideas are submitted at a certain rate. Here, by rate, we mean "ideas per unit of time" for example ideas per year. This submission rate determines the inflow rate into the database. That inflow is represented on Figure 3-1 by a double line arrow. The x-like symbol represents a valve that controls the flow. For example, in the case of the stock of water in a bathtub, we can think of the water flowing from the faucet as an inflow. In general, in system dynamics, we talk about stocks and flows (inflow and outflows). Mathematically, stocks and flows are related to each other the following way: the stock is the integral of the flow and the flow is the derivative of the stock. In common language, we can state that at any moment the level of a stock is determined by its initial level, its inflow, and its outflow.

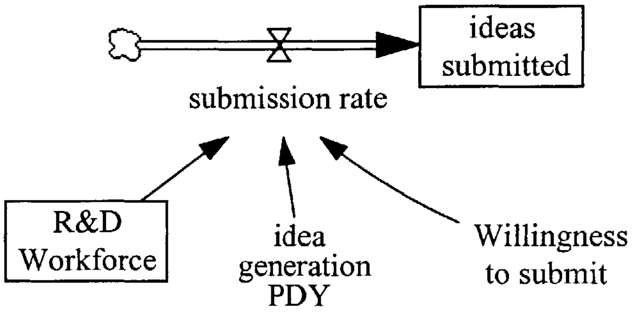


Figure 3-1: Inflow for Ideas Submitted

The Idea Management Process is aimed at the whole R&D population. Each employee generates a number of ideas per year. We therefore bring the notion of "idea generation productivity" (PDY stands for productivity) which is on average the number of ideas generated yearly per employee. At this point, it is important to distinguish between idea generation and idea submission. A person can have an idea in his/her head but not submit it. It is not only convenient but also realistic to capture this fact by using a factor called "Willingness to submit." For now, the idea generation PDY and the willingness parameters are constants. In the real world, they are variable and part of different feedback structures; we hold them constant, in order to focus on the structure of the "ideas fuel growth" hypothesis. The submission rate is the product of the workforce, the idea generation productivity, and the willingness to submit ideas.

Once ideas are submitted and reside in the database, they are subject to a review process (Figure 3-2). In reality, Company A's review process has several steps including possible return to the submitters for more information, coaching, technical reviews and an executive review. In this model, we feel it is appropriate to aggregate those several steps into one major review step. Previously, we considered the inflow drivers for submitted ideas. Here we explain the outflows from the stock of ideas submitted.

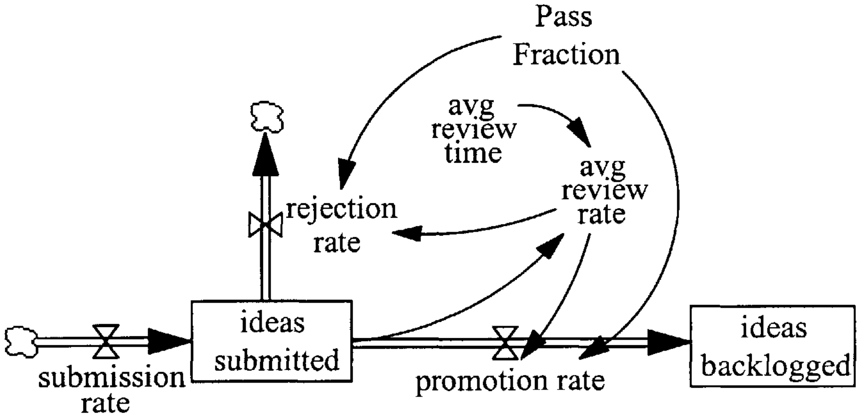


Figure 3-2: Stock and Flow for Ideas Submitted

An idea will eventually be accepted or rejected. If an idea is accepted, it means the idea has passed the review and ends up in a stock of backlogged ideas. In a sense, by the fact that it passed the review, it is a "good" idea. The promotion rate (or acceptance rate) and the rejection rate are determined by two key factors: the average time it has taken to review the ideas and the fraction of ideas that are accepted into backlog.

The promotion rate outflow from the stock of ideas submitted becomes the inflow to the stock of backlogged ideas (Figures 3-2 and 3-3).

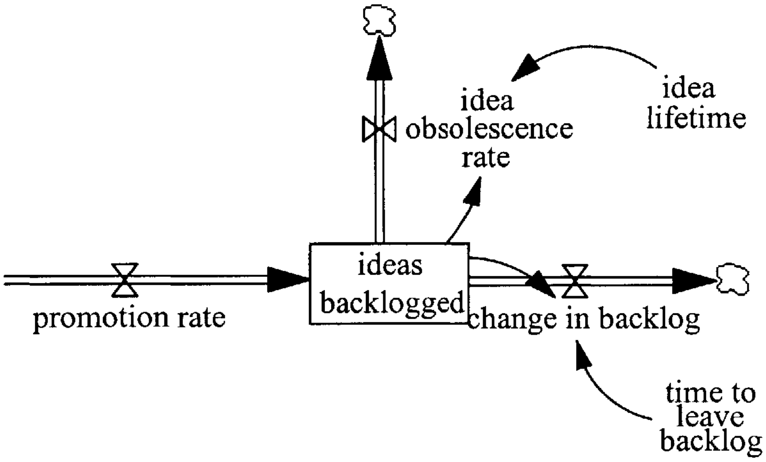


Figure 3-3: Stock and Flow for Ideas Backlogged

Backlogged ideas are ideas that present technical and business potential. The emphasis is on technical ideas because we are in an R&D organization. What happens to a backlogged idea?

Three things can happen: the idea dies (becomes obsolete naturally or independently developed by the competition), or leaves the backlog to go into product development, or leaves the backlog without being selected. The parameter called idea lifetime determines the obsolescence rate (outflow) of the backlogged ideas. The parameter "time to leave backlog" is the average time it takes for a backlogged idea to enter into product development if selected.

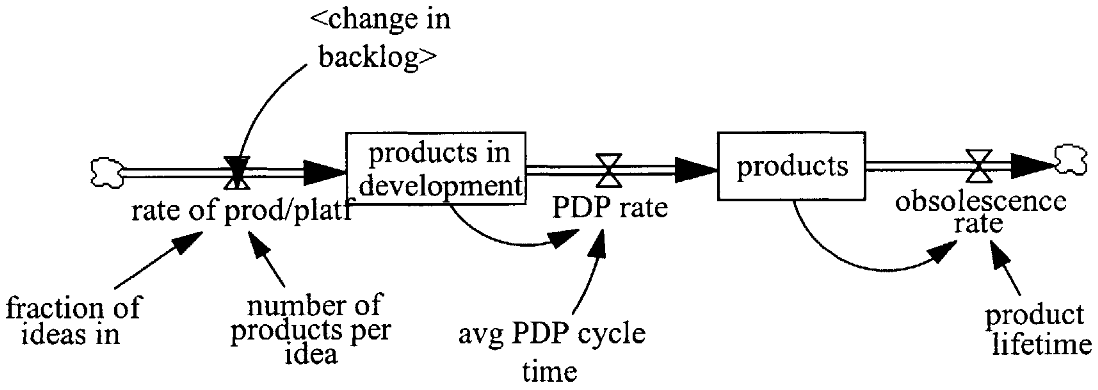


Figure 3-4: From Backlogged Ideas to Products

The "transformation" of a backlogged idea into products is shown on Figure 3-4. A certain fraction of the backlogged ideas will be selected to enter the Product Development Process. Also, one idea may be a good point product idea while another may be more of a platform type idea. While people often disagree on the exact definition of a platform, here we simply consider that a platform idea gives birth to more than one product. The parameter "number of products per idea" captures that definition. For now, that parameter is a constant set to one. The rate of product starting in development is therefore the product of the rate at which ideas are taken out of the backlog ("change in backlog") and the fraction of ideas selected ("fractions of ideas in") and the number of ideas per product. That rate is the inflow to the stock of products in development. These products are developed at a rate corresponding to an average cycle time and they accumulate in a stock called "products." The "products" stock represents different types of products such as for example a black and white photographic medium versus a color medium. These products have a certain lifetime on the market after which they become obsolete.

Let's pause a moment to reflect on the partial model so far (Figure 3-5)

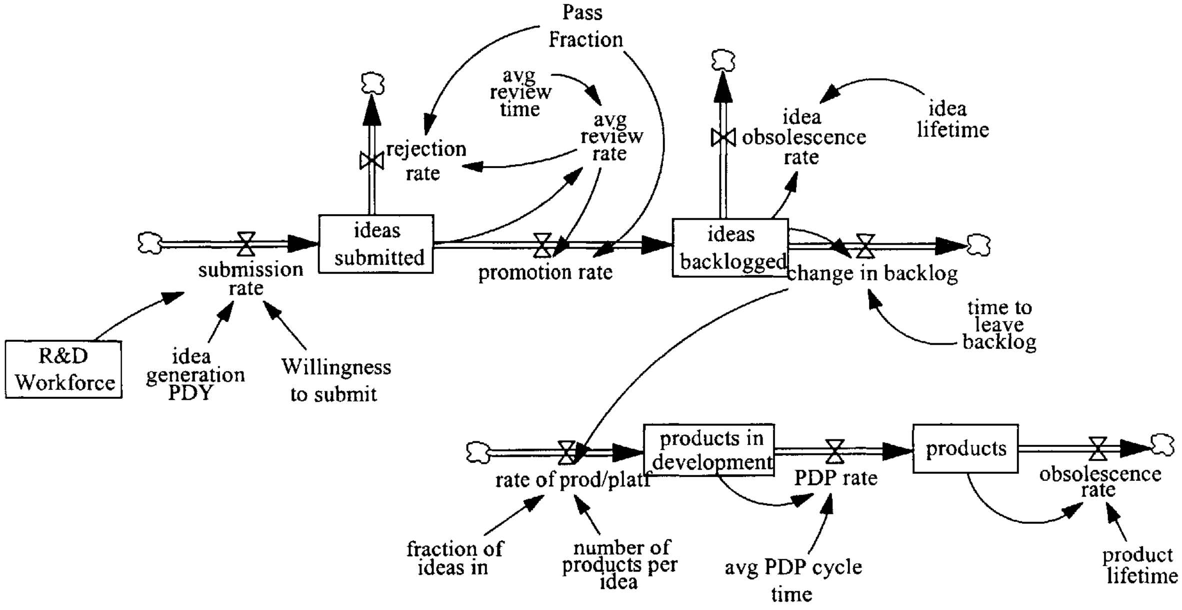


Figure 3-5: Partial Model

We have captured the fact that ideas go through an aging chain from being submitted to being backlogged. We have assumed that the review process itself guarantees that the average quality of an idea in backlog is higher than the average quality of an idea first submitted. We then modeled the fact that only a fraction of the good ideas will enter into product development; also, we consider the fact that one idea can lead to more than one product. Now we model the links of the "ideas fuel growth" hypothesis that relate the products to the R&D workforce. First of all, assuming that each product sells at a certain average price and volume, we can relate the available products to revenue (Figure 3-6).

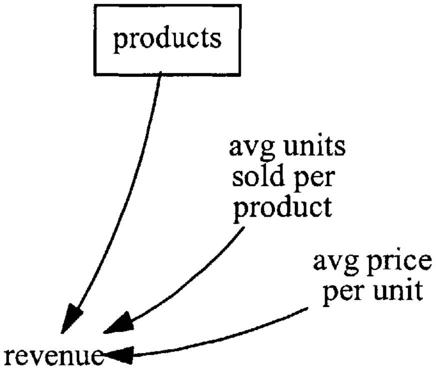


Figure 3-6: Products and Revenue

The R&D Workforce budget is determined yearly as a fraction of the revenue (Figure 3-7). The affordable workforce (referred to as indicated workforce or Indicated WF) is therefore equal to the workforce budget divided by the average R&D employee salary.

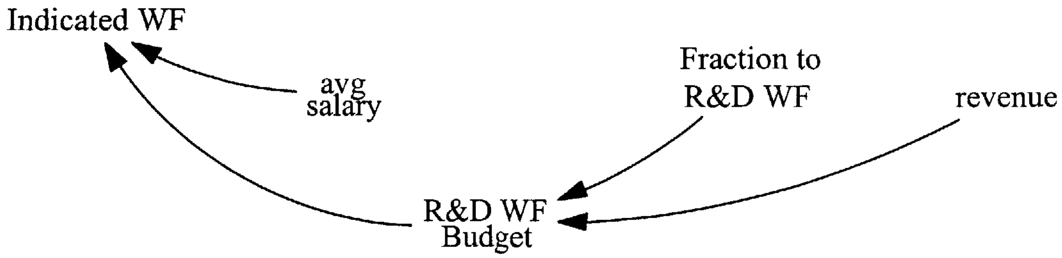


Figure 3-7: From Revenue to Indicated Workforce

The hiring rate is then derived from the gap between the current R&D WF and indicated R&D WF and the average time it takes to hire (Figure 3-8).

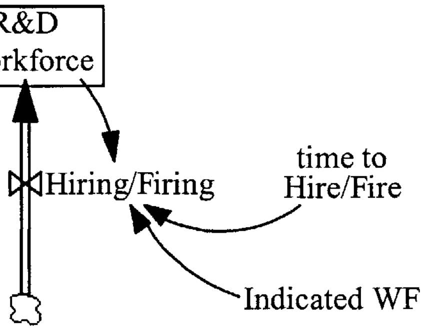


Figure 3-8: Stock and Flow for R&D Workforce

We have now closed the major loop and the full model is presented in Figure 3-9. Appendix B describes the model's equations.

