LINKING R&D SPENDING TO REVENUE GROWTH

Potential outcomes of alternative R&D budget plans can be simulated with a model that links growth rate, R&D intensity, and shapes of the revenue and investment streams.

George C. Hartmann

OVERVIEW: *A recently proposed model for revenue growth clarifies the linkage between R&D intensity and the annual revenue growth rate. A key assumption is that the lifetime revenue generated by a group of products launched in a particular year is proportional to the total R&D investment in that year. In practice, the product-related R&D investment occurs over several years preceding the year of product launch. By decomposing the total R&D into product-related investment streams, distributed over the years prior to launch, the link between the revenue growth rate and product development schedule can be modeled. The extended model yields a formula that links the growth rate, R&D intensity, and shapes of the revenue and investment streams. Management can use the simulation method as a planning tool, to quantify potential ramifications of their R&D decisions.*

Marvin Patterson has presented an analytic model that postulates a causal linkage between a firm's R&D investment and its revenue, and gives a formula that links the annual revenue growth rate to the R&D intensity (*1*). The key assumption is that the R&D investment creates products, which in turn generate a "wave" of revenue after launch, cresting after a few years, and then declining. The lifetime revenue of these products is assumed to be proportional to the R&D investment in that year. The proportionality factor is called the "new product revenue gain."

This article has two objectives. One is to extend the model by relaxing Patterson's simplifying assumption that the R&D investment associated with products launched in a particular year occurs solely in that year. In practice, several years are required for product development. One would like to understand how product development schedule affects the revenue growth rate.

The second objective is to present a time-dependent version of the extended model to illustrate how hypothetical "what if" scenarios can be simulated. This can be useful as a tool to help senior management understand possible ramifications of their R&D decisions. I do not defend the key assumption that R&D investment drives revenue, and acknowledge that there are many other important factors. Nevertheless, such a model provides a means for quantitatively projecting revenue, given a specific R&D investment profile and product development schedule. The simulations presume that certain model parameters will have values in the future similar to those in the recent past.

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Extending the Model

Patterson postulated that the lifetime revenue W_i for products launched in a particular vintage year is proportional to the annual R&D investment E_i. He called the constant of proportionality the "new product revenue gain," G. He also made a simplifying assumption that the R&D investment for the products launched in the "vintage" year is concentrated solely in that year.

Patterson proceeded by decomposing the revenue R_i in a particular "vintage" year (for example, the year 2000) into contributions from revenue waves W_i from products launched in earlier years, as shown by Eq. 1 (see "Model Formulation," next page). He characterized the shape of a typical revenue wave by a set of fractions α_k that describe the percentage of the lifetime revenue collected k years *after* product launch. They can be extracted from the firm's historical revenue records by product.

To extend the model, the annual R&D budget is also decomposed, this time into investments for products currently under development that will be launched in the vintage year and future years. Year over year, the annual R&D budget can be thought of as a series of product

Model Formulation

Revenue Decomposition. Patterson decomposed the revenue R_i of a particular "vintage" year (for example the year 2000) into contributions from revenue waves from products launched earlier,

$$R_{2000} = a_0 W_{2000} + a_1 W_{1999} + a_2 W_{1998} + \ldots \qquad \text{Eq. 1}$$

Here W_i is the *lifetime* revenue for the year indicated, and α_k is the fraction of the lifetime revenue collected k years after product launch. They describe the shape of the revenue wave, and sum to unity, $\Sigma\,\alpha_k = 1$.

R&D Decomposition. The annual R&D budget E_{2000} is decomposed into investments for products currently under development that will be launched in the vintage and future years,

$$E_{2000} = \beta_0 P_{2000} + \beta_1 P_{2001} + \beta_2 P_{2002} + \ldots \qquad \text{Eq. 2}$$

Here, P_i is the *lifetime* PAS for products that will launch in the indicated year, and β_k is the fraction of the investment occurring k years before launch, normalized so that $\Sigma\,\beta_k = 1$. The shape of a typical PAS wave can be determined from the firm's investment records by product.

