Evaluating Investments in Disruptive Technologies

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May 18, 2000

Abstract. A computer simulation model for the valuation of investments in disruptive technologies is developed. Based on the conceptual framework proposed by Christensen (1997) for explaining the *Innovator's Dilemma* phenomenon, an investment project is divided into two sequential phases representing the evolution of the disruptive technology from an emerging to a mainstream market. In each of these phases, development costs and net commercialization cash flows are modeled using various stochastic processes that interact with each other. As a result, the initial estimate on the value of the project is continuously updated to reflect the stochastic changes of these variables. An example illustrates the usefulness of the model for understanding the effects of cash flow and cost volatilities in the value of a disruptive technology investment.

1 Introduction

Innovation, defined as the creation of something new or as the adoption of an idea or behavior that is new for the organization that adopts it, has become the fundamental process to promote the growth of an organization. After decades of cost reductions and down-sizing, organizations have understood that they have to innovate their administrative processes, the products and services they deliver, and the technology they use in order to obtain a differentiation that allows them to compete successfully (Tushman and O'Reilly 1997). Jonash and Sommerlatte (1999) have found strong evidence of an innovation premium: the top 20% companies of *Fortune*'s ratings on innovation enjoy double the shareholder returns of the other companies in their industries.

In spite of its importance, most executives have serious doubts about how they should invest in a process that traditionally has been full of uncertainty and high costs. Emerging technologies do not fit well with the traditional project evaluation methods used in most organizations and projects involving these technologies are often ignored or considered a second priority. The situation is even more dramatic in the case of *disruptive technologies* whose performance is worse than that of existing technologies according to prevailing value networks (Christensen and Rosenbloom 1995). Consider, for instance, what happened when early PCs first appeared in the market. As pointed out by Christensen and Overdof (2000), early PCs were not powerful enough to run the computing applications of existing mainframes and minicomputers. PCs had other attributes, such as their low cost, that enabled new applications for the personal user to emerge; however, in their earlier

stages, PCs did not address the next-generation needs of the leading customers of mainframes and minicomputers. Therefore, leading manufacturers of minicomputers such as Digital Equipment Corporation gave higher priority to projects related to enhancing existing technologies than to those involving the development of the emerging disruptive technology.

Several frameworks have been proposed for the valuation of investment projects under uncertainty including the use of real options (Amram and Kulatilaka 1999, Dixit and Pindyck 1994, Schwartz and Zozaya-Gorostiza 2000), decision trees (Tipping, Zeffren 1995), scenario-analysis (Jovanovic 1999) and Monte Carlo simulation (Boer 1999). Each of these frameworks provides the decision maker with additional elements for evaluating an investment decision in comparison with traditional valuation methods. Real options, for instance, allow to value of the flexibility of an investment project in terms of postponing the decision to invest, suspend (or resume) the execution of a project or abandon it completely (Brennan and Schwartz 1985), as well as to model the growth opportunity acquired when investing in a new technology (Schwartz and Moon 2000a).

Computer simulation, and its application in the analysis of multiple scenarios, has proven to be useful in modeling complex phenomena for which analytical solutions are difficult to obtain. Schwartz and Moon (2000b) developed a simulation model for the valuation of Internet companies and found that the pricing of Internet stocks may be rational given high enough growth rates and volatilities in the corresponding cash flows. Bers, Lynn and Spurling (1999) note that, despite the power of scenario analysis as a planning tool, there have been few published reports of its successful application to business planning. They developed a Monte Carlo simulation model designed to assist technical professionals in developing business plans for emerging technologies in emerging markets under different scenarios.

In this paper we develop a computer simulation model for the valuation of investments in disruptive technologies. Based on the conceptual framework proposed by Christensen (1997) for explaining the *Innovator's Dilemma* phenomenon, an investment project is divided into two sequential phases representing the evolution of the disruptive technology from an emerging to a mainstream market. In each of these phases, development costs and net commercialization cash flows are modeled using various stochastic processes that interact with each other. As a result, the initial estimate on the value of the project is continuously updated to reflect the stochastic changes of these variables.