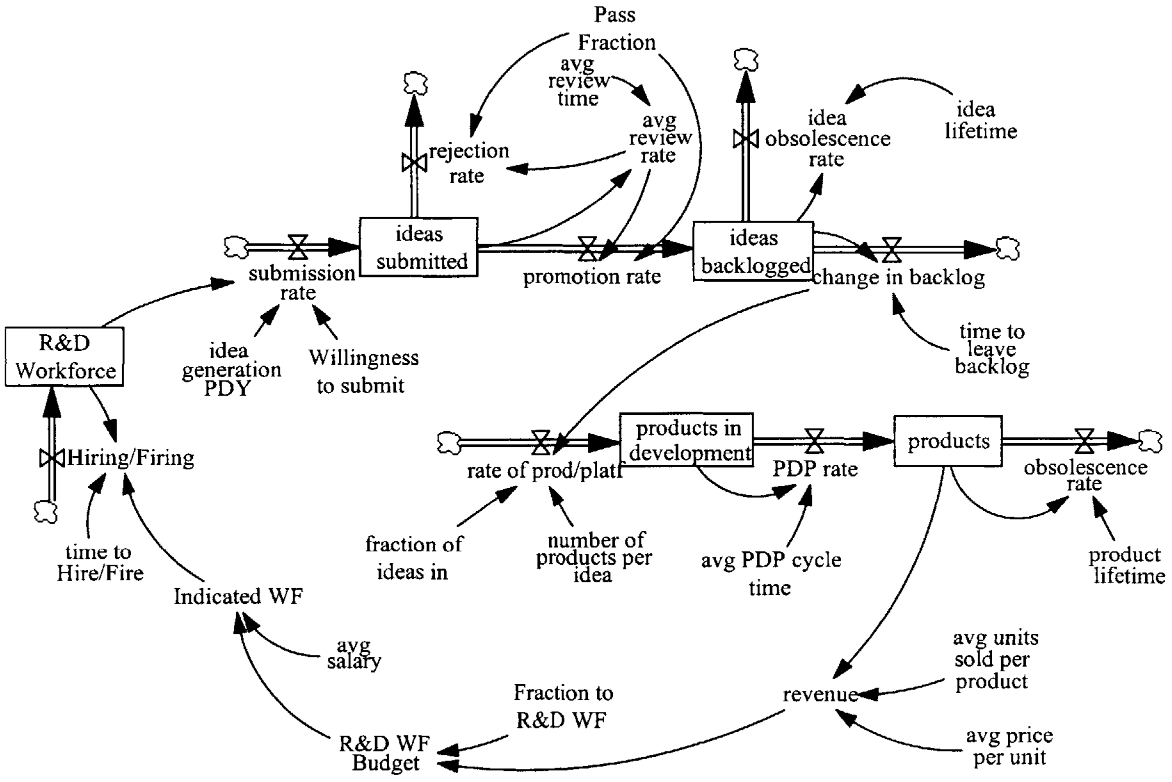


Figure 3-9: The Model

Equilibrium state: the fundamental equation

Finding the equilibrium state of a model usually facilitates model testing and model understanding. Note that not all models can be initialized in a balanced equilibrium [Sterman 2000]. A balanced equilibrium is achieved when all stocks in the system are constant over time. This implies that for each stock, the sum of its outflows equals the sum of its inflows. Our model contains five stocks and hence constitutes a system of order five. Let us derive the model's equilibrium conditions.

We investigate the system's equilibrium starting with the R&D Workforce stock. The R&D workforce is constant if the hiring/firing rate is zero:

$$Hiring\,/\,Firing = 0 \qquad (3.1)$$

$$\Leftrightarrow \frac{IndicatedWF - R\,\&\,DWF}{timetoHF} = 0 \qquad (3.2)$$

$$\Leftrightarrow R\,\&\,DWF = IndicatedWF \qquad (3.3)$$

But the indicated workforce or affordable workforce is also related to the budget:

$$IndicatedWF = \frac{R\,\&\,DWFBudget}{avgSalary} \qquad (3.4)$$

Also:

$$R\,\&\,DWFBudget = revenue * FracToR\,\&\,DWF \qquad (3.5)$$

Combining (3.3), (3.4) and (3.5), we obtain:

$$avgSalary * R\,\&\,DWF = revenue * FracToR\,\&\,DWF \qquad (3.6)$$

Equation (3.6) is interesting. It tells us that in equilibrium, the R&D workforce is such that the total spending on R&D payroll is exactly covered by the fraction of revenue allocated to it.

We can further develop the revenue term:

$$revenue = products * avgUnitsSold * avgpricePerUnit \qquad (3.7)$$

Substituting (3.7) into (3.6):

$$avgSalary * R\,\&\,DWF = products * avgUnitsSold * avgpricePerUnit * FracToR\,\&\,DWF \;(3.8)$$

But for the system to be in equilibrium, each stock has to be in equilibrium. The stock "products" which appears in equation (3.8) is in equilibrium if its inflow equals its outflow. This means:

$$PDPRate = prodobsolescenceRate = \frac{products}{productLifetime} \qquad (3.9)$$

$$\Leftrightarrow products = PDPRate * productLifetime \qquad (3.10)$$

But since the stock of products in development must also be in equilibrium, we have:

$$PDPRate = rateof\,\Pr od \qquad (3.11)$$

But we also have:

$$rateof\,\Pr od = changeInBack\log * fracIdeasIn * numOf\,\Pr odPerIdea \qquad (3.12)$$

Combining equations (3.10),(3.11), and (3.12) we obtain:

$$products = changeInBack\log * fracIdeasIn * numOf\,\Pr odPerIdea * productLifetime \qquad (3.13)$$

Developing further:

$$changeInBack\log = \frac{ideasBkl}{TimetoLB} \qquad (3.14)$$

where ideasBkl is a short notation for the "Ideas Backlogged" stock, and TimetoLB is the parameter "Time to Leave Backlog".

For the stock of ideas backlogged to be in equilibrium, we must have:

$$promoRate = ideaObsolRate + changeInBacklog \qquad (3.15)$$

Noting that:

$$ideaObsolRate = \frac{ideasBkl}{ideaLifetime} \qquad (3.16)$$

Combining equations (3.14), (3.15) and (3.16) we obtain:

$$promoRate = ideasBkl * (\frac{1}{ideaLifetime} + \frac{1}{TimetoLB}) \qquad (3.17)$$

$$\Leftrightarrow promoRate = ideasBkl * (\frac{ideaLifetime + TimetoLB}{ideaLifetime * TimetoLB}) \qquad (3.18)$$

$$\Leftrightarrow ideasBkl = promoRate * (\frac{ideaLifetime * TimetoLB}{ideaLifetime + TimetoLB}) \qquad (3.19)$$

Substituting (3.19) into (3.14):

$$changeInBacklog = promoRate * \frac{ideaLifetime}{ideaLifetime + TimetoLB} \qquad (3.20)$$

Developing further for the promotion rate:

$$promoRate = avgReviewRate * PassFrac \qquad (3.21)$$

$$\Leftrightarrow promoRate = \frac{ideasSubmitted}{avgReviewTime} * PassFrac \qquad (3.22)$$

The stock of ideas submitted must also be in equilibrium. Therefore:

$$submissionRate = promoRate + rejectionRate \qquad (3.23)$$

$$\Leftrightarrow submissionRate = \frac{ideasSubmitted}{avgReviewTime} * (PassFrac) + \frac{ideasSubmitted}{avgReviewTime} * (1 - PassFrac) \qquad (3.24)$$

$$\Leftrightarrow submissionRate = \frac{ideasSubmitted}{avgReviewTime} \qquad (3.25)$$

$$\Leftrightarrow ideasSubmitted = submissionRate * avgReviewTime \qquad (3.26)$$

Substituting (3.26) into (3.22):

$$promoRate = submissionRate * PassFrac \qquad (3.27)$$

Substituting (3.27) into (20):

$$changeInBacklog = submissionRate * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLB} \qquad (3.28)$$

But the idea submission rate is related to the R&D workforce:

$$submission\,Rate = R\,\&\,DWF * PDY * Willingnes\,s \qquad (3.29)$$

Where PDY is the idea generation productivity and Willingness is the willingness to submit ideas. Substituting 3.29 into 3.28 and 3.28 into 3.13, we obtain:

$$\begin{aligned} products = R\,\&\,DWF * PDY * Willingness * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLB} * \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \ (3.30) \end{aligned}$$

Substituting (3.30) into (3.8) we have:

$$\begin{aligned} avgSalary * R\,\&\,DWF = R\,\&\,DWF * PDY * Willingness * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLB} \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \\ * avgUnitsSold * avgpricePerUnit * FracToR\,\&\,DWF \qquad (3.31) \end{aligned}$$

Finally, as the stock term *R&DWF* cancels out in (3.31), we obtain equation (3.32). Equation (3.32) contains only parameters (i.e. no stock) and is the condition for our model's equilibrium.

$$\begin{aligned} avgSalary = PDY * Willingness * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLeaveBack \log} \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \\ * avgUnitsSold * avgpricePerUnit * FracToR\,\&\,DWF \qquad (3.32) \end{aligned}$$

We call equation (3.32) the fundamental equation for our model and we'll refer to it as such in the future. For the model to be in equilibrium, the average yearly salary of an R&D employee must equal the right hand side of equation (3.32). We wish to gain more insight about this right hand side. Mathematically, the units do match: each side of the equation is expressed in (dollars/person/year). But is there a more concrete, "real-world" explanation? We recall the simple equation (3.6) and we realize that from (3.6) to (3.32) we essentially used the model's equations and the fact that each stock must be in equilibrium. Therefore, the concept of revenue versus salary must be present in some way. Intuitively, it seems logical for the right hand side of (3.32) to contain factors such as idea generation productivity, willingness to submit, review pass fraction, fraction of ideas getting into development, and number of products to develop per idea. The other intuitive factors are the average of units per product sold yearly, average price per unit, and fraction of revenue to R&D workforce. What is more surprising is the presence of the product lifetime factor and even more interestingly the factor $(\frac{ideaLifetime}{ideaLifetime + TimetoLB})$. In order to understand (3.32) better, let us first consider a simpler model that we call model A (Figure 3-10).

In model A, we notice the following characteristics:

- There is no notion of idea lifetime. This essentially means that an idea can never be obsolete.
- There is no product lifetime: products do not become obsolete.
- There is no products stock; the selling of products occurs practically instantaneously as products come out of development. Here the parameter "average units sold per product" is expressed in units per product rather than in units per product per year. This is because the outflow from products in development determines the rate of products per year.

All three characteristics listed above are less realistic than the situation of our model. However, investigation of model A's equilibrium will shed light on the equilibrium of our model of Figure 3-9.

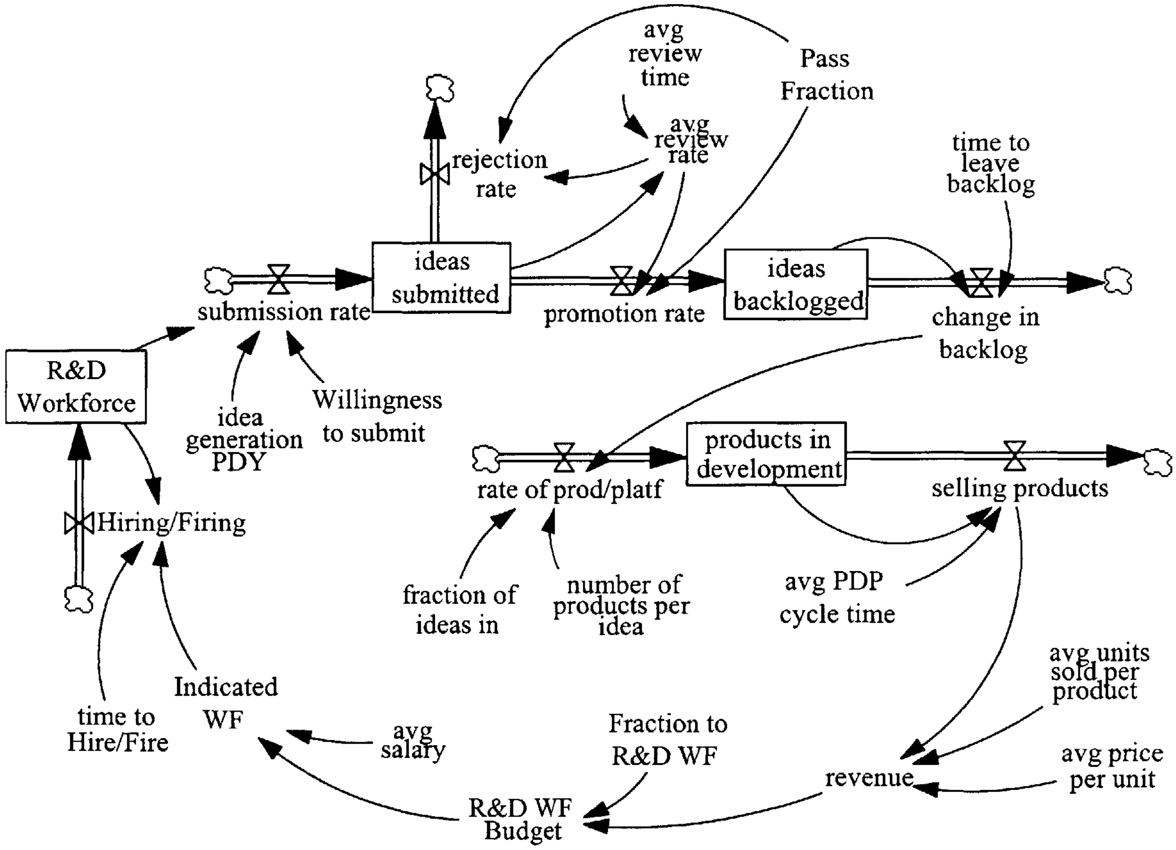


Figure 3-10: Intermediate Model A

We develop the equilibrium conditions for the four stocks of model A in a similar manner as for our model and obtain:

$$\begin{aligned} \mathit{avgSalary} &= (\mathit{PDY} * \mathit{Willingness} * \mathit{PassFrac} * \mathit{FracIdeasIn} * \mathit{numOfprodPerIdea}) \\ &\quad * (\mathit{avgUnitsSold} * \mathit{avgpricePerUnit}) * \mathit{FracToR\&DWF} \end{aligned} \tag{3.33}$$

Equation (3.33) is relatively easy to explain, and easier to tackle than (3.32). One way to look at it is to think of Jay Forrester's market growth model [Forrester 68] where equilibrium implies that each salesperson must sell exactly the equivalent of his/her salary amount. Here, in model A, we can consider the term (PDY*Willingness*PassFrac*FracIdeasIn*numOfprodPerIdea) as an overall "Fuzzy Front End efficiency." The product avgUnitsSold*avgpricePerUnit (average units sold per product * average price per unit) is like a "sales/marketing efficiency." The term FracToR&DWF (Fraction to R&D WF) reflects Company A's policy with regard to R&D budgeting.

We can even decompose our FFE (Fuzzy Front End) efficiency into more concepts. PDY is the idea generation productivity or the average number of ideas a person comes up with each year. But we can think of the term (PDY*Willingness*PassFrac) as an "ideation efficiency" because even though we start with a certain idea generation productivity, this productivity is tempered by the willingness to submit and by the fact that only a fraction of the submitted ideas are good enough to go into backlog. The FracIdeasIn factor can be viewed as the efficiency of management to select and prioritize the good ideas while assessing current resource conditions. In a sense it is the conversion efficiency of ideas into concept or feasibility phase of the Product Development Process. The factor numOfprodPerIdea (number of products per idea) is used here as a hybrid of idea platform potential and resource management. In our model, we assume the possibility of concurrent development of several products from the same platform. In a more detailed model, we could dissociate the two notions; an idea could have the potential for many products, but the products would be developed more or less concurrently depending on strategy and resource availability.

So, reviewing (3.33) with more insight, we find it logical that, for example, if any of the terms in the right hand side increases, it translates into more revenue and therefore allows for a higher salary. But model A assumes no product obsolescence, which is not realistic. How do we take into account the existence of the lifetime of a product?

Let us build model B based on model A by adding a stock of products and the fact that a product has a lifetime associated with it (Figure 3-11). In other words, products become obsolete and therefore are not sellable after a certain time, that time being the lifetime duration.