Formula for Steady-State Growth Rate. A relationship between parameters can be derived for the special case where the percent annual growth, g, and R&D intensity, $D_i = E_i/R_i$, are constant. If the growth rate is constant, $W_{k+1} = (1 + g)W_k$. Eq. 1 becomes,

$$R_{2000} = W_{2000}\left[\alpha_0 + \frac{\alpha_1}{(1+g)} + \frac{\alpha_2}{(1+g)^2} + \ldots\right]$$

Use the same relation in Eq. 2 after expressing the lifetime PAS investment in terms of the lifetime revenues, $P_i = W_i/\Omega_i$,

$$E_{2000} = W_{2000}/\Omega_{2000}[\beta_0 + \beta_1(1+g) + \beta_2(1+g)^2 + \ldots]$$

Eliminate W_{2000} from these two equations. The resulting equation contains the ratio E_{2000}/R_{2000} (e.g., the R&D intensity in 2000), which by assumption is constant year over year. Thus,

$$\Omega D = \frac{[\beta_0 + \beta_1(1+g) + \beta_2(1+g)^2 + \ldots]}{\left[\alpha_0 + \frac{\alpha_1}{(1+g)} + \frac{\alpha_2}{(1+g)^2} + \ldots\right]} \qquad \text{Eq. 3}$$

Again, g is the percent annual growth of the firm, and D is the R&D intensity.

Approximate Formula for Steady-State Growth Rate. Eq. 3 can be simplified if the revenue and PAS waves are hypothetically very sharply spiked in the year m_p and n_p respectively; e.g., the coefficients α_k and β_k are zero except for the year m_p and n_p, where they are unity. Eq. 3 becomes,

$$\Omega D \to (1+g)^{m_p + n_p} \qquad \text{Eq. 4}$$

Eq. 4 is strictly valid only if the revenue and PAS waves are sharply spiked. Even if they are not, but distributed somewhat before and after the spike year, Eq. 4 is surprisingly accurate given the following expressions, which estimate the year of the peak: $m_p \sim \Sigma\, i\alpha_i$ and $n_p \sim \Sigma\, i\beta_i$. Eq. 4 was compared numerically with Eq. 3 for a range of parameter values and found to be adequate for many purposes.

Eq. 4 can be rearranged to express the growth rate as a function of ΩD and $\tau = m_p + n_p$. Figure 8 shows how g increases as ΩD increases or τ decreases.

Parameter Estimation. Determination of the gain from historical revenue and R&D time series is easy, if g and D happen to be constant over a sufficiently long time interval. In that case, g is the slope of a semi-log plot of the revenue time series, m_p and n_p is estimated from the shapes of the revenue and investment waves, and the gain is computed using Eq. 4.

The uncertainty in the gain can be estimated if the parameters are not correlated. The sum of the squares of the partial derivatives of Eq. 4 gives

$$(\Delta\Omega/\Omega)^2 = \left(\frac{\Delta D}{D}\right)^2 + (\Delta\tau)^2[\ln(1+g)]^2 + \tau^2\left[\frac{\Delta g}{1+g}\right]^2$$

where $\tau = m_p + n_p$. As an example, if $D = 10\%$, $\Delta D = 0.5\%$, $g = 10\%$, $\Delta g = 0.5\%$, $\tau = 5$, and $\Delta\tau = 0.5$, we find $\Omega = 16.1$, and $\Delta\Omega/\Omega = 7\%$.—**G.C.H.**

acquisition spending "waves," or PAS waves, each targeted at specified launch years. Thus, the annual R&D budget can be decomposed (see Eq. 2, "Model Formulation"). In this case, the shape of a typical PAS wave is characterized by a set of fractions β_k that describe the percentage of the PAS occurring k years *before* launch. The shape of a typical PAS wave can be determined from the firm's investment records by product.

For the extended model, the lifetime revenue W_i of products launched in a particular year is assumed to be proportional to the lifetime product acquisition spending, P_i, that created those products. This differs from Patterson's assumption, where the lifetime revenue is proportional to the annual R&D budget. I call the constant of proportionality the "corporate gain", Ω, and explain in a moment how it is related to G.

A general time-dependent model was constructed using Eqs. 1 and 2 restated recursively for every vintage year, together with a spreadsheet to keep track of revenue and R&D spending elements by year.

Special Case of Steady-State Growth

A formula linking model parameters can be derived for the special case where the percent annual growth, g, and R&D intensity, D, are constant over a time interval long

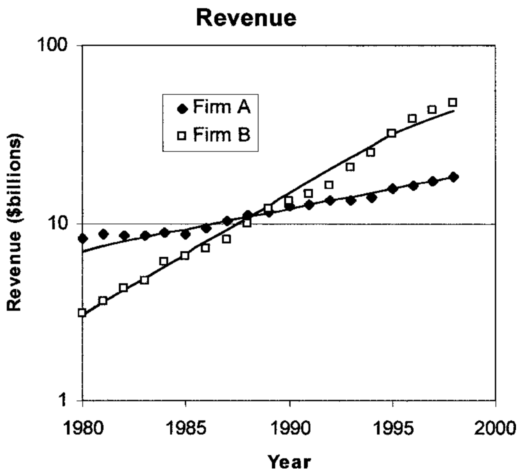

Figure 1.—Comparison of the actual revenue (symbols) to simulated values (lines).