The next section describes some characteristics of disruptive technologies as a background for subsequent discussion. Section 3 describes Christensen's conceptual model of the evolution of disruptive technologies over time. Based on this conceptualization, Section 4 describes the proposed valuation model for investments in disruptive technologies. First, the stochastic processes associated with the evolution of development costs and commercialization cash flows are presented. Then, the manner in which these processes are used to compute the expected value of the project is discussed. Section 5 provides the reader with a pseudo-code of the overall simulation process. Section 6 illustrates the application of our model for the valuation of a hypothetical project involving the development of a disruptive optical technology for data storage. Finally, Section 7 discusses some possible extensions to the proposed model and provides some conclusions of our work.

2 Disruptive Technologies and Change

In his book entitled "The Innovator's Dilemma", Chistensen (1997) explains why leading companies fail when they are confronted with certain types of market and technological changes:

- There is a strategically important distinction between a *sustaining* and a *disruptive* technology. *Sustaining* technologies are new technologies that foster improved product performance. They can be discontinuous radical or incremental. In contrast *disruptive* technologies result in *worse* product performance, at least in the near term.
- When faced with disruptive technologies, good management practices (planning better, working harder, becoming customer driven and taking a long-time perspective) do not work and may lead to failure. Even though most disruptive technologies are originated in the leading firms, they are often neglected and their creators have to continue their development in a new firm.
- The pace of technological progress can outstrip what markets need. Leading firms are generally aggressive and innovative in sustaining technologies but they were unable to confront a *downward* vision. They often "overshoot" their mainstream markets by giving their customers more than what they need or are willing to pay for, but they fail to look at new technologies that might bring a new value proposition provided by disruptive technologies. As a result, when disruptive technologies are able to satisfy the minimum performance required by the low end of the market, the new value proposition comes into play and incumbent firms find that they are unable to react successfully.
- Customers and financial structures of successful companies affect the sorts of investments that appear to be attractive to them, relative to certain types of entering firms. Leading companies often invest aggressively in technological innovation. However, they often disregard projects involving disrupting technologies because they are less attractive than those of sustaining technologies. Investing aggressively in disruptive technologies is not a rational financial decision according to traditional project evaluation techniques because it promises lower margins (i.e., products are generally simpler and cheaper) in emerging and insignificant markets. Furthermore, the most profitable customers do not want the disruptive technology products.

3 Conceptual Model

In order to develop a formal model for the valuation of investments in disruptive technologies, it is necessary to understand the decision making traps in which a successful organization falls as well as the trajectories followed by established and disruptive technologies. Christensen summarizes the pattern of decisions regarding disruptive technological change as follows (Christensen 1997, p. 43):

a) Disruptive technologies are first developed within established firms. These innovations are the result of many factors including creativity, serendipity, and entrepreneurial spirit of the technical personnel in the leading firms. Instead of being sponsored by senior management, these initiatives generally use bootleg resources.

b) Marketing personnel tests the reactions from their lead customers. The most profitable customers are unwilling or unable to benefit from the disruptive technology new capabilities

because they are concerned with the current performance measures of the established technologies.

c) Established firms step up the pace of sustaining technological development. In order to satisfy (and exceed the expectations of) their customers, firms develop sustaining technologies even at a faster rate than the corresponding market needs.

d) New companies are formed, and markets for disruptive technologies are found by trial and error. The lack of attention and support to disruptive technologies causes some of the technical personnel to leave and create new companies to commercialize the disruptive technologies.

e) The entrants move up and enter the mainstream market. The disruptive technologies normally improve at very fast rates and get to a point in which their performance is enough to satisfy the needs of the mainstream market with respect to the current measures of performance. In addition, the new technologies provide better value along other performance dimensions so customers are willing to switch.

f) Established firms belatedly jump on the bandwagon to defend their customer base. However, their organizational structures and processes difficult them to react effectively.

Figure 1 shows the intersecting trajectories of the performance demanded by mainstream and emerging markets and that supplied by current and emerging technologies. As pointed out by Christensen, what matters is not whether the established technology is improving at increasing or decreasing rates, but whether the disruptive technology is improving from below along a trajectory that will ultimately intersect with what the market needs ($t = \tau$).