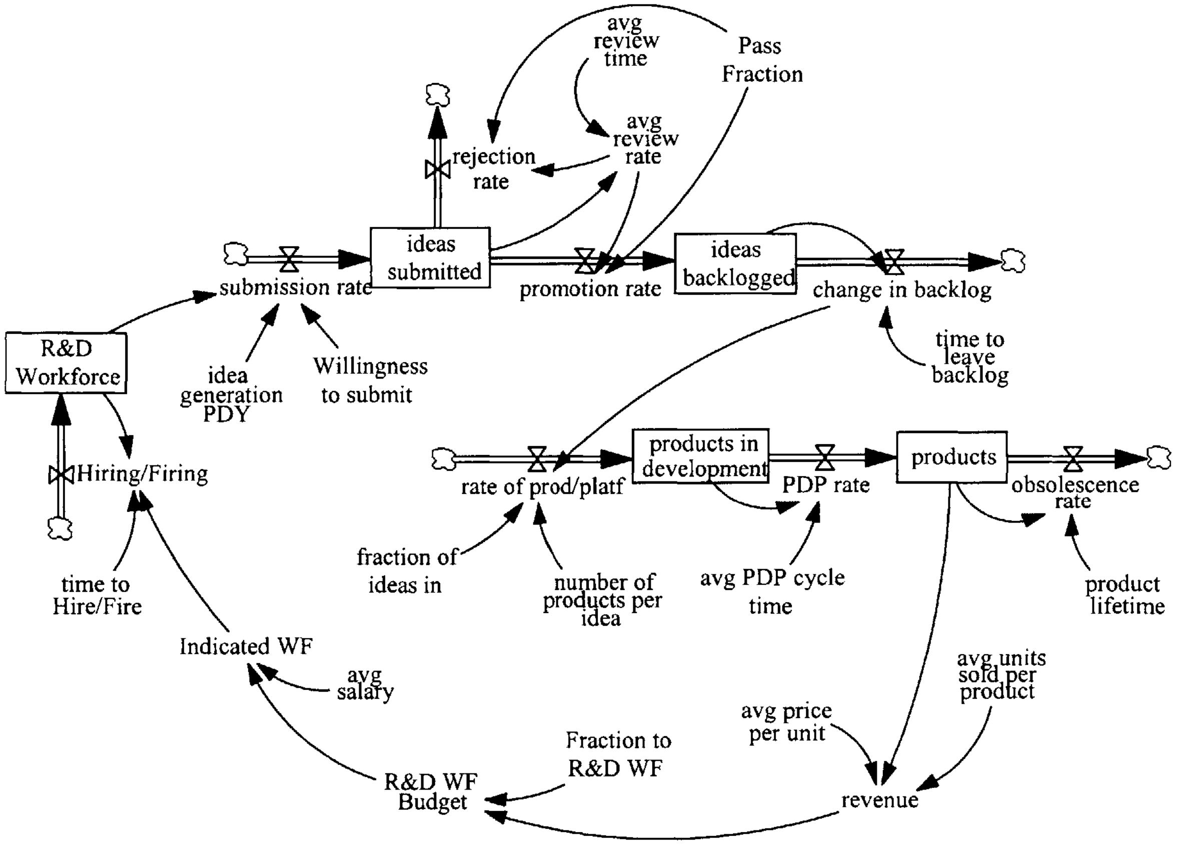


Figure 3-11: Intermediate Model B

Let us investigate the impact of this more realistic situation on the equilibrium of the system. If we proceed through the equilibrium conditions, we obtain the following equation:

$$
\begin{aligned}
avgSalary = {} & PDY * Willingness * PassFrac * FracIdeasIn * numOfprodPerIdea \\
& * productLifetime * avgUnitsSold * avgpricePerUnit * FracToR\&DWF \qquad (3.34)
\end{aligned}
$$

Let us note first that, as in our model, the average units sold is expressed in unit per product per year. Mathematically, the reason why the term "productLifetime" comes into play is because of the requirement for the products stock to be in equilibrium and the fact that revenue is a function of the products stock. Since the PDP rate (inflow) must equal the product obsolescence rate (outflow) and since the obsolescence rate is defined as the products stock divided by the product lifetime (see equation 3.9), we see how the term productLifetime is kept in the right hand side of equation (3.34) and (3.32). A non-mathematical perspective is useful too since we want to really understand our model. One way to think about productLifetime is to realize that we are really interested in the term (productLifetime*units sold per product) or the total number of units (from all different products types) sold. For example, if we have only one product in our stock and its lifetime is half a year, the total number of units sold is only half of the predicted units sold per year.

To build up from model B (Figure 3-11) to our model (Figure 3-9), we just need to include an outflow from the stock of backlogged ideas that corresponds to the obsolescence rate of ideas. We already derived the equilibrium conditions and found out that equation (3.32) must be verified. Reviewing equation (3.34) for model B and our fundamental equation (3.32) for our model, we see that the only difference is the term:

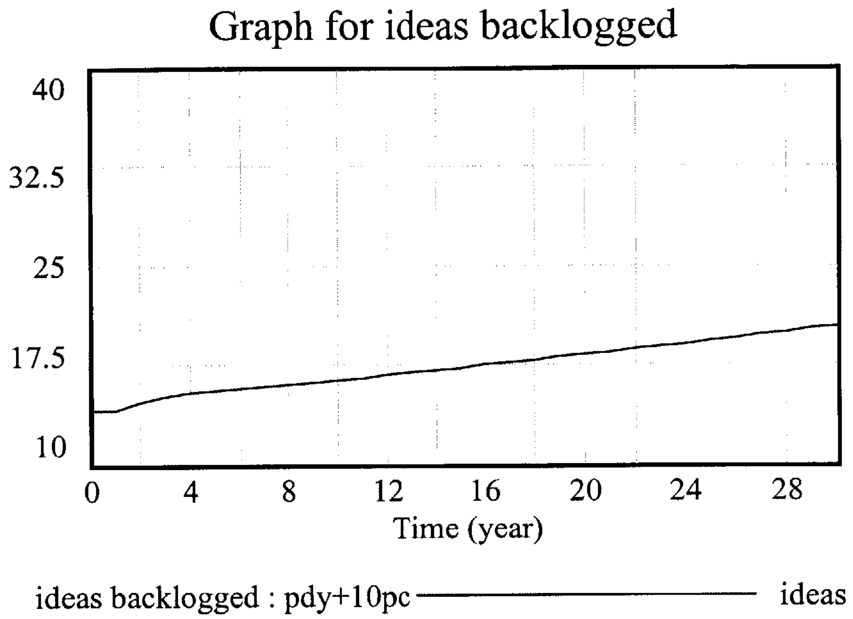
[idea lifetime/(idea lifetime+TimeToLeaveBacklog)] appearing in (3.32). A helpful perspective for understanding this term is to realize that it is equal to:

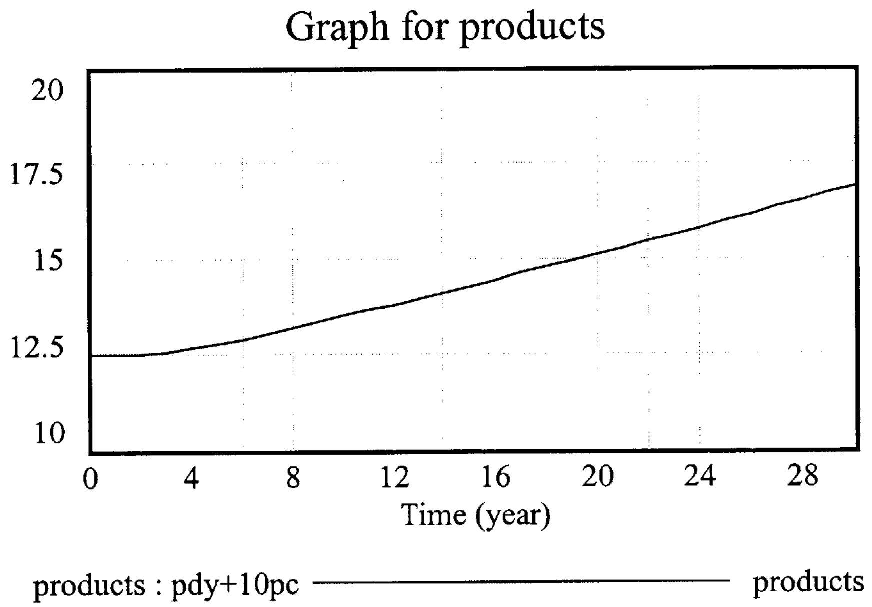
(change in backlog)/(change in backlog + idea obsolescence rate)

This ratio is a ratio of rates and represents the "survival" fractional rate for an idea. In other words, it is a warning to management: " What is the point of backlogging ideas if by the time we can work on them they are already dead!"

The model's behaviors

At this point, we have a model (Figure 3-9), and a fundamental equation for the idea management process. Let us now simulate our model and observe its possible behaviors. We first focus on the idea generation productivity PDY. We start our model at equilibrium and apply in year one a ten-percent increase (as a step function) to PDY. What happens? The following plots of Figure 3-12 show the responses of our key variables (ideas backlogged, products, revenue, R&D workforce). To ensure that we fully capture the dynamic trend, we have extended the time horizon to thirty years.


Graph for ideas backlogged
40
32.5
25
17.5
10
0
4
8
12
16
20
24
28
Time (year)
ideas backlogged : pdy+10pc
ideas


Graph for products
20
17.5
15
12.5
10
0
4
8
12
16
20
24
28
Time (year)
products : pdy+10pc
products

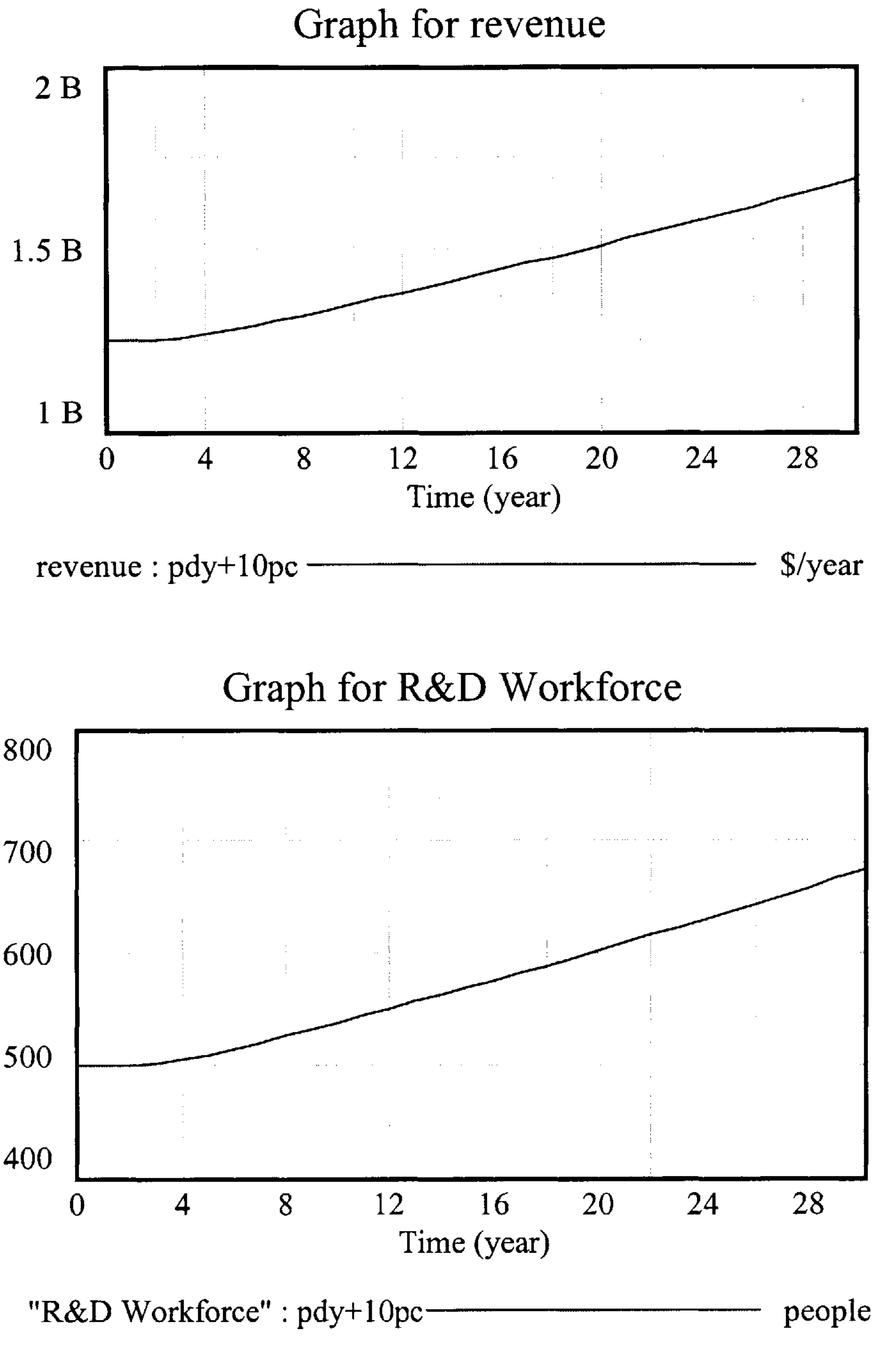


Figure 3-12: Step Responses to PDY Increase

We are happy to see growth in all of our key variables: we have captured the firm's "hope" reference modes presented in Chapter 1. We intuitively expected our "ideas fuel growth" hypothesis would produce growth and that policies to increase the idea generation productivity of the R&D workforce must be considered. We will discuss policies in Chapter 4. First, let us observe the effect of a decrease in PDY. The simulation (Figure 3-13 shows the stock "products") reveals a downward goal-seeking behavior for all of our variables of interest. This is interesting: our "ideas fuel growth" model is actually capable of leading the firm to decline to zero. When the PDY drops just a little (step function in year one), fewer ideas are backlogged, fewer products made and sold. This situation implies less revenue, a lower R&D budget and a reduction in R&D workforce, which slows down the ideation process. Unless a different mechanism is put in place, the vicious circle continues leading the firm to bankruptcy. In the real world, there is the potential of non-technical ideas that continue to bring revenue of Company A. But here, we are focused on new products issued from new technical ideas. We count on these ideas for the longer term and we are even more motivated to find policies that will enhance our idea generation productivity, now that we have observed our "fear" reference mode.