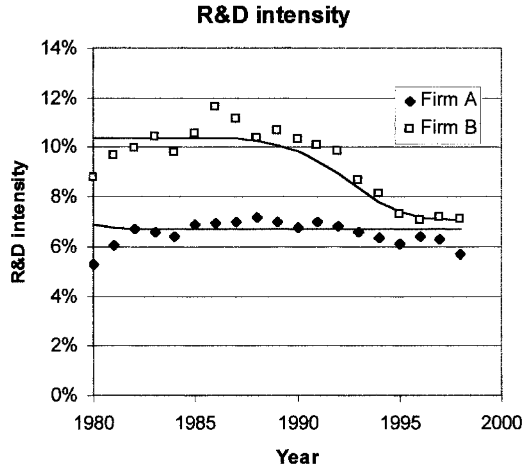

Figure 2.—Comparison of the actual R&D intensity (symbols) to simulated values (lines).

compared to the combined duration of the revenue and PAS waves. The formula (see Eq. 3, "Model Formulation") can be used to compute the growth rate if the corporate gain, R&D intensity, and shapes of the revenue and PAS waves are known. It also shows that the firm's growth rate will be zero if the product of the corporate gain and R&D intensity is unity, that is, if $\Omega D = 1$. If the product development schedule is modified (represented by a new set of shape parameters β_k), Eq. 3 can be used to compute the resulting change in the annual growth rate.

Patterson's model corresponds to a situation where the PAS investment occurs solely in the "vintage year" (that is, $\beta_0 = 1$, and $\beta_k = 0$, for $k > 0$). With this specialization of Eq. 3, a relation between the corporate gain Ω and Patterson's new product revenue gain G is found, namely $\Omega = G[\beta_0 + \beta_1(1 + g) + \beta_2(1 + g)^2 + \ldots]$.

Case Study

Model parameters for a firm can be determined using historical revenue and R&D budget information published in annual reports. To illustrate, consider two large multinational firms, denoted A and B, in similar businesses. The shapes of the revenue and PAS waves are inputs to the analysis. The annual revenue and R&D intensity data for the firms are plotted in Figures 1 and 2, respectively.

Assumptions for the Simulation

The product development schedule at firm A typically requires 2 to 5 years, depending on product complexity (measured by the number of drawings and lines of software code). Figure 3 shows two examples of the PAS wave shape, for which the weighted average duration n_p (defined in "Model Formulation") is 2.7 and 1.9 years, respectively. Information on product development time at firm B is not available. For the case study, we assumed the PAS wave shape for both firms was the same, with n_p = 2.7 years.

The revenue wave shape at firm A typically reaches a peak 3 to 4 years after launch. Figure 3 shows three examples, labeled by the weighted average duration m_p

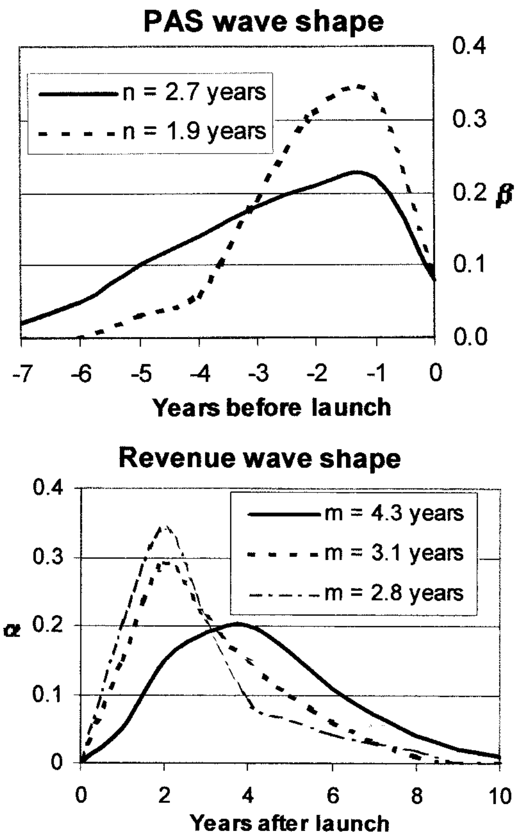

Figure 3.—Examples of PAS and revenue wave shapes.

(defined in "Model Formulation"). The simulations used the curve with $m_p = 4.3$ years for firm A, and the curve with $m_p = 2.8$ years for firm B (*1*).