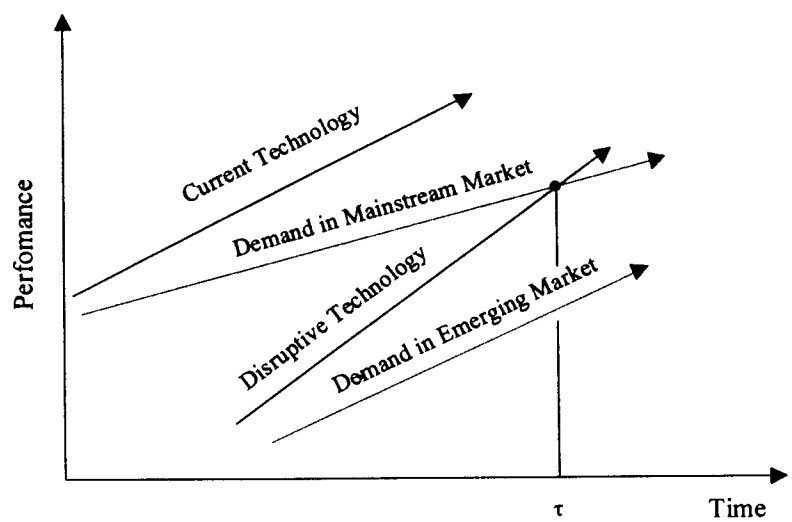

Figure 1: Intersecting Trajectories of Performance Demanded and Supplied by Technologies (adapted from (Christensen 1997))

4 Valuation Model

In this section we explain the elements used in our model for the valuation of investments in disruptive technologies. Following the conceptual description presented in the previous section,

our model assumes that a firm that invests in disruptive technologies goes through two sequential phases (see Figure 2):

- *Emerging Market Phase.* This phase has two stages: one in which the technology is being developed and tested in the emerging market, and a second stage in which it is commercialized only in this market. In this second stage, the organization continues to invest in the technology to enhance its performance according to several attributes including those valued by the mainstream market. The costs and times for developing the technology for any of the markets as well as the cash flows that will be received when the technology is ready for commercialization are uncertain.

- *Mainstream Market Phase.* Once the technology has achieved an acceptable performance level for the mainstream market, the organization moves up and starts competing for the most profitable customers.

At the beginning of the project, the organization will have an initial estimate of the development costs and cash flows associated with each phase, but these values will be updated periodically as time moves forward. Furthermore, there will be a probability of failure in each of the phases to represent the cases in which the development and/or commercialization of the technology are unsuccessful and the project is permanently abandoned.

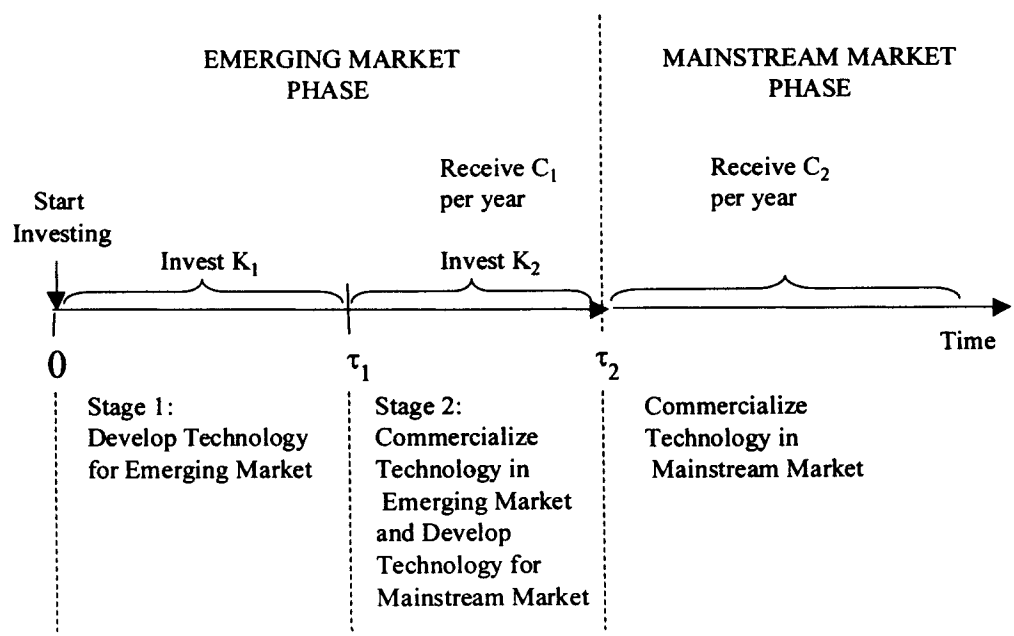

Figure 2: Phases of a Disruptive Technology Project

As an initial approximation, our valuation model accounts for uncertainty in development costs and cash flow rates using three stochastic processes associated, respectively, with the development costs of Stages 1 and 2 of the Emerging Phase and with the evolution of net commercialization cash flows, as explained below.