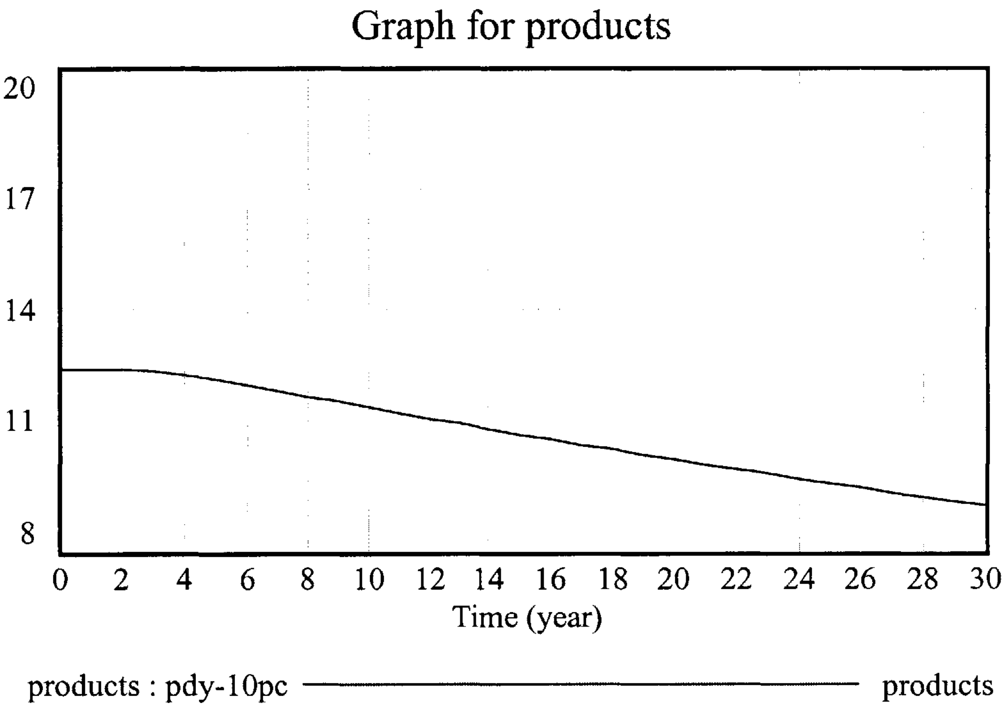


Figure 3-13: Step Response to PDY Decrease

Let us reflect back to our fundamental equation (3.32):

$$\begin{aligned} avgSalary = PDY * Willingness * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLeaveBack\,\mathrm{log}} \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \\ * avgUnitsSold * avgpricePerUnit * FracToR\,\&\,DWF \end{aligned}$$

The link between the fundamental equation and the model's behaviors is especially clear after our previous two simulations. Interestingly, our fundamental equation reveals a number of parameters that are mathematically similar to the idea generation productivity PDY. Company A has been focusing on the idea submittal rate primarily via PDY but we see clearly that other levers merit consideration. In addition to the idea generation PDY illustrated above, the following parameters belong to the fundamental equation and therefore constitute levers for the growth or decline of the firm (we use here the full parameter names as found in Figure 3-9):

- Willingness to Submit
- Pass Fraction
- Idea Lifetime/(Idea Lifetime + TimeToLeaveBacklog)
- Fraction of Ideas in
- Number of Products per Idea
- Product Lifetime
- Average Units Sold per Product
- Average Price per Unit
- Fraction to R&D WF
- Average Salary

Let us investigate the "TimeToLeaveBacklog" parameter. As predicted from our fundamental equation, if we start the model at equilibrium and simulate a drop in the parameter TimeToLeaveBacklog in year one, growth is triggered through the dominance of the major positive loop and products, revenue, and workforce behave as in Figure 3-12. Interestingly, when we look at the "ideas backlogged" variable, we obtain the behavior shown in Figure 3-14. At first, this is surprising. We expected a growth curve similar to the one for "ideas backlogged" in Figure 3-12. But we realize that the decrease in TimeToLeaveBacklog implies a sudden increase in the "change in backlog" rate which is an outflow for the ideas backlogged. So just after the step function is applied, the stock of ideas backlogged is subjected to a bigger outflow than inflow and starts to deplete. However, the impact of the shorter time for ideas to leave backlog is a faster rate of entry into product development and the virtuous cycle takes off. After a certain period of depletion of the backlogged ideas, the stock starts to grow again. This is a good illustration for cautiousness in "localized" metrics. If one were to focus only on the number of ideas backlogged, one may reach a false conclusion when the stock depletes. One may think that the inflow is at fault when in reality the outflow into product development is increasing leading to more product development projects.

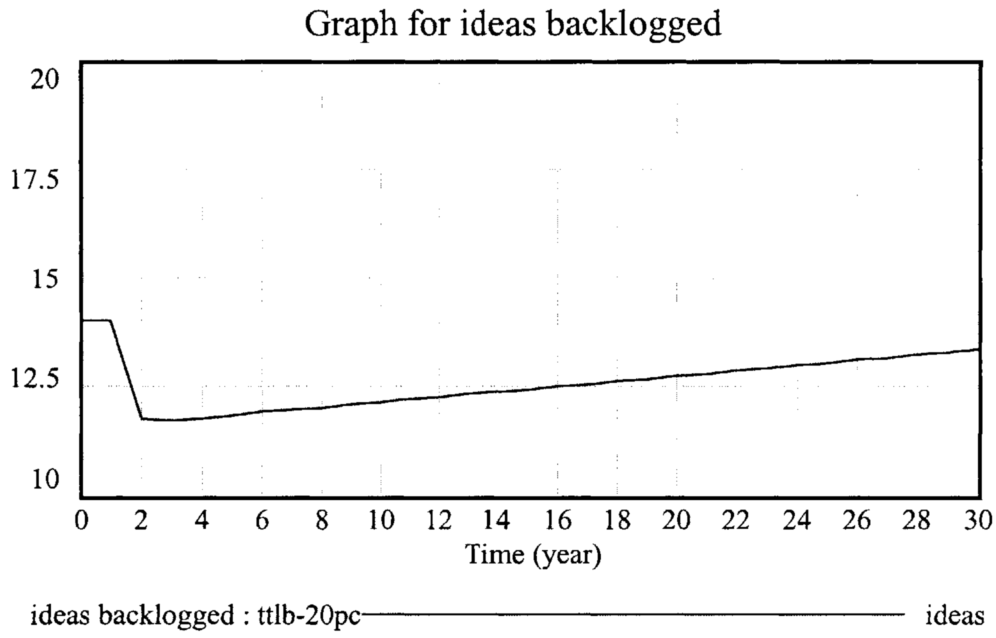


Figure 3-14: Step Response to Decrease in TimeToLeaveBacklog

Three model parameters do not appear in the fundamental equation. They are: Average PDP Cycle Time, Average Review Time, and Time to Hire/Fire. How does a step change in any of those parameters impact the system's behavior?

Let us first consider the parameter Average PDP Cycle Time. As shown in Figure 3-15 with the revenue behavior, the system responds to an Average PDP Cycle Time step by reaching a new equilibrium. To explain this, it is useful to refer to the model (Figure 3-9). As the Average PDP Cycle Time is stepped down (in this example by 50 percent - in curve 1 of Figure 3-15 -), more products are available. Revenue increases and the budget allocated to R&D workforce follows. This triggers hiring and the R&D workforce grows. This in turn contributes to a higher submission rate and more ideas in backlog.

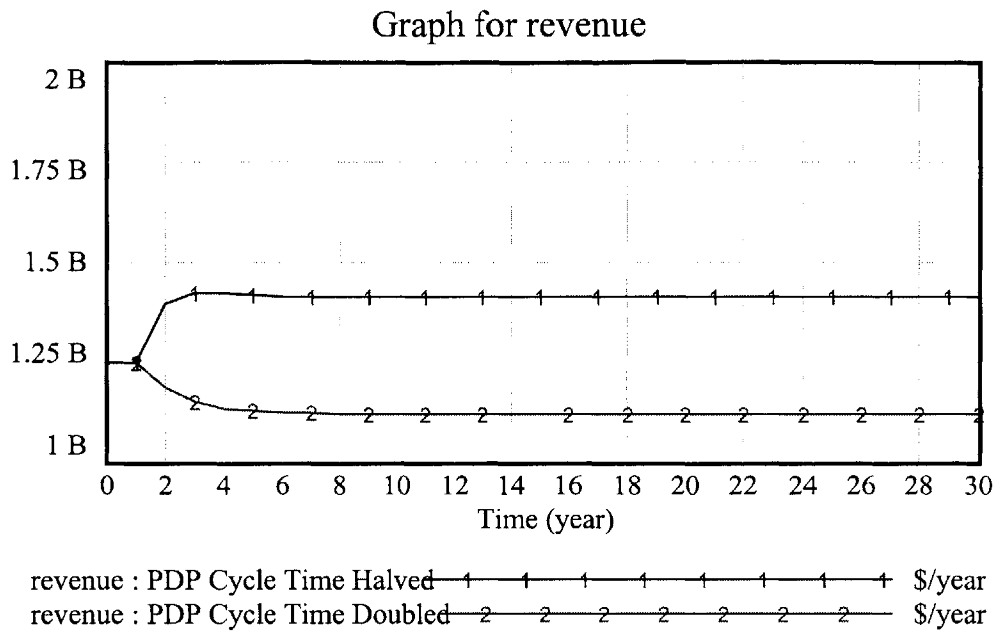


Figure 3-15: Step Responses to Average PDP Cycle Time for Revenue

However, as illustrated in Figure 3-16, the stepping down of the PDP Cycle Time also triggers a decrease in the stock of products in development due to the increased PDP rate (outflow from products in development). This brings the PDP rate down and the overall system ends up in a new state of equilibrium. The new equilibrium is "directionally" logical in the sense that a shorter product development cycle time is beneficial to the firm. However, the PDP Cycle Time parameter constitutes mathematically a weaker lever than the previous parameters since it does not produce growth by itself.

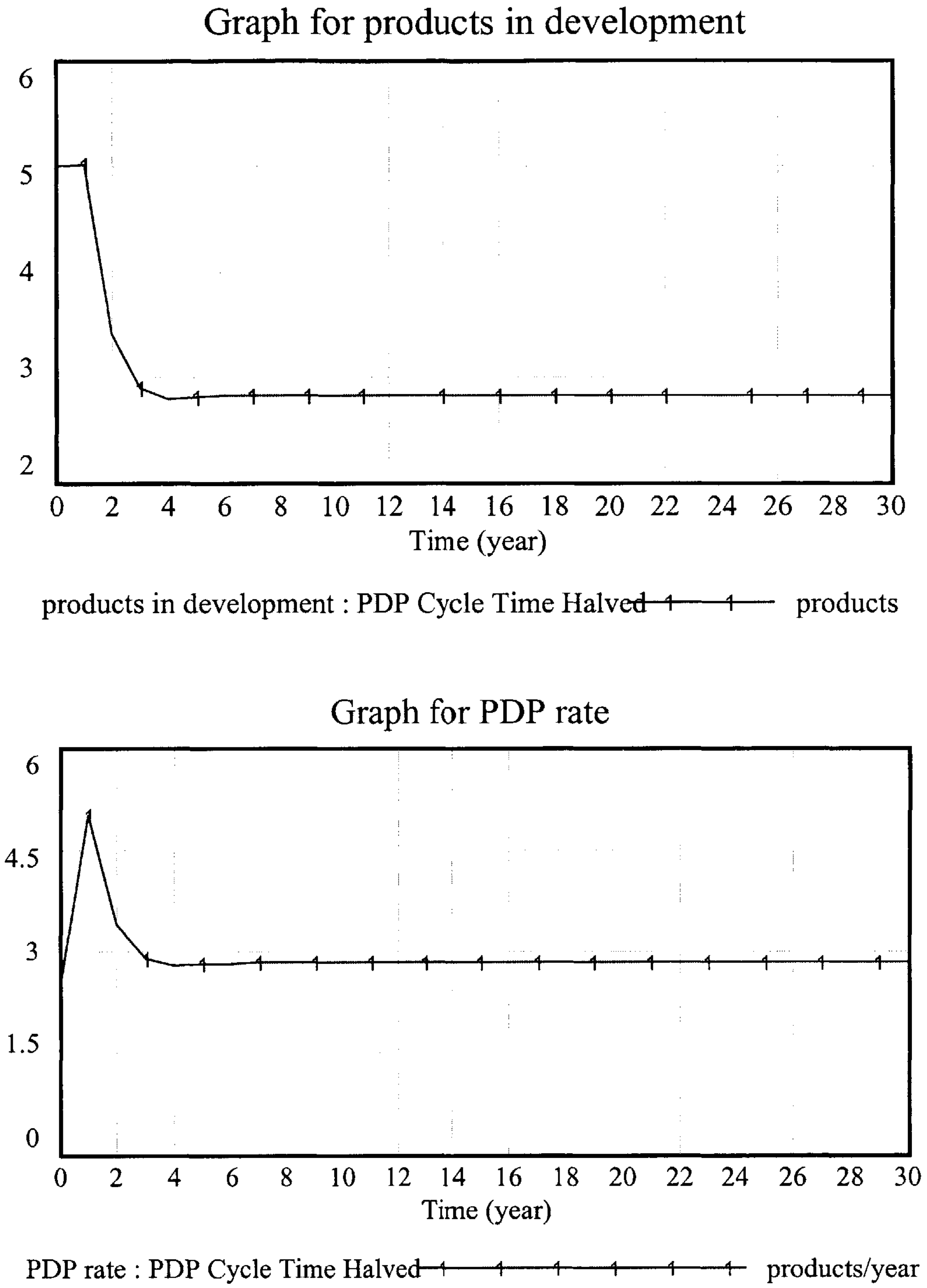


Figure 3-16: Step Response to PDP Cycle Time for Products in Development &PDP Rate

Let us now explore the parameter Average Review Time. The simulation gives a similar behavior for revenue as in Figure 3-15. When the time to review ideas is shortened (respectively lengthened), revenue increases (respectively decreases) and reaches a new equilibrium at a higher (respectively lower) level than the initial equilibrium. If the Average Review Time is stepped down, ideas are reviewed faster, more ideas arrive in backlog, more products are made, and revenue increases. This leads to more hiring and to more R&D employees who submit more ideas. However, the faster review rate has resulted in a depletion of the stock of ideas submitted. This effect eventually balances the increase of ideas submitted due to the additional workforce and the system settles at a new equilibrium level. We draw a similar conclusion about the leverage property of Average Review Time as for the PDP Cycle Time.

The third parameter that does not belong to the fundamental equation is the Time to Hire/Fire. Interestingly, when we change this parameter, the system remains in its original equilibrium. This is due to our hiring/firing policy being based on the gap between our current R&D workforce and the workforce that can be sustained by the R&D budget. The budget is determined as a constant fraction of revenue. Since we start our system in equilibrium, the workforce is stable at this point where its contribution to revenue is just enough to maintain the staff. Therefore, the model expresses no need to hire or fire. If we do not hire or fire, it is logical that the time constant to hire or fire has no effect on the system.

However, if the system is not in an equilibrium state to start with, the time to hire/fire will impact the system's behavior. For example, if the system is in a growth mode, a shorter hiring time helps the system grow faster. Figure 3-17 shows a growth behavior triggered by a stepped-up PDY (curve marked 2) and the effect on that growth of a fifty percent shorter time to hire/fire (curve marked 1). We notice that the impact is quite small even though the time to hire/fire was halved. This is due to the fact that the initial time to hire/fire is much smaller than the overall duration of ideation plus product development. Of all the model's parameters the Time to Hire/Fire exhibits the least leverage.