The R&D intensity at firm A has an average value of ~6.7%, as shown in Figure 2. For firm B, the R&D intensity dropped from ~10.4% during the 1980s to ~7.1% during the 1990s. This is an appreciable change, which we modeled by a corresponding decrease in the growth rate of the PAS waves, beginning in 1987.

Simulation Results

The simulation was made using Eqs. 1 and 2 to generate expressions for each year, and a spreadsheet to sum the annual revenue and R&D budgets. There were three adjustable parameters: Ω, g, and the PAS investment for the year when the simulation begins, P_0.

The PAS investment was increased year over year by the annual growth rate. As mentioned above, the PAS growth rate was decreased beginning in 1987 for firm B.

The parameter-fitting procedure was to adjust g and P_0 to minimize the difference between the actual and simulated R&D time series, and then adjust Ω to minimize the difference between the actual and simulated revenue time series. Several iterations of this procedure were done to achieve the best fit. (The parameter P_0 adjusts the magnitude of the simulated R&D intensity; once P_0 is fixed, the parameter Ω adjusts the magnitude of the simulated annual revenue; the parameter g adjusts the slopes of both curves.) The accuracy is estimated to be $\Delta\Omega/\Omega$ ~7% (see "Model Formulation").

The parameters for the simulations are compared in Table 1. Surprisingly, the gains Ω for the two firms have similar values, 21.5 and 23.0 for firm A and B, respectively. Yet the simulated growth rates are quite different: 5.4% for firm A, and 17.0% (gradually decreasing to 9% due to the reduction in R&D) for firm B. Why is there such a large difference in growth rates? The difference can be understood from Eq. 3 or 4 (see "Model Formulation"). Quantitatively, the difference in growth rates is caused by the revenue wave duration m_p (4.3 and 2.7 years, respectively) and the R&D intensity D (6.7% and 10.4%, respectively).

Comparing Corporate and Product Gain

It is instructive to compare the corporate gain Ω with values computed for individual products. In general, they differ, and I discuss why. The "product gain" for individual products is the ratio of lifetime product revenue to lifetime PAS, denoted by γ_k.

Figure 4 displays product gains for a sample of 30 products from six product families, offered by firm A over 20 years. The product gains have a wide range of values, from 6 to 272. Parent products typically have small values, whereas variants have large values. When products are analyzed according to product family, the range narrows appreciably. To analyze products as a family, the lifetime revenues of product family members were summed and divided by the sum of the correspond-

Table 1.—Model Parameters for Simulations of Firm A and B.

Parameter	Firm A	Firm B
Average R&D intensity D (%)	6.7 ('80–'98)	10.4 ('89–'92) 7.1 ('95–'98)
Revenue wave duration m_p (years)	4.3	2.8
PAS wave duration n_p (years)	2.7	2.7
Patterson gain G	18.7	15.1
Corporate gain Ω	21.5	23.0
Annual growth rate g (%), ('80–'98)	5.4	17.0

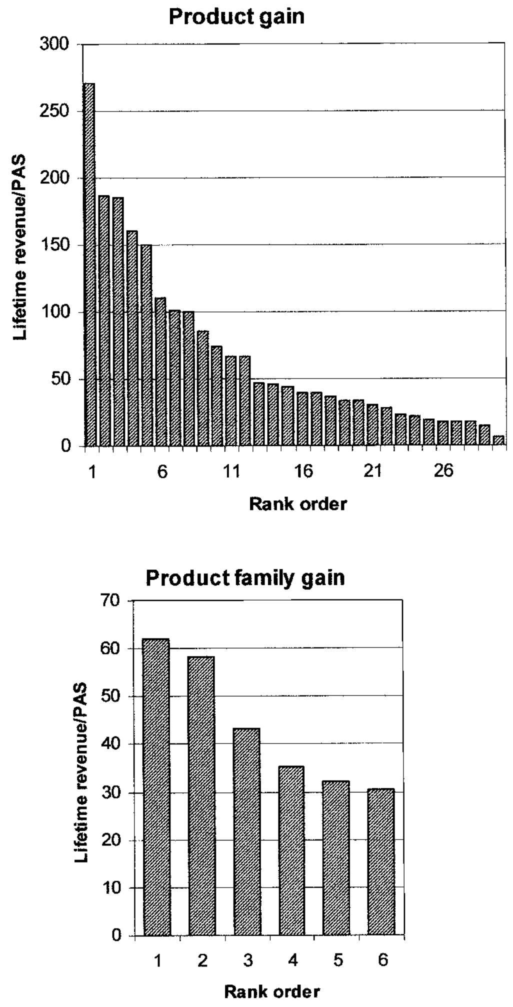

Figure 4.—Gains computed for a sample of 30 products that belong to 6 product families.

ing PAS figures. The range of values is smaller, from 30 to 62, shown in Figure 4.