4.1 Development Costs

In Pindyck's model (1993) for investment under uncertainty, the expected cost of completion of a project K(t) is assumed to follow a controlled diffusion process given by the following expression:

$$dK = -I\ dt + g(I,K)\ dz \tag{1}$$

where I is the rate of investment, dz is an increment to a Wiener process that might or might not be correlated with the economy and the stock market, and g is a function such that $g_I \geq 0$, $g_{II} \leq 0$, and $g_K \geq 0$. According to this model, the expected cost to completion declines with ongoing investment but also changes stochastically. If $g_I > 0$, the effect of the stochastic component increases as we invest more in the project; if $g_{II} < 0$, the changes in these increasing effects will be smaller as we proceed forward; finally, if $g_K > 0$, the effect of the stochastic component decreases when the expected cost of completion is reduced. Pindyck also shows that letting $g(I,K) = \beta(IK)^{1/2}$ provides a formulation that complies with the following conditions that make economic sense: a) an increase in the expected cost of an investment reduces its value; b) the instantaneous variance of dK is bounded for all finite K and approaches to zero as $K \rightarrow 0$; and c) if the firms invests at a maximum rate I_m until the project is complete, K is indeed the expected cost to completion.

Following Pindyck's reasoning, our model assumes that the completion costs of developing a technology evolve according to the following stochastic process:

$$dK = -I\ dt + \beta(IK)^{1/2}\ dz \tag{2}$$

where dz is an increment to a Wiener process that is uncorrelated with the economy, β is the instant standard deviation of the proportional changes in K (i.e., the volatility of the costs) and I is the corresponding investment rate.

In our model an organization is assumed to keep investing in a technology until its performance is adequate for the target market (i.e., the technology "catches up" with the market) unless a disaster occurs and the development project is aborted. Also, completion costs include both the costs required for improving the disruptive technology and the launching costs required prior to the commercialization of the technology. Examples of launching costs are those associated with advertising the technology as well as with the development of the appropriate distribution channels.

After a technology is ready to be commercialized (i.e., completion costs of initial development are zero), the organization incurs in sales, operating and other types of technology enhancement costs. In our model, however, these post-launch costs are not modeled separately but considered within the *net* cash flows of the commercialization process.

For each simulation run, Equation (2) is used to compute the development cost for Stages 1 and 2 of the *Emerging Phase* as follows:

- *Stage 1: Development of Technology for the Emerging Market.* First, the new completion costs for Stage 1 of the Emerging Phase is obtained from the completion cost of the previous time step using the following expression:

$$K_{1,\,t+1} = K_{1,\,t} - I_1\ \Delta t + \beta(I_1 K_{1,t})^{1/2}\sqrt{\Delta t}\,\varepsilon_1 \tag{3}$$

where Δt is time interval from t to t+1 and ε_1 is a N(0,1) standard normal. The total cost for Stage 1 is updated by adding the corresponding investment over time:

$$TotCost_{1,\,t+1} = TotCost_{1,\,t} + I_1\ \Delta t \tag{4}$$

At the end of Stage 1, this value is then used to obtain an estimate of the expected completion costs of Stage 2 of the Emerging Phase:

$$K_{2,\,\tau_1} = TotCost_{1,\,\tau_1} * CostRatio \tag{5}$$

where *CostRatio* is an input parameter representing the ratio of total development costs for the Emerging and Mainstream markets.

- *Stage 2: Development of Technology for the Mainstream Market.* Once Stage 2 has been started, the completion cost for this stage is updated using Eq. 2 as follows:

$$K_{2,\,t+1} = K_{2,\,t} - I_2\ \Delta t + \beta(I_2 K_{2,t})^{1/2}\sqrt{\Delta t}\,\varepsilon_1 \tag{6}$$

In our model, no risk premium for costs is considered[1]. Therefore, the development costs in any of the stages can be discounted using the risk-free rate without further adjustment for risk.

4.2 Commercialization Cash Flows

The net cash flow rates received from commercializing a technology in a particular market are assumed to behave according to the following expression:

$$dC = \alpha\, C\, dt + \phi\, C\, dx \tag{7}$$

where dx is an increment to a Wiener process that is uncorrelated with the economy but that might be correlated with the costs of developing the technology, and ϕ is the instantaneous standard deviation of the proportional changes in C (i.e., the volatility of the cash flows). The term (α C dt) describes the expected change in cash flows over time. A positive α might be used for modeling situations in which cash flows increase during the commercialization of the disruptive technology due, for instance, to a major penetration in the market. In contrast, a negative α might be used for situations in which cash flows decrease due to a reduction in prices triggered by more intense competition.