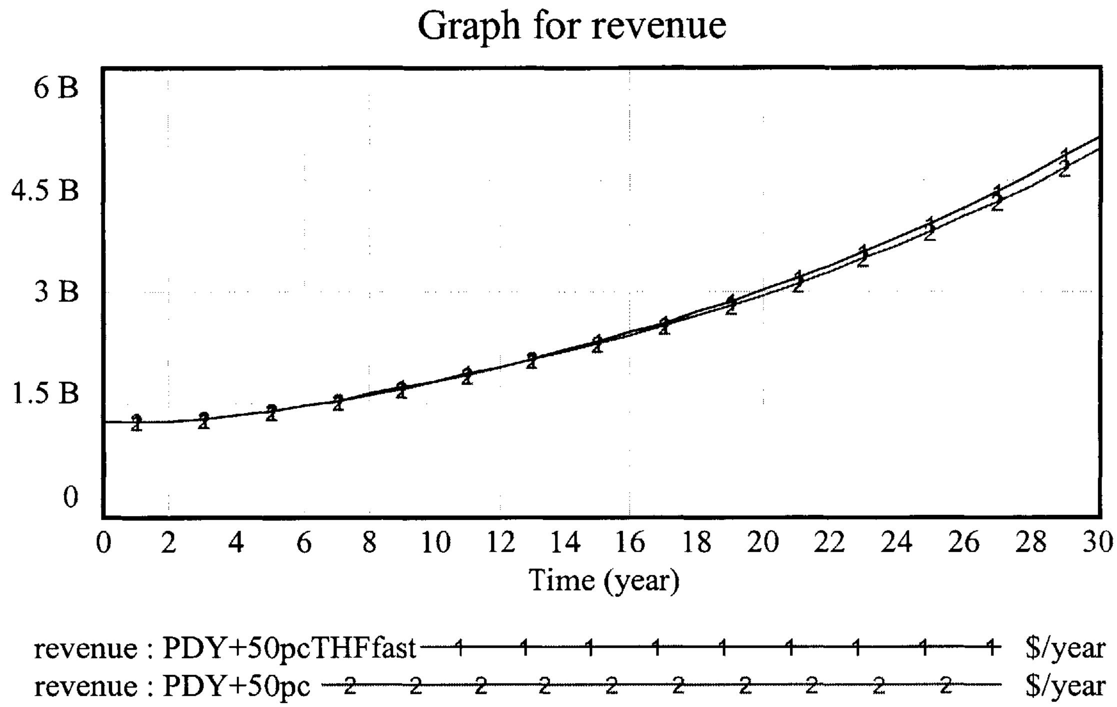


Figure 3-17: Effect of Time to Hire/Fire on Growth

Eigenvalue analysis

Several engineering disciplines have used eigenvalue analysis for a long time, especially to study the stability of servo-mechanisms systems. Here, we use this engineering rooted approach to better understand the relationships between our model's behaviors and our model's structure.
Our model contains five stocks (or levels) and constitutes therefore a system of order five. The model is linear because each rate is a linear combination of stocks. We suggest that our model can be described in the following way:

$$\frac{\partial x}{\partial t} = Ax$$

where x is the vector of our model's stocks and A is a 5x5 matrix.

We need to determine matrix A. Using the equations relating flows to stocks from the section "Equilibrium state: the fundamental equation" we find that:

$$\frac{\partial x}{\partial t} = Ax \qquad (3.35)$$

where x is the vector of stocks:

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix} = \begin{bmatrix} IS \\ WF \\ IB \\ PDEV \\ P \end{bmatrix} \qquad (3.36)$$

with, for notational convenience:

IS = ideas submitted
WF = R&D Workforce
IB = ideas backlogged
$PDEV$ = products in development
P = products

and where matrix A is defined as:

$$A = \begin{bmatrix} \frac{-1}{ART} & PDY * Will & 0 & 0 & 0 \\ 0 & \frac{-1}{THF} & 0 & 0 & Z \\ \frac{Pass}{ART} & 0 & -\left(\frac{1}{TTLB} + \frac{1}{IL}\right) & 0 & 0 \\ 0 & 0 & \frac{FII * NPPI}{TTLB} & -\frac{1}{ACT} & 0 \\ 0 & 0 & 0 & \frac{1}{ACT} & -\frac{1}{PL} \end{bmatrix} \qquad (3.37)$$

with, for notational convenience:

ART = Average Review Time

PDY = Idea Generation PDY

$Will$ = Willingness to Submit

THF = Time to Hire/Fire

$Pass$ = Pass Fraction

$TTLB$ = Time to Leave Backlog

$TTLB$ = Time to Leave Backlog

IL = Idea Lifetime

FII = Fraction of Ideas in

$NPPI$ = Number of Products per Idea

ACT = Average PDP Cycle Time

PL = Product Lifetime

$$Z = \frac{FractiontoR\,\&\,DWF * AvgUnitsSoldper\,\mathrm{Pr}\,oduct * Avg\,\mathrm{Pr}\,iceperUnit}{THF * AvgSalary}$$

Putting equations (3.35), (3.36) and (3.37) together:

$$\frac{\partial}{\partial t}\begin{bmatrix} IS \\ WF \\ IB \\ PDEV \\ P \end{bmatrix} = \begin{bmatrix} \frac{-1}{ART} & PDY * Will & 0 & 0 & 0 \\ 0 & \frac{-1}{THF} & 0 & 0 & Z \\ \frac{Pass}{ART} & 0 & -\left(\frac{1}{TTLB} + \frac{1}{IL}\right) & 0 & 0 \\ 0 & 0 & \frac{FII * NPPI}{TTLB} & -\frac{1}{ACT} & 0 \\ 0 & 0 & 0 & \frac{1}{ACT} & -\frac{1}{PL} \end{bmatrix} \begin{bmatrix} IS \\ WF \\ IB \\ PDEV \\ P \end{bmatrix} \qquad (3.38)$$

Now that we have shown that our system can indeed be described as suggested (i.e. $\frac{\partial x}{\partial t} = Ax$ and x is the vector of stocks), we can use our knowledge about differential equations and eigenvalues/eigenvectors. The vector x is called the state vector, and the matrix A is called the state matrix. The solution of our system is of the form:

$$x = x_0 V \exp(Dt) V^{-1}$$

where x_0 is the state vector at time zero, D is the matrix of A's eigenvalues (D is diagonal), and V is the matrix of associated eigenvectors.

The form of the solution for x reveals a very interesting fact: all the dynamics of the system reside in the term exp(Dt) which is itself characterized by the eigenvalues of the state matrix A. A real positive eigenvalue corresponds to a growth mode, a real negative eigenvalue corresponds to a decay mode, and a complex eigenvalue corresponds to an oscillation mode. For a system of order n (i.e. n stocks or levels), there will be n eigenvalues and n eigenvectors. Note that each entry a_{kl} (row k, column l) of matrix A is the *strength* (or *gain*) of the link between stock x_l and stock x_k. Also, each entry on the diagonal of matrix A corresponds to a minor loop where the stock has an influence on itself (for example the stock "products" or P affects itself through the link strength $\frac{1}{PL}$ that appears in $\frac{\partial P}{\partial t} = \frac{1}{ACT} * PDEV - \frac{1}{PL} * P$). All of our minor loops are negative loops (signs of entries are negative). Off-diagonal entries represent effects from stocks other than the one under consideration.

Once the eigenvalue associated with the system's behavior of interest is identified, we can conduct an eigenvalue sensitivity analysis. This sensitivity analysis also called "elasticity analysis" determines the percentage change in the eigenvalue resulting from a one percent increase in a link's strength. By observing which links reinforce the behavior of interest, we can determine which loop or loops in the model's structure are dominant and generator(s) of the behavior under consideration.

In each of the following two sections, we conduct an eigenvalue elasticity analysis to identify the dominant loops that are responsible for the model's behaviors. We first examine the model's growth mode and then the model's decay mode.

Eigenvalue analysis: growth mode

Let us investigate the growth mode of our model from an eigenvalue/eigenvector perspective. What underlying structure makes our model grow? In order to proceed with the analysis, we consider our model starting in equilibrium and subject to a step increase in the Idea Generation PDY. We know from the fundamental equation and our earlier simulation (Figure 3-12) that under this condition the system grows exponentially. From the simulation, we can also approximate the time constant of this exponential growth. We observe that the doubling time for the system is $T_{double} = 60.5\,\text{years}$ (each stock's value doubles every 60.5 year). Using the relationship linking time constant to doubling time, we derive the time constant of the exponential growth to be approximately 87 years ($= \frac{T_{double}}{\ln 2} = \frac{60.5}{0.693}$).

We use Analyzit™ [Hines 2000] to extract the eigenvalues of our model subjected to a ten percent step increase in PDY. The numerical state matrix A_1 is:

$$A_1 = \begin{bmatrix} -1 & 0.77 & 0 & 0 & 0 \\ 0 & -4 & 0 & 0 & 160 \\ 0.1 & 0 & -2.5 & 0 & 0 \\ 0 & 0 & 0.178 & -0.5 & 0 \\ 0 & 0 & 0 & 0.5 & -0.2 \end{bmatrix}$$

and we find the following five eigenvalues λ_i with $i = 1\ to\ 5$:

$$\begin{aligned} \lambda_1 &= -2.59762 \\ \lambda_2 &= -0.81627 + 0.44118j \\ \lambda_3 &= -0.81627 - 0.44118j \\ \lambda_4 &= 0.01123 \\ \lambda_5 &= -3.98107 \end{aligned}$$

The units for the eigenvalues are ($year^{-1}$) or (1/time). This makes sense since, as mentioned before, the solution of $\frac{\partial x}{\partial t} = A_1 x$ is $x = x_0 \exp(D_1 t)$ with D_1 being the matrix of A_1's eigenvalues.

We know from simulation that we are analyzing our system under a growth behavior. The corresponding eigenvalue can only be real and positive. We suspect that λ_4 is the eigenvalue associated with the growth behavior of our system since it is the only positive real eigenvalue. Furthermore, we can calculate λ_4's equivalent time constant which is $\tau_4 = \frac{1}{\lambda_4}$ = 89 years. Our time constant approximation from simulation was 87 years which is very close to τ_4. This confirms that λ_4 is responsible for the growth mode of our model. Using Analyzit™ for elasticity analysis on λ_4, we find the link elasticities which are listed in the table below.

Link	**Link Elasticity (%)**
ideas backlogged→ products in development	10.68
products → R&D Workforce	10.68
products in development → products	10.68
R&D Workforce → ideas submitted	10.68
ideas submitted → ideas backlogged	10.68
R&D Workforce → R&D Workforce	-10.65
ideas backlogged → ideas backlogged	-10.63
ideas submitted → ideas submitted	-10.56
products in development → products in development	-10.45
products → products	-10.12

Each positive elasticity of value 10.68% means that when the corresponding link strength increases by 1%, the eigenvalue λ_4 increases by 10.68%, leading to a sharper growth. On the other hand, a negative elasticity signifies that the link under consideration makes the eigenvalue less positive. The above table indicates that the links that reinforce the growth behavior are all the links that belong to the major positive loop of the model (ideas submitted → ideas backlogged → products in development → products → R&D Workforce). The minor negative loops, however, diminish the growth. Hence, growth is caused when the major positive loop dominates over the minor negative loops.

Eigenvalue analysis: decay mode

We conduct a similar analysis as in the previous section, but now we focus on the model's decay mode (refer to Figure 3-13). With the step decrease of ten percent in PDY, we obtain the following state matrix A_2:

$$A_2 = \begin{bmatrix} -1 & 0.63 & 0 & 0 & 0 \\ 0 & -4 & 0 & 0 & 160 \\ 0.1 & 0 & -2.5 & 0 & 0 \\ 0 & 0 & 0.178 & -0.5 & 0 \\ 0 & 0 & 0 & 0.5 & -0.2 \end{bmatrix}$$

We find the following five eigenvalues β_i with $i = 1\ to\ 5$ (and units in $year^{-1}$):

$$\begin{aligned} \beta_1 &= -2.58097 \\ \beta_2 &= -0.81126 + 0.39675j \\ \beta_3 &= -0.81126 - 0.39675j \\ \beta_4 &= -0.01192 \\ \beta_5 &= -3.98107 \end{aligned}$$

A decay, or goal-seeking behavior corresponds to a real negative eigenvalue. Also, the model's simulation indicates a time constant of roughly 87 years for the decay. We conclude that β_4 which corresponds to a time constant of 84 years is the eigenvalue responsible for the observed decay mode. An elasticity analysis of the eigenvalue β_4 gives the following results:

Link	Link Elasticity (%)
products → products	-9.87
products in development → products in development	-9.51
ideas submitted → ideas submitted	-9.39
ideas backlogged → ideas backlogged	-9.32
R&D Workforce → R&D Workforce	-9.30
products in development → products	9.28
ideas backlogged→ products in development	9.28
R&D Workforce → ideas submitted	9.28
products → R&D Workforce	9.28
ideas submitted → ideas backlogged	9.28

The links that reinforce the goal-seeking behavior are the links that trigger a negative elasticity (because a negative elasticity means a smaller β_4 eigenvalue). From the above table, we see that the five top links lead to negative elasticities. Those links represent the minor loops (stock influencing itself) in the model. Also, the links belonging to the major loop make the eigenvalue β_4 "less negative", since the elasticities of those links are positive. Therefore, decay is caused when the minor negative loops dominate over the major positive loop.

The dominance of the major positive loop causes growth. The major positive loop corresponds to the self-reinforcing idea generation mechanism by which new ideas provide the resources for more new ideas. The dominance of the negative minor loops causes decay. The minor loops represent the processes of obsolescence (idea obsolescence and product obsolescence). Equilibrium occurs when the minor negative loops and the major positive loop balance, in other words when growth exactly compensates for obsolescence. Clearly, management wishes for the idea generation process to outdo the obsolescence processes.

The fundamental equation and loop dominance

Let us go back to the fundamental equation (3.32):

$$\begin{aligned} avgSalary = PDY * Willingness * PassFrac * \frac{ideaLifetime}{ideaLifetime + TimetoLeaveBack\log} \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \\ * avgUnitsSold * avgpricePerUnit * FracToR \,\&\, DWF \end{aligned}$$

It turns out that practically each parameter that belongs to the fundamental equation affects a minor negative loop only or the major positive loop only, but not both. For example, *productLifetime* affects only the minor negative loop associated with the stock "products" (by determining the obsolescence rate of the products). Since our model has only one major positive loop, it is easy to verify our previous observation by inspecting the state matrix A (see equations 3.37 and 3.38). Any parameter that appears in a diagonal entry affects the corresponding negative minor loop, and any parameter in an off-diagonal entry impacts the major positive loop. Except for TimeToLeaveBacklog, we see that our fundamental equation's parameters are either in an off-diagonal or in a diagonal entry of matrix A, but not in both. This means that the parameters of the fundamental equation (leaving aside TimeToLeaveBacklog for now) are the parameters that control loop dominance.

What about TimeToLeaveBacklog?