If the products are aggregated again into a single population, a value of 37.4 is obtained. This compares to the corporate gain value of $\Omega = 21.5$ obtained earlier. The ratio is 21.5/37.4, ~0.6. There are two reasons that this ratio is not unity. One is that the product sample did not include all products developed by the firm—in particular, a number of product families with disproportionately smaller lifetime revenues are missing from the sample. A second reason is that some R&D development efforts did not yield products.

I next consider these two points. The gain factor for the product sample, labeled A, can be written $\gamma(\mathrm{A}) = W(\mathrm{A})/P(\mathrm{A})$, where $W(\mathrm{A})$ is the sum of the lifetime revenue for sample A, and $P(\mathrm{A})$ is the total product R&D investment for sample A. Similarly, the corporate gain can be written $\Omega = [W(\mathrm{A}) + W(\mathrm{B})]/[P(\mathrm{A}) + P(\mathrm{B}) + P(\mathrm{C})]$. Here, B refers to the products not in sample A, and $P(\mathrm{C})$ is the R&D investment that did not yield products. From these relationships, the ratio $\Omega/\gamma(\mathrm{A})$ can be written as the product of two factors,

$$\frac{\Omega}{\gamma(\mathrm{A})} = \frac{\gamma(\mathrm{A+B})}{\gamma(\mathrm{A})} \frac{P(\mathrm{A}) + P(\mathrm{B})}{P(\mathrm{A}) + P(\mathrm{B}) + P(\mathrm{C})}$$

The second factor is the "efficiency" of the product development process, expressed as the fraction of the total product development effort that yielded launched products. This is different from the "product effectiveness index" described by McGrath and Romeri (*2*), which, incidentally, can be compared by expressing it in terms of this model's parameters. From experience, the "efficiency" is estimated to be about 0.8. Using this and the estimate $\Omega/\gamma(\mathrm{A}) \sim 0.6$, the ratio of the gain of all of the firm's launched products, compared to the gain of those just in sample A is $\gamma(\mathrm{A + B})/\gamma(\mathrm{A})$, ~0.7.

I conclude that the connection between corporate gain and individual product gains is clear if one considers how product data are sampled, and what the "efficiency" is of the product delivery system.

Time-dependent Simulations

In practice, management must make R&D investment decisions that may not affect revenue until many years in the future. It would be helpful to have a method to project future revenue at the time when key R&D alternatives and decisions are being considered. Probable outcomes of hypothetical scenarios could be simulated, given the assumptions of the model. The simulated results can be complex because of the time lag between investment and revenue, and because there are always several waves of investment and revenue in the pipeline at once. Each scenario starts from the same initial state, and the model parameters are changed in the year 2000 to simulate the decision.

Our simulations use Eqs. 1 and 2, restated for each year, and a spreadsheet to keep track of investment and revenue year over year. The shapes of the PAS and revenue waves are inputs. The steady-state growth equations are valid before and after the perturbation.

Four simulations were made. Simulations 1, 2 and 3 have the goal to increase the annual growth rate. For the first, the R&D budget was increased; for the second, product development time was decreased; and for the third, the revenue wave duration was shortened. Simulation 4 illustrates what can happen when two interacting decisions are made simultaneously. Results are summarized in Table 2 and Figures 5–7.

■ *Simulation 1.*—In this scenario, to stimulate growth, management increases the annual growth rate of the budget for new PAS waves in the year 2000 (and subsequent years) from 5.4% to 10%. As a result, the total R&D intensity gradually rises to a steady-state value of 9.0%, and the firm's simulated growth rate rises to a steady-state value of 10%. As indicated in Figure 5, the transient time is ~8 years, equal to the sum of the product development time and revenue wave duration.

■ *Simulation 2.*—This scenario presumes that the firm has made an improvement in the product delivery process that has shortened the product development time by 0.8 years (from 2.7 to 1.9), starting in the year 2000. The shorter product development schedule results in a temporary reduction of expenses that management harvests by delaying the startup funds for subsequent PAS waves. As shown by the simulation in Figure 6, the annual R&D budget (and R&D intensity) temporarily decreases, and the steady-state revenue growth rate increases from 5.4% to 6.3%.

Simulation 2 shows that a reduction in product development schedule will modestly increase the steady-state revenue growth rate.