Our model considers that there is a risk-premium associated with the cash flows. Therefore, the true process of cash flows described by Eq. (7) is transformed into the following risk-adjusted process:

$$dC = (\alpha - \eta_C)\, C\, dt + \phi\, C\, dx \tag{8}$$

[1] That is, we assume that development costs are uncorrelated with aggregate wealth.

where η_c represents the risk-premium for cash flow values. Once this adjustment has been made, risk-adjusted cash flows can be discounted using the risk-free rate for valuating the project under a risk-neutral scenario.

The model uses one stochastic process for representing the evolution of the net cash flows of the emerging market phase. This evolution is used to obtain an estimate of the expected net cash flows of the mainstream phase. Once the first phase has been completed and the technology is ready for being commercialized in the mainstream market, the expected cash flow of the mainstream phase is obtained as a multiple of the final cash flow from the first phase.

We allow the stochastic changes in the net cash flows to be correlated with the stochastic changes in the development costs:

$$dx\,dz = \rho dt \tag{9}$$

A positive ρ could represent, for instance, that higher development costs will lead to higher commercialization benefits because the customers are willing to pay more for a better product. In contrast, a negative ρ could represent, for instance, that the inability to control the costs of developing the technology are associated with an inability to commercialize the technology in an adequate manner.

For each time step of the simulation run, Eq. (8) is used to update the cash flows received during the commercialization of the disruptive technology in the emerging market as follows:

$$C_{1,t+1} = C_{1,t} * e^{[(\alpha_1 - \eta_c - \frac{1}{2}\phi^2)\Delta t + \phi\sqrt{\Delta t}\,\varepsilon_2]} \tag{10}$$

where Δt is time interval from t to t+1, α_1 is the drift of cash flows in the emerging market, η_c is the risk-premium for cash flow values, ϕ is the volatility of cash flows and ε_2 is a N(0,1) standard normal which has a correlation of ρ with ε_1. During Stage 1, $C_{1,t}$ represents the cash flow that the organization *expects* to receive once this stage is completed. During Stage 2 of the Emerging Phase, $C_{1,t}$ represents the *actual* cash flows that the organization is receiving when the technology is being further developed for the mainstream market.

At the end of the Emerging Phase, the initial cash flow of the Mainstream Phase is computed as a multiple of the final cash flow of the first phase:

$$C_{2,\tau_2} = C_{1,\tau_2} * CashRatio \tag{11}$$

where *CashRatio* is an input parameter of the simulation representing the increase in cash flows that the organization would get if it is able to commercialize the disruptive technology in the mainstream market.

Finally, the following equation is used to update the cash flows received during the commercialization of the disruptive technology in the mainstream market:

$$C_{2,t+1} = C_{2,t} * e^{[(\alpha_2 - \eta_c - \frac{1}{2}\phi^2)\Delta t + \phi\sqrt{\Delta t}\,\varepsilon_2]} \tag{12}$$

where Δt is time interval from t to t+1, α_2 is the drift of cash flows in the mainstream market, η_c is the risk-premium for cash flow values, ϕ is the volatility of cash flows and ε_2 is a N(0,1) standard normal.

4.3 Value of the Project

The *Value* of the investment project (V) is computed by subtracting the present value of the development costs (*PVCost*) from the present value of the future cash flows (*PVCash*). This assumes that the organization will invest in the development of the disruptive technology immediately if the value of the project is positive:

$$V = PVCash - PVCost \tag{13}$$

In the next section we consider the possibility of abandoning the project once it has been started; however, in this section we also assume that investment will proceed without interruptions unless a disaster occurs and the project is permanently interrupted.

For the purpose of comparisons, we will compute the value of the project for two scenarios: one in which only the emerging phase is considered (V_e) and another in which both phases are included. (V_T). This will allow us to measure the disruptive impact of the technology in the mainstream market. As we will see later on, there are many projects which are unprofitable if only the emerging phase is considered, but that are very profitable when both phases are included.