The parameter TimeToLeaveBacklog is part of the link relating the stock "ideas backlogged" to itself (minor negative loop) and the link relating the stock "ideas backlogged" to the stock "products in development" (major positive loop). However, another way to look at TimeToLeaveBacklog is to recall that this parameter is part of the term [idea lifetime/(idea lifetime+TimeToLeaveBacklog]. We observed at the end of the model building section (present chapter) that this term represents the fraction of backlogged ideas that survive idea obsolescence and could potentially move into development. We can actually build an equivalent model to our model with a different formulation for the outflows of the "ideas backlogged" stock. We illustrate the modifications in Figure 3-18. The rest of the model would be exactly as described in Figure 3-9. This new version of the model, or as we call it the equivalent model behaves exactly as our model does. The "new" parameters are "fraction survival" and "avg residence time in backlog" and are defined as:

fraction survival = [idea lifetime/(idea lifetime+TimeToLeaveBacklog] (3.39)

*avg residence time in backlog = [(idealifetime*TimeToLeaveBacklog) / (idealifetime + TimeToLeaveBacklog)]* (3.40)

The other new and modified relationships are:

avg rate = 1/(avg residence time in backlog) (3.41)

*idea obsolescence rate = avg rate * (1-fraction survival)* (3.42)

*change in backlog = avg rate * fraction survival* (3.43)

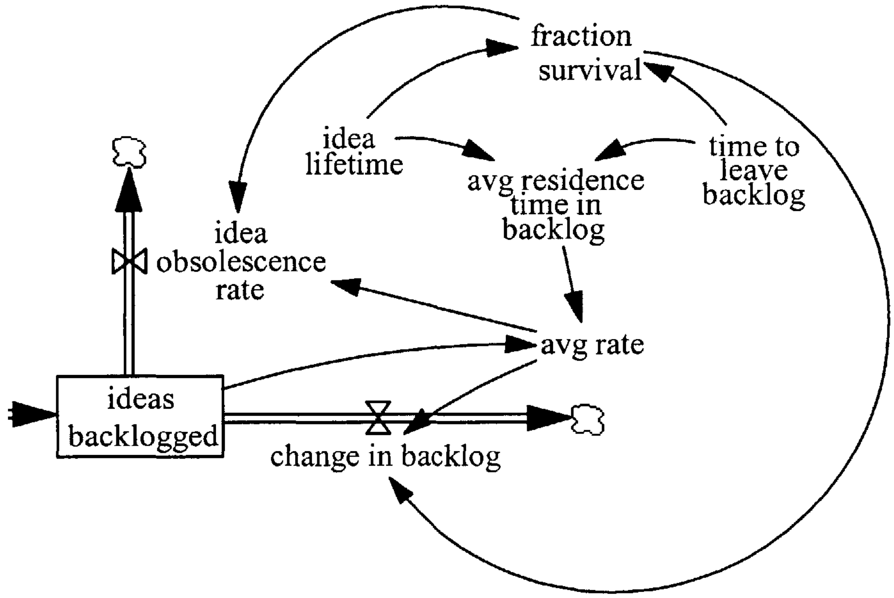


Figure 3-18: Equivalent Partial Model

We essentially have a similar formulation for the outflows of "ideas backlogged" as for the outflows from "ideas submitted": fraction survival corresponds to the pass fraction, and average residence time in backlog corresponds to the average review time.

When we carry out the equilibrium equations for the equivalent model, we find the following equivalent fundamental equation:

$$\begin{aligned} avgSalary = PDY * Willingness * PassFrac * FractionSurvival \\ * FracIdeasIn * numOfprodPerIdea * productLifetime \\ * avgUnitsSold * avgpricePerUnit * FracToR \,\&\, DWF \end{aligned} \quad (3.44)$$

This makes perfect sense in view of equations (3.32) and (3.39). Now, after deriving the rate equations, we find the equivalent state matrix $A_{equivalent}$ (see equation 3.45):

$$A_{equivalent} = \begin{bmatrix} \frac{-1}{ART} & PDY * Will & 0 & 0 & 0 \\ 0 & \frac{-1}{THF} & 0 & 0 & Z \\ \frac{Pass}{ART} & 0 & -\left(\frac{1}{residenceTime}\right) & 0 & 0 \\ 0 & 0 & \frac{FracSurviv * FII * NPPI}{residenceTime} & -\frac{1}{ACT} & 0 \\ 0 & 0 & 0 & \frac{1}{ACT} & -\frac{1}{PL} \end{bmatrix} \qquad (3.45)$$

where *residenceTime* is the parameter "avg residence time in backlog" and *FracSurviv* is the parameter "fraction survival".

Note that the two parameters *idea lifetime* and *TimeToLeaveBacklog* that appear explicitly in matrix A have been absorbed into *residenceTime* and *FracDev* in matrix $A_{equivalent}$.

Now, let's look at the relationship between loop dominance and the parameters of the equivalent fundamental equation. Each parameter present in the equivalent fundamental equation is part of either an off-diagonal entry of $A_{equivalent}$ or part of a diagonal entry of $A_{equivalent}$, but is not part of both. In other words, each parameter present in the equivalent fundamental equation affects either a negative minor loop or the major positive loop, but not both. Furthermore, we observe that the only equivalent fundamental equation parameter affecting a minor negative loop is *PL* or the product lifetime (process of product obsolescence). All the other parameters of the equivalent fundamental equation affect only the major positive loop. So we can say that the parameters of the fundamental equation are the ones that control loop dominance.

Chapter 4

THE FUNDAMENTAL EQUATION: IMPLICATIONS

In Chapter 3, we concluded from our fundamental equation and simulations that our model's parameters offer leverage of different strength depending upon their belonging to the fundamental equation or not. In Chapter 4, we focus on the managerial implications of those parameters' properties. Our main objective is to recommend policies for enabling the hoped-for growth of Company A. We start with the "stronger" control parameters[1] (those which are part of the fundamental equation) and pursue with the "weaker" ones (those which do not appear in the fundamental equation).

Idea Generation PDY

The parameter "Idea Generation PDY" represents the average productivity for generating ideas in R&D. We segment this section according to the following possible sources of ideas in R&D: accumulated knowledge and interactions within R&D, interactions between R&D and other functions in the Company, interaction between R&D and the outside world. We then address creativity enhancement programs and the hiring of creative people.

Ideas have the potential to be born internally from knowledge accumulated inside R&D. The following elements can stimulate the generation of new ideas based on internal knowledge: interactions (communication and sharing), easy access to internal knowledge, product development projects, and diversity.

Interactions between scientists and engineers usually occur through informal networks: people talk with each other and share ideas. This often results in idea "building", leading to the second idea being better than the first one or simply to new ideas. We can think of this as the recombination phenomenon in the context of biological evolution [Hines 99]. This mechanism is crucial and depends on personal relationships and mostly on currently existing relationships. One element that the IMP (Idea Management Process) brings to the party is a database of ideas that everybody can access for submittal and for reading. This "virtual" exposure to someone else's

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[1] we exclude the parameters Average Units Sold and Average Price per Unit as they bring little insight to our problem of ideation.

ideas adds a new idea building capability to the already existing capability based on a personal network. Also, since the idea author's name is present along with the idea description, anybody who is intrigued by the idea can contact the author and start a new relationship therefore increasing the size of the network. The R&D department can therefore potentially boost PDY by ensuring that awareness of the database is always high and that the access to the database is extremely easy. The IMP committee should make it part of its charter to communicate regularly about the existence of the idea database. The committee should continue to work with the Information Technology group to make sure that everybody's desktop is set up functionally for easy access to the database. The current state of awareness about the IMP and the database is quite high; in addition, submitting and reading ideas has become very easy in the past few months. However, it is important to regularly probe the current state of awareness and access, especially when new people are hired. Interestingly, only a few people have been using the idea database to read the submitted ideas. We need to encourage everybody to look into the database. We recommend that once a week a very visible but non-threatening message (a Dilbert-like cartoon perhaps) appear on people's computers asking, "Have you read your colleagues' ideas lately?"

When is the interaction between technical people the most likely to produce great ideas? Most interviewees stated that they are most likely to generate ideas if they are presented with a clear and somewhat difficult problem. In other words, technical people feel that a brainstorming session around the general request " Give me your best ideas" is much less powerful than a problem-solving session where the problem is expressed as a need. The need can be articulated as a customer need or as a technical requirement.

A lot of the knowledge accumulated over the years in R&D has been transmitted verbally among employees, when transmitted at all; the level of written or electronic documentation, as well as the level of accessibility to this knowledge are uneven. In order to improve this situation, a Knowledge Management Initiative has recently started and there is conscious effort to link this initiative to the IMP initiative. Both initiatives have been evolving in the direction of Web-enabled utilities, partly for speed and interoperability reasons. We recommend identifying all the areas of knowledge that would potentially benefit PDY by being more accessible. One such area is the firm's past patent disclosures that are not currently part of the IMP database. The patenting process is much older than the IMP and people wanting to protect their inventions use it regularly. As one person in firm A said "Any disclosure automatically contains at least an idea whereas not every idea necessarily needs to become a disclosure". Company A needs to protect the security of an invention until a patent is issued. It is therefore important to carefully consider the implications of making disclosures easily available internally. It may be possible to institute a secured electronic database open to the research community only.

So far we have mainly considered explicit knowledge but tacit knowledge is extremely important too. Tacit knowledge is subtle and much more difficult to handle than explicit knowledge. If tacit knowledge is lost, potential new ideas are lost too. The Company must therefore be constantly aware of pockets of tacit knowledge and be especially prepared for people leaving (through retirement or voluntary departure or layoff). We believe that in R&D, functional managers play an important role with respect to the awareness of tacit versus explicit knowledge that exists in their group. Regular conversations between managers and their people should help a lot in maintaining that awareness, in anticipating potential issues associated with loss of knowledge, and in finding corrective actions. For example, R&D is currently in the process of capturing the knowledge of some people about to leave through videotaped interviews. We recommend considering these efforts as part of an overall knowledge transfer policy.

As far as projects are concerned, we believe there are opportunities to increase PDY through better within-project and between-project learning (by project, we mean a funded project which is in the PDP - Product Development Process -). For example, within a project, instead of just post-mortem sessions once the project is finished, there could be intermediate learning sessions, such as at the end of each PDP phase. Ideas for improving the PDP may be the most prevalent, but technical ideas also can arise from constraints such as the need to accelerate the schedule or to reduce cost. It may be more difficult to organize and motivate people from different product development projects to meet; however, the potential for new ideas may be even greater as long as the projects have sufficient skill overlap. A mechanism to carry out those meetings could emerge through respected scientists/engineers from both project teams who would call a meeting to resolve a current problem that one of the teams is facing.

The more challenging a project is, the more likely it is that new ideas will be born. Projects that are technically challenging motivate scientists and engineers and often require inventions. In Company A, challenging projects have spawned many ideas for new, better, or cheaper platforms. Obviously, the drawback of a challenging project is its risk. But even if a project is canceled mid-way, ideas captured while the project was alive can be precious and become the source of new projects leading to successful products.

Diversity helps the stimulation of new ideas. *Diversity* is used here in a broad sense including diversity of backgrounds and experiences within a project team, diversity in thought processes, diversity in age and personalities, and diversity of projects. Going back to the between-project learning example, we believe diversity is an important enabler for new ideas to emerge. Also, many of the Company's ultimate products are systems. A team may be focused on a new chemical component, but early dialog with other functions such as mechanical, electrical, or software engineering can trigger new ideas for the chemistry team thanks to the diversity of technical points of views. This is particularly true in the case of imaging systems where, for instance, software can sometimes take over functionality that used to be handled by chemistry and hardware. Through its phase gate based Product Development Process, Company A explicitly states that multifunctional teams including engineering, manufacturing and marketing be formed early in the project. For the Fuzzy Front End, and specifically for ideation, there is no such structure. However, it is at this early stage of ideation that technical diversity can be so valuable. At Company A, technical networks are usually made of people from the same technical field. It is rare that technical experts take the initiative to meet with experts from another technical field unless they are forced to. We recommend initiating such encounters by organizing informal "get to know each other" sessions ("brown-bag" lunches for example) where small groups of people from diverse technical backgrounds (chemists, physicists, image scientists, software engineers, etc..) meet and discuss their experiences in past R&D projects involving imaging systems. Even though less numerous, technical people with significant system expertise would benefit from knowing many specialized experts. Such technically multidisciplinary and interactive forums would complement the popular technical seminars currently in place where an individual or a team presents on-going work to an audience.

Ideas are often stimulated from interactions between the company's R&D people and other parts of the Company specifically manufacturing and marketing. Company A was traditionally technology-driven and manufacturing has always had an important role. Interactions between R&D and manufacturing occur regularly and occasionally new ideas, especially for incremental improvement, emerge. Recently, the firm has emphasized a market-driven orientation, and such transitions are always organizationally difficult. We believe that PDY would greatly benefit from more active interaction between the R&D community and the Business Units (especially through marketing people). We encourage more group meetings involving marketing and technical people where ideas are exchanged for a couple of hours. Of course, interaction does currently exist outside the typical project context but it is often in the form of a presentation from one marketing person to many R&D people or in the form of one-on-one meetings. The former case is a good informational start especially if the marketing person was not known at all by the technical people; however, there is rarely enough time at the end of the presentation to go beyond superficial questions and the group is "unbalanced" in size. In the latter case, the interpretation of the conversation relies on too few people, leading to possibly costly misunderstandings. We propose something in the middle where small groups of technologists and marketers simply talk to each other. By using this approach, relationships get established at a level that is between the "ad hoc" one-on-one level and the formal high level functional relationship. In such a framework, the marketer who presents customer needs is likely to catalyze substantial technical ideation especially if those customer needs are well defined.

When it makes sense, management should promote lateral transfers and job rotations. For example, Ms. X who was in R&D is now working in the Legal Department to help increase revenue from licensing fees. Since Ms. X has deep functional knowledge, this was a very good decision. There may be opportunities for some R&D people to have a role in Marketing or Market Research and to therefore strengthen the relationship and understanding between marketing and technical people.

Ideas are often born from interactions between R&D and the outside world (i.e. outside the corporation). These sources of ideas and innovation include: customers, partners, suppliers, competitors, events (conferences, trade shows). Research [von Hippel 88] has shown that in some cases customers or suppliers come up with considerable innovations which under the right organizational and contractual circumstances become innovations for the company. In these well-managed circumstances, PDY is suddenly increased by an "indirect workforce." The R&D organization has been encouraging technical people and project managers to visit customers and we believe this is important; visits to customers per R&D person per month has recently become a metric. In addition, to reporting the quantity of visits, we recommend investigating visit "quality." An example of low quality would be if the technical person has applied unconsciously his/her mental bias to the customer's data. We recommend that technical people become more familiar with the voice of the customer techniques [Burchill 97] to ensure raw unfiltered information is captured. Internal or outsourced training may be valuable. When possible, R&D engineers and/or scientists should visit customers along with marketing people. Generally, listening to the average current customer can give rise to new ideas, although those are often incremental ideas. We recommend that technical and marketing people investigate the appropriateness of going after lead users [von Hippel 88] in particular for the commercial imaging side of the business. Such work can be quite costly; however, it can bring considerable insight on what the leading edge customers really need. These insights have a greater potential to lead to the next big (not necessarily incremental) idea.

Relationships between Company A and partners have been uneven over the years. We recommend that teams who have had to deal with partners share their experience with the rest of the corporation. Under the knowledge management initiative, "partnering" would be a theme and a link between experienced people (from program manager down) and people about to engage in partnerships could be enabled.