Table 2.—Parameter Values for "What If" Simulations. (Corporate gain value is Ω = 21.5 for all four simulations.)

Parameter	Initial value	Simulation 1	Simulation 2	Simulation 3	Simulation 4
R&D intensity D (%)	6.7	9.0	6.7*	6.7*	4.7
Revenue wave duration m_p (years)	4.3	4.3	4.3	3.1	3.1
PAS wave duration n_p (years)	2.7	2.7	1.9	2.7	2.7
Corporate gain Ω	21.5	21.5	21.5	21.5	21.5
Growth rate g (%)	5.4	10	6.3	6.5	0

*final state value

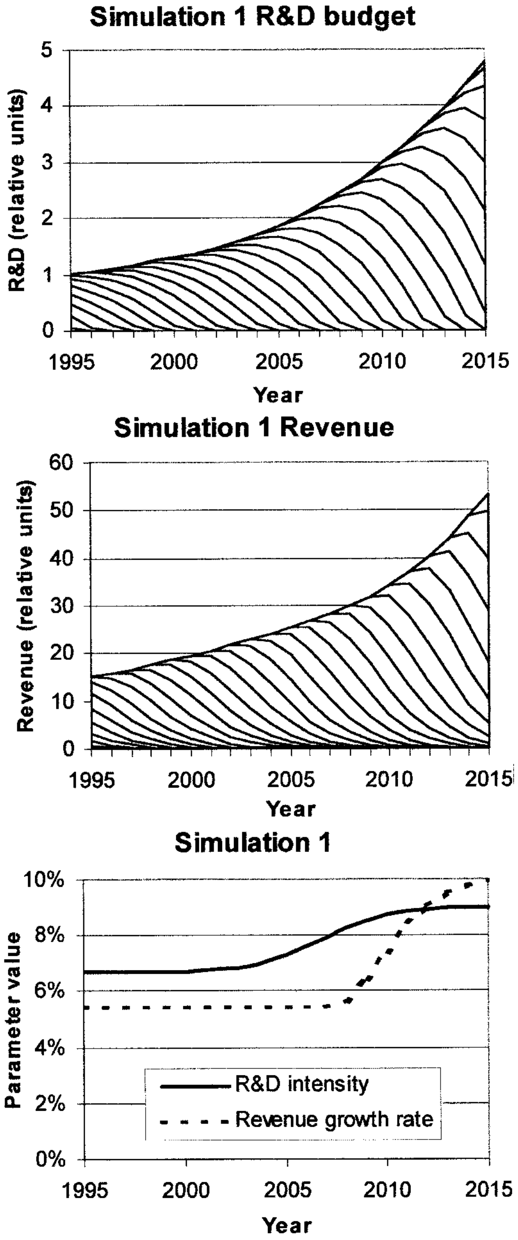

Figure 5.—For simulation 1, the annual growth rate of the R&D budget for PAS new waves in 2000 and subsequent years was increased from 5.4% to 10%. The bands are the annual PAS and revenue waves.

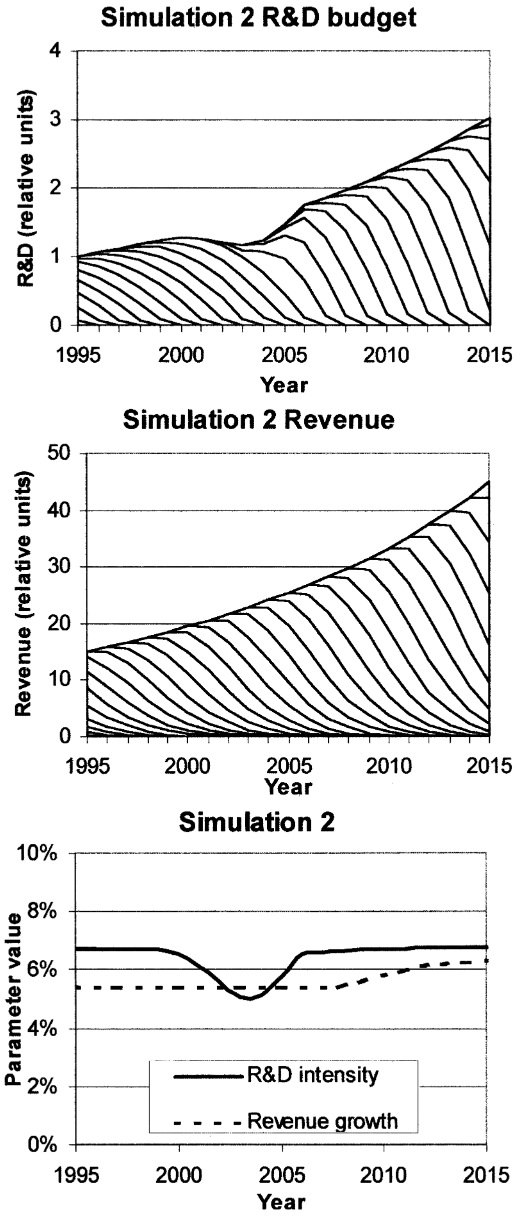

Figure 6.—For simulation 2, improvements in engineering practices enable the product development schedule to be shortened, beginning in 2000.