The expected present value of the development costs for entering the emerging market is obtained by integrating Eq. (2) during the interval from t=0 to t= τ_1[2]:

$$PVCost_{Stage\ 1} = E_o\left[\int_0^{\tau_1} I_1 e^{-(r_f+\lambda_1)t}\,dt\right] \tag{14}$$

where I_1 is the rate of investment during Stage 1 of the Emerging Phase, r_f is the risk-free rate, τ_1 is a random variable representing the end of Stage 1, and λ_1 is a constant rate of failure for this stage assuming that failures follow a Poisson process. Similarly, the expected present value of the development costs for entering the mainstream market is obtained by integrating Eq. (2) during the interval from t=τ_1 to t= τ_2 and by discounting the result from t=τ_1 to time zero:

$$PVCost_{Stage\,2} = E_o\left[\left(\int_{\tau_1}^{\tau_2} I_2 e^{-(r_f+\lambda_2)(t-\tau_1)}\,dt\right) * e^{-(r_f+\lambda_1)\tau_1}\right] \tag{15}$$

where I_2 is the rate of investment during Stage 2 of the Emerging Phase, r_f is the risk-free rate, τ_2 is a random variable representing the end of Stage 2, τ_1 is a random variable representing the end of Stage 1, and λ_1 and λ_2 are respectively the constant rates of failure for the two developmental stages of the Emerging Phase.

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[2] As explained in Schwartz and Moon (2000a), if failures of a particular project follow a Poisson distribution with mean rate of failure per unit time λ, the cash flows of the project should be discounted at a rate equal to the risk-free rate plus λ when computing their present value under a risk-neutral scenario.

The present value of the future cash flows from commercialization of the disruptive technology in the emerging market is obtained by integrating Eq. (8) from the time in which the technology is ready to be commercialized in this market ($t=\tau_1$) to the time in which this technology has reached the end of its useful life for this market ($t=T_1$) and by discounting the result from $t=\tau_1$ to time zero:

$$PVCash_{Emerging} = E_o\left[\left(\int_{\tau_1}^{T_1} C_{1,t} e^{-(r_f-\alpha_1^*)(t-\tau_1)} dt\right) e^{-(r_f+\lambda_1)\tau_1}\right] \tag{16}$$

where α_1^* is the risk-adjusted growth rate of the net cash flows obtained by subtracting a risk-premium due to cash flow uncertainty, η_c, from the rate of cash flow growth α_1 in the emerging market; λ_1 and λ_2 are the constant rates of failure for Stage 1and 2 of the Emerging Phase assuming that failures follow a Poisson process; and r_f is the risk-free rate.

Similarly, the expected present value of future cash flows from continuing the development and commercialization of the disruptive technology into the mainstream market is obtained by discounting the cash flows of Eq. (8) for the second stage of development and adding the result to the present value of the commercialization cash flows from the time in which the technology is ready to be commercialized in this market ($t=\tau_2$) to the time in which the technology has reached the end of its useful life for this market ($t=T_2$):

$$PVCash_{Mainstream} = E_o\left[\begin{array}{l}\left(\int_{\tau_1}^{\tau_2} C_{1,t} e^{\alpha_1^*(t-\tau_1)} e^{-(r_f+\lambda_2)(t-\tau_1)} dt\right) e^{-(r_f+\lambda_1)\tau_1} \\ +\left(\int_{\tau_2}^{T_2} C_{2,t} e^{\alpha_2^*(t-\tau_2)} e^{-r_f(t-\tau_2)} dt\right) e^{-(r_f+\lambda_2)(\tau_2-\tau_1)} e^{-(r_f+\lambda_1)\tau_1}\end{array}\right] \tag{17}$$

Equations (14) through (17) cannot be solved analytically because they involve random variables τ_2 and τ_1 in the integration limits. Therefore, we use a simulation approach to solve the problem. For each simulation run, we proceed by iteratively by adding the benefits and subtracting the costs at each point in time to the value of the project V_t. The formula for updating V_t depends on the phase and stage of the simulation as follows:

$$V_{t+1} = V_t - I_1 \Delta t\, PVF_{1,t+1} \qquad \text{if } 0 \le t \le \tau_1 \text{ (Stage 1)} \tag{18}$$

$$V_{t+1} = V_t + (C_{1,t} - I_2)\Delta t PVF_{2,t+1} \qquad \text{if } \tau_1 \le t \le \tau_2 \text{ (Stage 2)} \tag{19}$$