Knowledge of the competition can be a powerful trigger for new ideas. We recommend a tighter link between the technical people and the market research people. Market research people could actually join in the group meetings involving technical and marketing people. A small number of R&D people are assigned to perform technical competitive analysis of imaging systems. These people should be invited regularly to discuss updated information with the rest of R&D.

Functional/technical people have the opportunity to go to technical conferences where they and/or their peers present imaging related papers. These events often trigger really new technical ideas in scientists and engineers. When asked how exactly conferences helped him come up with new ideas, one of the scientists of Company A made the following observation: "I find that the best trigger of ideas is a paradox. For example, in this conference, a person presented an experiment that I had vaguely thought of in the past but was sure it would not work because of an apparent physics paradox. But as soon as I saw it work, I understood the phenomenon and thought of several ideas for new products in relationship to our technologies." What happened with this scientist (Company A) is that the "suppressed" idea (due to the mental model he had at the time) suddenly was shaken at the conference thanks to a challenge (the demonstration it can work); after that event, classic idea building (mentioned earlier) took off.

Creativity enhancement programs can be conducted internally or with the help of external consultants. Several organizations claim to teach how to unleash creativity and imagination that have often been repressed in people (some say by leaving childhood and going to school!). Even the famous product design firm IDEO is offering to teach customers the "art and science of creativity" [Garner 2000]. Obviously, Company A is not alone in wanting to be more innovative: as of March 2000, so many firms had signed up that IDEO's new innovation service brought in 25% of its revenues! We recommend that Company A look into some these outside services and try to evaluate whether they could offer additional value to the current internal efforts or whether they represent the fad of the day. It is important to keep a healthy skepticism concerning the often-touted approaches (such as brainstorming, and synectics) for increasing the productivity of idea generation among engineers and scientists. Edward Roberts, for instance, is not convinced that these methods are so effective in themselves [Roberts 88]. He believes that "...effective individual and group supervision, including proper maintenance of group diversity and task challenge, seem ...more likely to produce useable ideas." This may be true. However, internal attempts to unleash creativity should not be discouraged. Such an attempt was conducted recently by the IMP committee in Company A. Several brainstorming sessions were organized, each with a different group of scientists. The problem statement involved a technical challenge. The session leader had asked people to read the book "What a great idea" [Thompson 92] prior to the sessions. Interestingly, even though people generally agreed with the book's argument that great ideas come from a "ready, fire....aim" attitude, people felt somewhat uncomfortable practicing it. Acting like a curious impulsive child throwing wild ideas was quite difficult for them. However, after about an hour, people were warmed up and ideas started to emerge (the one hour warm up time seemed true for all sessions). From all the ideas emitted, a couple stood out for their promise and the idea generators submitted them to the database.

The average idea generation productivity would increase if the newly hired people were more creative than the current average workforce. If management were to focus on such hiring, it is important to assess the difficulties (appropriate criteria defining a very creative person, cost) and the potential benefits of such policy.

Willingness to Submit

The parameter "Willingness to submit ideas" acts as a filter to the idea generation productivity. If the intrinsic idea generation increases through individual effort but at the same time a barrier eliminates the willingness to submit, then the firm's growth is in jeopardy. We identified the following elements that can negatively affect the willingness to submit ideas: concern that the idea will be "stolen", lack of time to develop the idea for submittal, lack of confidence in the IMP, lack of incentives, perception that technical innovation is not valued or that the idea will not be accepted "anyway", low morale.

In the interviews, a few people brought up concern about ideas being stolen by somebody else in the Company. This is obviously a sensitive issue to bring up with people, and it is difficult to evaluate the extent of those concerns. However, since some of the comments came from a couple of very creative people, it is important to consider them. Certainly, a patent disclosure can, to some extent, protect an idea that is embodied in an invention. The IMP committee has told people that if they are concerned about the security of their idea, they should use the patent disclosure process first, and then submit the idea in the database. One possible unintended effect could be that people abuse this suggestion, disclose many low quality or "not well thought out" ideas and end up flooding the patent department. In order to alleviate this, the IMP committee with the help of senior management must continue to communicate IMP's objectives (i.e. gather ideas from everybody in the division, review them, dispatch them appropriately) and provide information about the patent process. Recently, the patent department has been presenting this information more frequently and especially to the R&D community. These communications are particularly important for people who have no prior experience in applying for a patent and for new hires. In addition to the occasional verbal presentations, we suggest that the IMP Web page provide a link to an electronic document describing the patenting process.

There is an interesting connection between the willingness to submit and the idea generation productivity PDY. People who are concerned that their idea will be stolen are most likely not sharing their idea with others and therefore reduce the likelihood of a potential better idea being born through dialog. The lack of willingness to submit can therefore negatively impact the idea generation productivity, hence resulting in a doubly negative effect on the idea submission rate.

The willingness to submit is also related to the willingness to put more effort into an idea. This in turn is highly dependent on the task priority policy. The first priority is to work on current projects. For most people, this implies the full forty hours a week and more! One argument advanced by some is that ideas come to people's minds unpredictably, during work or outside work, and that it does not take much effort or time to submit those ideas in the database. Another argument is that often it does take time and effort to develop an idea to the point where it is worth being presented in the database; this time can involve designing some simple-to-medium complexity experiments, or visiting potential suppliers. Usually, project and administrative pressures delay the development of the idea. If the idea generator is sufficiently tenacious and enthusiastic about his/her idea, he/she will pursue the idea by working late or by waiting until the high priority project is finished; eventually he/she will submit the idea. Otherwise the idea may not be submitted. Of course, extremely tenacious technologists, who through their technical excellence have been recognized in the past, will always find a way to present a new idea to senior management. One can argue that these rare people do not need the IMP process to move ahead. However, one important goal of the IMP is to offer a democratic submission and fair review process to the R&D community at large and to prevent a bad idea from getting funded just because the idea generator knew which personal strings to pull.

For the IMP to be successful, it is important that people have confidence in it. One element of building trust and confidence in the IMP is for the committee to ensure that submitters feel they are listened to. Currently, following the first screening of the idea, the IMP committee emails a response to the idea submitter (within one to two weeks of submittal). The screening is done by a few technical experts who are members of the committee; the idea submitter is not present (except if he/she is a committee member). We recommend that personal contact be established early on between the submitter and the IMP committee. We believe the personal contact and ensuing dialog will have beneficial effects on the willingness of the submitter to continue to submit ideas in the future. We suggest that the committee invite the submitter to present and discuss his/her idea "live" to the committee during the weekly idea screening currently in place. Today, the database submittal alone constitutes the basis for the screening by the committee. One danger with this process is that the committee misunderstands the idea and decides to stop (or for that matter to pursue) the idea, based on wrong assumptions. The other danger is one of unfairness: the occasional times when the submitter is present are the times when the submitter is also an IMP committee member. That person, even if unintentionally, is privileged by this "dual status" with respect to the majority of submitters. Even though a written feedback is sent to the submitter, some damage (submitter losing confidence in the IMP) or delay in the life cycle of the idea may have occurred. A live discussion between the idea's author and the committee will decrease the probability for those problems to exist. First, the submitter will actively witness the committee's interest in his/her idea; this should in itself encourage him/her to use the IMP even more in the future. Second, most misunderstandings that may have happened without the presence of the submitter will be eliminated in this session. If the result of the first screening is that the idea is worth pursuing, resources (dollars and/or people) will be offered so that the idea can be worked on and go through a more formal technical review. We recommend the IMP committee ensure the appropriateness and timeliness of further technical panels. An interesting suggestion we heard from a high level scientist was that idea reviewers (screening, formal technical review, overall technical and business review) be subjected to an exam. This is a suggestion that management may want to consider if there is compelling evidence of lack of confidence in the adequacy of the membership of the IMP committee and/or of other review panels.

One way submitters can lose confidence in the IMP initiative is if there is an initial gap between expectations about the fate of the idea and the reality of new product development. For example, once an idea passes all the reviews, it does not necessarily mean it will enter the development process right away or at all. This will depend on resource availability, the financial situation of the firm, and prioritization. It is therefore crucial to explain this very well to all (i.e. to all potential idea submitters). Non-selected ideas should not turn submitters off. A study on innovation [Stevens 99] finds that a very small proportion of submitted ideas ever become products, and an even smaller proportion ends up commercially successful. We recommend the IMP committee clearly communicate these findings which may be well known in the technical community but might not be internalized. We believe that this communication in conjunction with a regular reminder of the IMP will enhance the willingness to submit ideas. We suggest that a message occasionally come up on people's computers reminding them of the importance of submitting ideas.

Management has recognized that in order to maintain a high level of willingness to submit ideas, incentives are very important. Upper management offers recognition and rewards to idea submitters that include free group lunches with small gifts and/or monetary rewards. We recommend a staged recognition system that follows the flow of ideas. A possible system is to reward the idea generator for submitting and later on reward him/her when if the idea is selected for backlog.

As far as the perception of how important technical innovation is, it has been somewhat of a roller coaster. Company A was founded on technical innovation several decades ago. A few years ago, Company A decided to seriously improve its marketing savvy. While marketing improved, the technical community felt somewhat abandoned. The pressure was a hundred percent on current projects and core competencies and the feeling in R&D was that one was not even allowed to think about anything else. However, this has changed in the past couple of years, and upper management has been publicly stressing the importance of technical innovation for long-term growth. Several concrete actions followed including allocation of more resources for the patent office, and well publicized company-wide technical poster sessions. Today, the R&D community is regaining confidence that it is highly valued in the eyes of top management. As far as the IMP is concerned, it did suffer a few years back during difficult financial times when R&D felt left out. One aspect was that people with extremely creative ideas that were not exactly aligned with the company strategy would not submit their ideas, thinking to themselves "why put the effort since my idea will not be considered anyway?" In order to address this, the IMP committee along with upper management in R&D decided to accept a wider range of ideas, even if some are not aligned with the core competencies or strategy. For those ideas, the main objective becomes patent filing and future revenues from technology licensing.

Of course, morale is very important for the well being of any organization. Low morale can affect the willingness to submit new ideas, or even the motivation to simply think about work (in which case I would argue that PDY itself is also affected negatively!). In the past couple of years, R&D management has attempted to improve morale whenever possible. Work environment committees were formed and worked hard to understand people's desires. To the extent possible, action was taken and the morale has improved. Concrete steps included free coffee for everybody, and the formation of clubs to learn about different topics.

Idea Lifetime and Time to Leave Backlog

It is obviously quite difficult if not impossible to know the lifetime of an idea. However, knowledge of competition can greatly help estimate it. Technology assessments are crucial for any R&D outfit in order to keep up to date with the most recent advances in academia and industry. Those assessments can come from internal experts (especially for core competencies), but also from external sources such as consultants or partners. Continuous technology assessments help develop a sense of the dynamics of different technologies. This in turn should help in estimating whether a submitted idea "carries" with it a short lifetime or not. Subsequently, the lifetime characteristic of the idea can be used in the prioritization process for pursuing work on the idea and deciding on how urgent it is to go into development (Time to Leave Backlog). If it is determined that the idea is promising and that for instance the competition is likely to reach this idea independently soon, priority should be given to this idea and a rapid decision should be made concerning the next steps. Obviously as for any idea, the decision should involve strategy, resource allocation, and finance. Management may decide to be a first mover on an idea that has a short estimated lifetime and bring it into development right away. On the other hand, management may feel that the risks of pursuing the idea right now outweigh the benefits. In any case, we recommend that idea generators and reviewers consider the notion of idea lifetime especially when deciding which backlogged ideas are to move into development. We suggest that R&D and the Business Units communicate the state of competitive products to the R&D community on a regular basis (of course, that is not to say that this information should be hidden from other parts of the firm).

The time for an idea to move into development (Time to Leave Backlog) could be shortened if the availability of people resources is increased. Current resources can be made available sooner if the project development productivity increase, in other words, if the product development cycle time is reduced. Outsourcing some of the down stream development activities may also help in bringing ideas into development faster.

Pass Fraction

The "Pass Fraction" parameter corresponds to the percentage of the submitted ideas that passed the reviews. Our model focuses on ideas that will ultimately turn into new platforms and products because new product development is a key objective for long-term growth. We should note, however, that the R&D organization of Company A encourages the submission of all types of ideas including cost reduction, process improvement, and technology licensing ideas.

Increasing the Pass Fraction helps our model to grow. Certainly, few managers advocate simply promoting more ideas without regard to their inherent qualities. Indeed, accepting bad ideas would negatively affect other parameters and variables such as revenue. We want to increase the Pass Fraction by increasing the number of high quality ideas submitted. As competent review panels evaluate more ideas, it will be possible to refine the criteria for quality and to communicate those findings to the R&D community. Interestingly, the perceived quality of an idea depends on two factors: the inherent quality of the idea and the quality of the submission (including completeness and readability). An unclear submission may hide from reviewers the inherent quality of the idea. A few months ago, I heard the following comment: " Some of the explanations -technical and/or business- are not comprehensible!" Of course, some would argue that a really good and well thought out idea should be easy to present. In any case, the IMP committee is responsible for coaching people to present high quality submissions. We suggest that selected backlogged ideas serve as examples of high quality for both the idea itself and the submission. A link present on employees' desktops could direct people to two or three backlogged ideas with not only their associated submission form but also comments from the review panel explaining why these ideas were selected as high quality ideas. We believe that the coaching in conjunction with the communication of successful examples can drive the quality of ideas up and therefore can increase the Pass Fraction. One interviewee even suggested that, as people read those ideas coming from colleagues, they may think to themselves: " I can do better than that!"

Fraction of Ideas In

The "Fraction of Ideas In" represents the percentage of the surviving backlogged ideas that enters the Product Development Process thereby becoming sanctioned and funded product development projects. As mentioned earlier in the chapter, we can view this parameter as the efficiency of management to select and prioritize from the stock of backlogged ideas while considering resource constraints. One way that the Fraction of Ideas In could be increased is through the reduction of person-hours per project. The designing of imaging systems requires a lot of experimentation and testing especially in the chemistry of the imaging medium and in the overall system's image quality evaluation. Company A is using more and more modeling tools in order to design and test faster while using less people resources. Hopefully, firm A will translate these improvements into more projects. In addition to modeling, platform strategy (see next section) can also enable faster and leaner product development thanks to the commonality of subsystems. Also, R&D people with entrepreneurial spirit can benefit the "Fraction of Ideas In" parameter by acting as "idea champions" vis-à-vis the Business Units and marketing. Entrepreneurial technologists are few, and firm A should investigate how and whether to increase the entrepreneurial skills in R&D.