■ *Simulation 3.*—In this scenario, market conditions change, and the revenue wave becomes shorter, beginning in the year 2000. A shorter revenue wave could arise, for example, if competitive pressures caused prices to drop, motivating customers to buy more products and simultaneously abandon old product lines more quickly. The shorter revenue wave means that more revenue is collected in the years just after the change. This causes the simulated revenue to temporarily surge, as shown in Figure 7. As the transient passes, the simulated revenue growth rate eventually settles down to a value of 6.5%, slightly larger than the initial value of 5.4%.

Simulation 3 shows that a shorter duration for the revenue wave leads to a larger steady-state revenue growth rate, all other factors being unchanged.

■ *Simulation 4.*—Simulation 3 illustrated that the revenue temporarily surged when the revenue wave duration became shorter. When the revenue surged, management might decide to cut R&D, reasoning that since

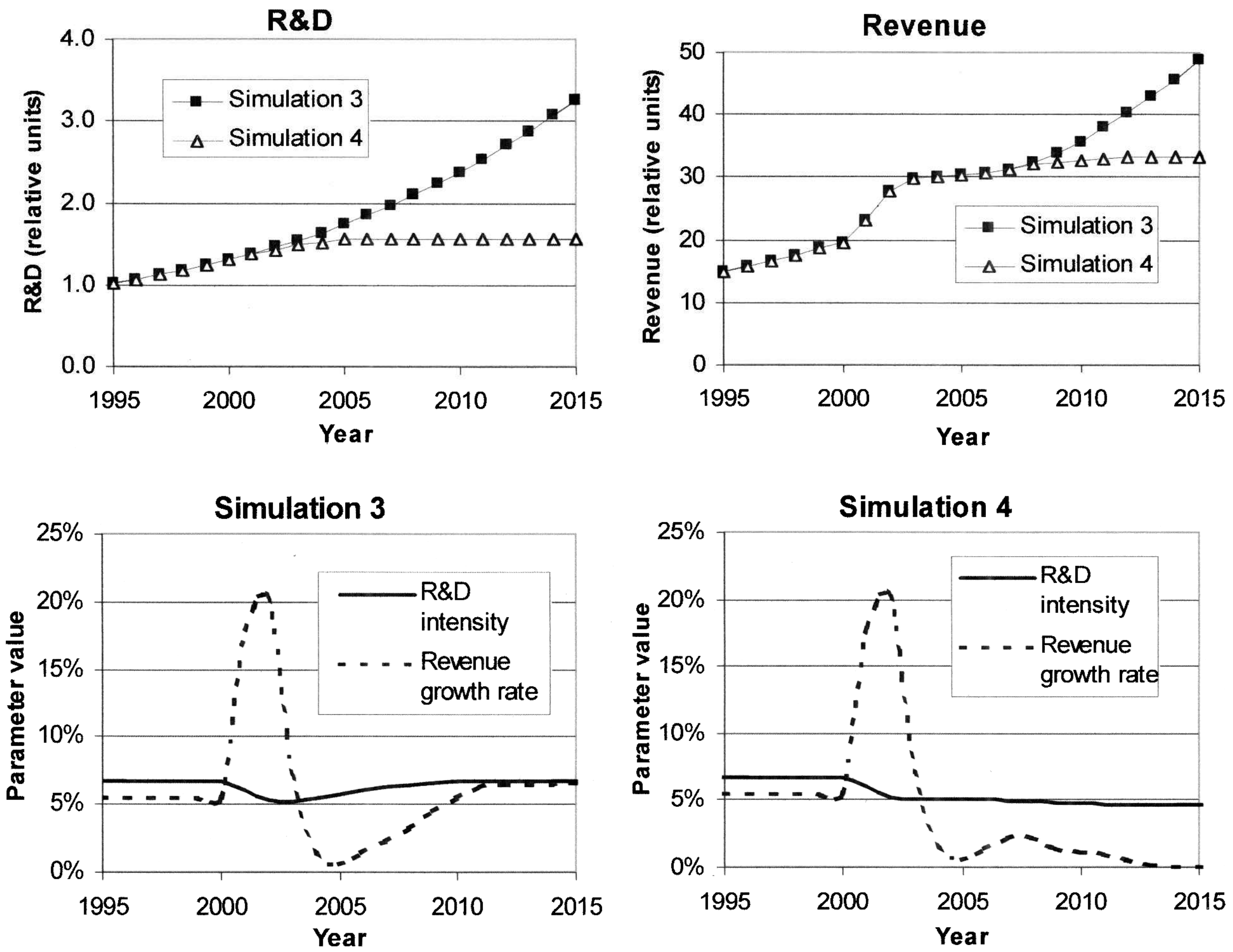

Figure 7.—For simulation 3 and 4, the revenue wave was shortened from 4.3 to 3.1 years beginning in the year 2000. For simulation 4, simultaneously, the R&D intensity was reduced to 4.7%, which leads to a growth rate of 0.

revenue conditions are improving, a smaller R&D budget will suffice. Figure 7 shows what happens if management decides to decrease the R&D intensity at the same time. The value of R&D intensity chosen is 4.7%, corresponding to $\Omega D = 1$, which is the condition for zero growth. For a few years, a surge in revenue is observed similar to Simulation 3. Eventually, however, the simulated revenue growth rate drops to zero.

These examples illustrate that the simulated revenue and R&D time series can have unusual transients, even though modest changes were made of only one or two parameters at one point in time. In general, simulations of a firm's historical revenue and R&D time series may require changes in several parameters continuously over time. Likewise, simulations of realistic future scenarios may require simultaneous changes of several parameters.

Applying the Model