$$V_{t+1} = V_t + C_{2,t}\Delta t\, PVF_{2,t+1} \qquad \text{if } \tau_2 \le t \le T_2 \text{ (Mainstream Phase)} \tag{20}$$

where $PVF_{1,t+1}$ and $PVF_{2,t+1}$ represent the present value discount factors and are obtained as follows:

$$PVF_{1,0} = 1.0 \tag{21}$$

$$PVF_{1,t+1} = PVF_{1,t} * e^{-(r_f+\lambda_1)\Delta t} \qquad \text{if } 0 \le t \le \tau_1 \text{ (Stage 1)} \tag{22}$$

$$PVF_{2,t+1} = PVF_{2,t} * e^{-(r_f + \lambda_2)\Delta t} \qquad \text{if } \tau_1 \le t \le \tau_2 \text{ (Stage 2)} \tag{23}$$

For each simulation run, a final value of the project V_T^i is obtained and used to compute the expected value of random variable V_T .

4.4 Abandonment Value

In our simulation model we allow an organization to abandon the investment project once it has been started whenever the future of the project does not seem promising. For instance, if a project is having substantially higher development costs than originally expected or cash flows are lower than expected, it might be convenient to permanently abandon it. For this purpose, we estimate the Net Present Value that we expect to receive from the project based on the current value of the completion costs ($K_{1,t}$ and $K_{2,t}$) and cash flows ($C_{1,t}$ and $C_{2,t}$) at each time step of a simulation run, assuming that there is no uncertainty.

Given that the major benefits from a disruptive technology come from moving up into the mainstream market, the value of the project when both phases are included will always be higher than the value of the project when the technology is only commercialized in the emerging market. Therefore, our decision to abandon or not the project will depend upon the present value of the remaining development costs and cash flows including both phases.

During Stage 1, the present value of the remaining development costs at each time step t is estimated based on the current value of the completion costs $K_{1,t}$ and $K_{2,0}$ by setting $\tau_1 = K_{1,t} / I_1$ and $\tau_2 = K_{1,t} / I_1 + K_{2,0} / I_2$ in Eqs. (14) and (15) and solving the corresponding integrals:

$$PVCost_t = \frac{I_1}{r_f + \lambda_1}\left(1 - e^{-(r_f+\lambda_1)\frac{K_{1,t}}{I_1}}\right) + \frac{I_2}{r_f + \lambda_2}\left(1 - e^{-(r_f+\lambda_2)\frac{K_{2,0}}{I_2}}\right) e^{-(r_f+\lambda_1)\frac{K_{1,t}}{I_1}} \quad \text{for } t < \tau_1 \tag{24}$$

Similarly, the present value of the remaining development costs at each time step of Stage 2 is estimated as follows:

$$PVCost_t = \frac{I_2}{r_f + \lambda_2}\left(1 - e^{-(r_f+\lambda_2)\frac{K_{2,t}}{I_2}}\right) \quad \text{for } \tau_1 \le t < \tau_2 \tag{25}$$

Once Stage 2 has been completed, there are no more development costs and $PVCost_t$ becomes zero since commercialization cost are already included in the corresponding net cash flows.

With respect to the present value of the cash flows, they are also estimated at each time step t by computing the length of each Stage in terms of its remaining development costs and investment rates and substituting the results in Eqs. (16) and (17). Letting T_1 and T_2 be large in comparison to τ_1 and τ_2 we obtain the following expressions for $PVCash_t$:

$$PVCash_t = \begin{cases} \dfrac{C_{1,t}}{r_f + \lambda_2 - \alpha_1^*} e^{-(r_f+\lambda_1-\alpha_1^*)\frac{K_{1,t}}{I_1}} \left(1 - e^{-(r_f+\lambda_2-\alpha_1^*)\frac{K_{2,0}}{I_2}} \right) & \text{for } t < \tau_1 \\ + \dfrac{CashRatio * C_{1,t}}{r_f - \alpha_2^*} \left(e^{-(r_f+\lambda_1-\alpha_1^*)\frac{K_{1,t}}{I_1}} \right) e^{-(r_f+\lambda_2-\alpha_1^*)\frac{K_{2,0}}{I_2}} & \end{cases} \tag{26}$$

$$PVCash_t = \begin{cases} \dfrac{C_{1,t}}{r_f + \lambda_2 - \alpha_1^*} \left(1 - e^{-(r_f+\lambda_2-\alpha_1^*)\frac{K_{2,t}}{I_2}} \right) & \text{for } \tau_1 \le t < \tau_2 \\ + \dfrac{CashRatio * C_{1,t}}{r_f - \alpha_2^*} e^{-(r_f+\lambda_2-\alpha_1^*)\frac{K_{2,t}}{I_2}} & \end{cases} \tag{27}$$

$$PVCash_t = \frac{C_{2,t}}{r_f - \alpha_2^*} \quad \text{for } \tau_2 < t \tag{28}$$