Number of Products per Idea

The "Number of Products per Idea" carries mainly the notion of "product platform." Here we use the definition provided in [Meyer 97 p.39]: "A product platform is a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced." An idea that fits the definition of a "product platform" idea and aligns with existing design and manufacturing capabilities (whether internal or through existing partnerships) is a powerful idea because it leads to more products faster and cheaper. One Senior Manager said that one of the thoughts that wake him up at night is the question: how could R&D people generate more platform ideas? We believe that in this area, as well as in the more general area of idea generation, strong interactions between marketing and R&D can greatly help. Indeed, Marketing can inform R&D about customer needs and market segments. R&D and the Business Units can then analyze what platform strategy could best fit this market segmentation, based on current capabilities. A framework of platform cost/performance versus market segment is a helpful tool to carry out this type of analysis. As described in [Meyer 97], different platform strategies exist, including the "horizontal platform leverage" strategy (leverage from one segment to another within a certain cost/performance range), the "vertical platform scaling" strategy (leverage within a market segment) and the beachhead strategy (combining horizontal and vertical strategies). A difficult aspect in executing a product platform strategy is the requirement for different parts of the organization to really work together. Meyer argues that platform strategy cannot happen without strong executive leadership. Ultimately the actual decision of pursuing a certain product platform strategy lies at the senior management level. However, more technical people could sharpen their strategic thinking skills and develop, jointly with marketers, product platform proposals for senior management. We believe that people in our R&D organization could improve their "platform thinking" by using tools such as the one mentioned earlier (cost/performance versus market segment matrix).

Fraction to R&D WF

The Fraction to R&D WF is the fraction of the firm's revenue dedicated to R&D's workforce. The overall R&D budget, which is a percentage of revenue, is comprised of the budget allocated to payroll and budget allocated to other activities. Due to short-term financial pressures, senior management is unlikely to increase this percentage. This may seem paradoxical: the current situation makes it difficult to increase R&D's budget, yet R&D is expected to greatly contribute to the long-term growth of Company A. Still, a more efficient utilization of the non-labor part of the budget could allow for an increase in the fraction of revenue allocated to the R&D workforce.

Product Lifetime

The "Product Lifetime" parameter represents the average lifetime of the products. The longer the lifetime, the longer the product generates revenue. A decline in the average product lifetime will make the product obsolescence dominate over the process of generating growth (Chapter 3). Here again, adopting a product platform mindset can be beneficial because it encourages the long-term view and attempts to ensure temporally overlapping products on the market. Of course, if the platform strategy adopted is poor in the first place, the associated negative effects will be greater than for a point product. But a sound platform strategy leading to sound product line strategy will increase the probability of maintaining a flow of new products out. This, in concert with appropriate marketing and advertising will contribute to the maintenance and hopefully the increase of the products' average lifetime.

Average Salary

The average salary is unlikely to be used as a contributor to growth as the model indicates. In the model, all else equal, a lowering of salary would trigger growth. Obviously, and especially in this healthy economy, salaries of current employees cannot be lowered, or even frozen. Company A could selectively hire engineers and scientists from lesser known colleges and offer lower pay but such a policy would be risky in terms of the firm's reputation and of the quality of the hires. We do not therefore suggest employees' salaries reduction as a managerial leverage parameter.

Average Review Time

As we saw in Chapter 3, this parameter constitutes a weaker lever that the parameters presented so far in the present chapter. On the other hand, even if longer review time may not precipitate a decline to zero behavior, it still brings key variables to unwanted lower levels.

In the recent past, there has been a concern about technical review panels not finding the time to review ideas. We recommend the IMP take the responsibility to set up the schedule for the technical review panels. In the past, such panels were assuming that responsibility but most often the "crisis of the day" was delaying the idea review. The IMP committee can greatly help discipline the process.

Average PDP Cycle Time

The "Average PDP Cycle Time" represents the duration from the start of the project to the launch of the product. As for the Average Review Time, a shorter Average PDP Cycle Time will benefit the firm but would not by itself drive growth. As mentioned earlier in this chapter, the increased usage of modeling tools for designing complex imaging systems is enabling and will continue to enable the reduction of the product development cycle time. Not only will the design be performed faster, but also the testing. In addition, computer-based modeling tools are greatly enhancing R&D's capability in documenting the design process. This in turn has the potential to accelerate the development of future products. We believe R&D should continue to use and improve the modeling tools for designing and testing imaging systems. Anticipating a growing need in those tools, we recommend R&D plan for the training of selected scientists and engineers in using the tools.

Time to Hire/Fire

As shown in Chapter 3, shortening the time to hire or fire will have very little impact on the growth of the system compared to all other parameters. This implies that management should not expend much energy in trying to hire faster. On the other hand, if management decides to focus on hiring very creative people in order to increase the parameter PDY, the time to hire may increase due to the difficulty of such search. If this time to hire gets closer and closer to the overall ideation and product development cycle time, then the growth would start to be more and more negatively impacted.

Chapter 5

REFLECTIONS

The System Dynamics Process

Due to changes in personnel and other priorities in the project, the modeling part was not done in conjunction with the client. However, at the beginning of the project, several R&D people were involved in the system thinking part of the process and participated in the building of the causal loop diagrams. This was a novel tool for them and they enjoyed the process of helping trace the diagrams on the board. The simple, yet powerful rules of causal diagramming enabled the surfacing of several shared but implicit assumptions such as the impact of the scope of corporate strategy on ideation. We noticed that coming up with open loop causal links was easy; however, for some of the dynamic hypotheses, "closing the loop" required much more effort. I therefore witnessed first hand the tendency we all have to "adopt an open-loop view of causality" [Sterman, 2000 p. 27].

System Dynamics: challenges

I found that the most difficult phases of the system dynamics process were the problem definition and the modeling. Once the problem was defined and the reference modes plotted it was easy to list the variables of interest. The development of dynamic hypotheses using causal diagrams and feedback loops occasionally required quite some effort, as aforementioned. I felt a real sense of accomplishment after several interesting dynamic hypotheses had emerged from the interviews. However, the modeling part was much more difficult than the previous steps. Modeling is a combination of art and science. Becoming a good modeler takes a lot of experience, and some people are probably more talented than others. When I felt that the more talented people were the other people, Jim Hines would remind me about what Jay Forrester says. Forrester founded the field of system dynamics (or "industrial dynamics" at the time) in the late 1950's. Currently in his eighties, he says that he is still learning about system dynamics.

I believe that modeling is especially challenging when we deal with "soft" variables such as willingness to submit an idea or employee morale. This is when the "art" part of modeling is required. Of course, obtaining data about such soft variables from the client can be difficult since most often, organizations do not really track these variables.

System Dynamics: strengths

The very fact that the soft variables can be considered at the same level of importance as any "hard" data (such as traditionally tracked financial data for example) is a tremendous strength of system dynamics. It may seem impossible at first (especially to an engineer!) to measure morale but in reality, figuring out a qualitative trend over time isn't that difficult. Managers often know more than they think about the behavior of soft variables. I strongly believe that quantifying soft variables approximately is better than simply ignoring them. In a speech to MIT students, Jay Forrester said that in his experience, eighty percent of the important variables linked to major problems in organizations (corporations or public organizations) were soft variables. That did not really surprise me. After all, organizations are made of people! Also, how many times do we hear: "Technology is not the main issue, we can find the technical specialists. It's managing them and the relationships that's difficult!"

A second strength I find invaluable is that system dynamics "seeks endogenous explanations for phenomena" [Sterman 2000, p. 95]. I believe this focus can drive individuals, teams, and organizations to improve because they learn about themselves instead of quickly blaming external factors when problems occur. In a sense, this focus is missing when organizations mainly emphasize benchmarking. Benchmarking is useful from the perspective of awareness of what other orgranizations are doing. However, it is often impossible for an outsider to really know what underlying structure actually drove an organization's success. Something that worked well in organization B may not work for A because of very different structures (cultural, incentives, organizational grouping and linking, etc.). System dynamics can greatly help an organization know itself better and therefore be better prepared to analyze the risks and benefits of a new policy (which may have been selected as a result of a benchmarking study).

I believe a third strength of the system dynamics process is its flexibility in the sense that, at any time in the process, opportunities arise to gain insights into the problem at hand. In many problem cases, the system dynamics approach adds value without the development of a fully calibrated model. Even in the early step of gathering variables, where people can throw in any variable they feel is relevant, there is a possibility of discovering a "corner" of a mental model. Certainly, creating causal loop diagrams greatly enhances value.

All models are false. But some are still useful.

This often cited statement (unfortunately we could not identify the source) is true and applies to system dynamics modeling as well as any other type of modeling. As one professor said about a geographic map, " if this model were accurate, it would be difficult to fold!" The point is that a model is useful for the very reason that it simplifies the problem at hand. Therefore, by definition, a model is wrong even if it is so only by its incompleteness.

In our case, the model represents only a small part of the concern we are tackling. Many factors and feedbacks are missing. One could even argue that the model is naïve. However, even this small model generated insights such as the race against the clock occurring between the idea lifetime and the time to enter PDP and the fact that the model can generate several types of behaviors.

Modeling is not easy. If the modeler is not careful, the model can grow out of control and become extremely difficult (if not impossible) to analyze and debug. Indeed, with just a few stocks, feedback loops, and non-linearities, a model becomes quite complex and practically any behavior is obtainable. Interestingly, many novice modelers rush into modeling more and more dynamic hypotheses instead of pausing after each one and taking the time to simulate, analyze, and really understand the model. Often, the best way to deal with a complex and not very well understood model is to restart from scratch.

Our model, through the very fact that it is small and hence well understood, offers the benefit of generality. Indeed our model is most likely applicable to many organizations. One may build upon this model and "specialize" it as needed.

Chapter 6

CONCLUSION

Summary

We started with the concern that R&D of Company A does not produce enough good ideas for the sustained long-term growth of the firm. We set out to better understand the embedded mental models of the clients and obtained several dynamic hypotheses around the concern. We presented those hypotheses and illustrated them using causal diagrams. We focused on a key dynamic hypothesis that supports the hopes of the Company, namely that the current process of idea management would fuel the long-term growth of the Company. We developed a computer model and we derived an associated fundamental equation. We developed intermediate and simpler models to gain progressive insights about our model. We analyzed the model's parameters and showed that they belonged to two categories: either they were part of the fundamental equation or not. Changes to the parameters belonging to the fundamental equation control whether the firm will grow or decline dramatically. These parameters represent levers for managing the system. The weaker parameters were not part of the fundamental equation and led to a new or current equilibrium. We conducted an eigenvalue-based analysis to deepen our understanding about the relationship between the model's behaviors and the model's structure.

We investigated the model's parameters further from a managerial perspective. The goal was to recommend policies in order to ensure the idea management process will be successful in contributing to the long-term growth of the Company. Recommendations included more intra and inter project knowledge sharing and increased communication between the Business Units and R&D concerning customer needs and competition.

We presented thoughts about the challenges and strengths associated with the system dynamics framework. We noted that even a simple and small model not only can reveal useful insights but also can offer the advantage of generality.

Future Work

The present study has focused on one central dynamic hypothesis and led to policy recommendations. We suggest the following areas for further work:

- Pursue the development of our model and bring in the notion of "limits to growth". No growth can continue ad infinitum. In our case, for instance, resource availability (people, dollars, manufacturing capabilities) will influence how many new platform/product development projects can be initiated and carried out. Modeling resource availability and allocation will reveal new insights and will most likely make several of our parameters become variables.
- Model the others loops presented in Chapter 2 starting with the effects of time pressure on submitters and reviewers, and the effect of review responsiveness on submitters.
- Analyze and model the potential new feedback loops emerging from the currently recommended policies. Although not often practiced, analyzing emerging loops and their effects on the original system is an excellent way to gain insights (whether through confirmation of the policies' appropriateness or through discovery of inconsistencies.)
- Investigate the evolution of the "types" of ideas (using Company A's history since its foundation) in the context of growth. This work would draw from published studies about product versus process innovation [Utterback 94], architectural innovation [Henderson 90], and disruptive technologies [Christensen 97].

APPENDIX A: List of variables

- # of ideas generated (expressed or not; not written down)
- # of ideas submitted (written down)
- quality of idea submission (clarity and completeness, experiments?, prior research?)
- quality of idea
- Ratio (# Good Ideas/Total # ideas)
- # “creative” people
- # idea-triggering events (internal, external, contacts with customers, web, KM Dbase, etc..)
- coaching (for better idea description, research, alignment)
- Clarity of process
- availability of idea reviewers
- average time for idea to arrive in backlog
- # people allocated to exploration
- incentives for submitting ideas
- # ideas that do not receive any response
- Alignment of idea with Strategy
- Breadth of strategy
- Communication between R&D and Business Units
- R&D budget
- % of R&D budget dedicated to exploration
- # new platforms
- cycle time for new platform (up to technical feasibility)
- # new products
- cycle time for new product (from program start to launch)
- revenue
- % revenue from new products (new being “less than m years”)
- # patent disclosures per year
- # patent issued per year
- # issued patents that ended up in (successful) product? (time lag)
- budget of patent department
- patent processing efficiency
- perception of company being innovative (from outside)
- attractiveness to work in R&D (inside and outside – i.e. retain and attract talent)
- employee morale
- employee’s fear of losing job
- risk aversion

APPENDIX B: The model's equations

Note: the figures in the model were altered for confidentiality purpose.

"rate of prod/platf" = change in backlog*fraction of ideas in*number of products per idea
Units: products/year

change in backlog = ideas backlogged/time to leave backlog
Units: ideas/year

idea obsolescence rate = ideas backlogged/idea lifetime Units: ideas/year

ideas backlogged= INTEG (+promotion rate-change in backlog-idea obsolescence rate, 14)
Units: ideas

idea lifetime = 2 Units: year

avg PDP cycle time = 2 Units: year

avg price per unit = 10 Units: $/units

obsolescence rate = products/product lifetime Units: products/year

ideas submitted= INTEG (+submission rate-promotion rate-rejection rate, 350)
Units: ideas

PDP rate = products in development/avg PDP cycle time Units: products/year

avg units sold per product = 1e+007 Units: units/products/year

fraction of ideas in = 0.089286 Units: Dimensionless

number of products per idea = 1 Units: products/ideas

rejection rate = avg review rate*(1-Pass Fraction) Units: ideas/year

revenue = avg price per unit*avg units sold per product*products
Units: $/year

products in development= INTEG (+"rate of prod/platf"-PDP rate, 5)
Units: products

time to leave backlog = 0.5 Units: year

product lifetime = 5 Units: year

products= INTEG (+PDP rate-obsolescence rate, 12.5) Units: products

promotion rate = avg review rate*Pass Fraction Units: ideas/year avg review rate = ideas submitted/avg review time Units: ideas/year

avg review time = 1 Units: year

avg salary = 100000 Units: $/people/year

"Fraction to R&D WF" = 0.04 Units: Dimensionless

"Hiring/Firing"= (Indicated WF-"R&D Workforce")/"time to Hire/Fire"
Units: people/year

idea generation PDY = 1 Units: ideas/people/year

Indicated WF = "R&D WF Budget"/avg salary Units: people

Pass Fraction = 0.1 Units: Dimensionless

"R&D WF Budget" = "Fraction to R&D WF"*revenue Units: $/year

"R&D Workforce"= INTEG ("Hiring/Firing", 500) Units: people

submission rate = idea generation PDY*"R&D Workforce"*Willingness to submit
Units: ideas/year

"time to Hire/Fire" = 0.25 Units: year

Willingness to submit = 0.7 Units: Dimensionless

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