The model can be used as a planning tool to simulate potential outcomes of alternative R&D budget plans. When simulating a forecast, assumptions must be made about the future value of certain model parameters, such as the corporate gain, or shapes of the product development and revenue waves. Current values of these parameters can be determined from analysis of historical R&D and revenue time series. Typically, these parameters change relatively slowly from year to year. Future values can be assigned to represent corporate strategic direction, and uncertainties can be characterized by a probability distribution.

For example, if actions are being undertaken to increase the corporate gain, or decrease product development time, the expected value of the relevant model parameter can be adjusted appropriately. Then, the future revenue stream (and its probability distribution) can be simulated using the planned R&D budget as an input. Sensitivity analysis can reveal which parameters have the most impact. If there are discrepancies between the model simulation and forecasts made using other techniques, identification of the sources often reveals hidden assumptions and yields more reliable outcomes.

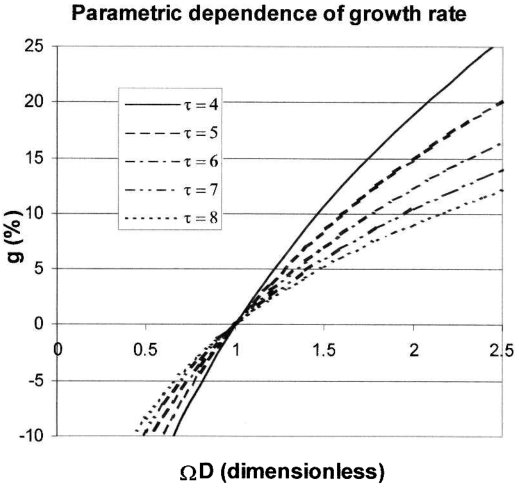

Figure 8.—Parametric dependence of the percent annual growth g *on the dimensionless parameter* ΩD *and* $\tau = n_p + m_p$, *expressed in years.*

The steady-state growth formulas are useful for examining the parametric dependence of revenue growth rate on product development schedule and other parameters. For example, imagine the current state and a hypothetical future state of the corporation that both approximately meet the steady-state growth criteria. In that case, Eq. 4 applies, which expresses the growth rate explicitly as a function of product development schedule and other parameters (see Figure 8). (If the two states don't meet the steady-state growth criteria, the dependence can be examined using the full time-dependent model.)

Advantages of the model's parameterization scheme are that it cleanly separates legacy product revenue from new product revenue, and correctly keeps track of the time delays between investment for product development and the corresponding revenue stream generated years later. Forecasting uncertainty is reduced because some parameters, such as the shapes of the revenue and investment waves, typically don't change appreciably from year to year. A disadvantage is that factors downstream of R&D, such as initiatives by competitors, or effectiveness of the firm's marketing and sales functions, are masked by the model's lumped corporate gain parameter, and additional analysis is required to reveal them. ⓐ

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