The model allows the decision maker to simulate the effects of different *abandonment policies.* A project can be never abandoned, abandoned as soon as the NPV at a particular time step t becomes zero (i.e., the traditional NPV criteria) or abandoned as soon as the difference between the present value of the benefits minus a percentage of the present value of the costs becomes zero. For this purpose, we compute an *abandonment value* using the following expression:

$$AbandonmentValue_t = PVCash_t - \gamma * PVCost_t \tag{29}$$

where γ is a number between 0 and 1. Note that when γ is 1 the abandon value equals the NPV of the project. Also, setting this parameter to zero will cause never to abandon a project since the abandon value will never become zero.

Abandoning a project implies foregoing any opportunity of things to improve in the future. Even if a decision to abandon the project is taken at a moment in which the NPV becomes substantially negative, this decision might be incorrect. As will be shown in the example, different abandonment policies have different effects on the value of the project. Therefore, we will refer to "optimal abandonment policy" to the abandonment criteria (i.e., the value of γ) that maximizes the value of the project for a given set of input parameters.

Note, however, that the above abandonment strategy is not optimal. Even if we search for the value of γ which maximizes the value of the project, the strategy would be sub-optimal. As it is well known from the vast literature on American options, the optimal exercise strategy is state dependant and varies depending upon the time to maturity. In our situation, time to maturity is

random and the problem is strongly path dependant since costs and cash flows in subsequent stages depend on the realization of the state variables of the preceding stages. In these circumstances, there is not a known optimal exercise strategy.

5 Simulation Process

Figure 3 shows the pseudo-code of the simulation process. The value of an investment project is obtained as the average of the values obtained over a certain number of simulation runs. On each simulation run, a realization of the stochastic processes representing the development costs and the cash flows associated with the project is obtained by taking as a starting point the corresponding initial expected values of these variables in Equations (2) and (7) updating these initial estimations over time.

```
For each simulation run (i)
  Initialize K_{1,0}, and C_{1,0} to their initial estimates
  Compute K_{2,0} and C_{2,0} using Eqs. (5) and (11) with TotCost_{1,0}=0
  For each time slice (t)
    -- Emerging Phase
    While K_{1,t} is positive DO (Stage 1)
        Determine the abandonment value using Eqs. (24), (26) and (29)
        IF the abandonment value is less than or equal to zero THEN
            Flag the project as abandoned
            Increase the counter of abandoned projects
        Update K_{1,t},TotCost_{1,t} and C_{1,t} using Eqs. (3), (4) and (10)
        Update V_t using Eq.(18)
    Compute K_{2,τ_1} using Eq. (5)
    While K_{2,t} is positive DO (Stage 2)
        Determine the abandonment value using Eqs. (25), (27) and (29)
        IF the abandonment value is less than or equal to zero THEN
            Flag the project as abandoned
            Increase the counter of abandoned projects
        Update K_{2,t} and C_{2,t} using Eqs. (6) and (12)
        Update Vt using Eq. (19)
    Compute C_{2,τ_2} using Eq. (11)
    -- Mainstream Phase
    Update Vt using Eq. (20)
Compute the Mean and the Std. Dev. of V_T
Compute other Statistics of the simulation
```

Figure 3: Pseudo-code of the Simulation Process

Figure 4 shows an example of a realization of the simulation using one hundred periods per year. The vertical dotted line represents the point in time in which the disruptive technology is starting to be commercialized in the emerging market. In this realization, Stage 1 of the Emerging Phase is finished at the end of period 240 (approximately 2 years and 5 months). At this point, the system computes the value of the project when only the Emerging Phase is considered. Then, the system continues the evolution of the stochastic processes representing the cash flows received in the

emerging market ($C_{1,t}$) and the development cost of Stage 2 of the Emerging Phase ($K_{2,t}$) until the technology is ready for being commercialized into the mainstream market (end of the Emerging Phase). At this point, the system estimates the expected cash flow in the mainstream market using the current value of the cash flow and the corresponding multiplying factor.

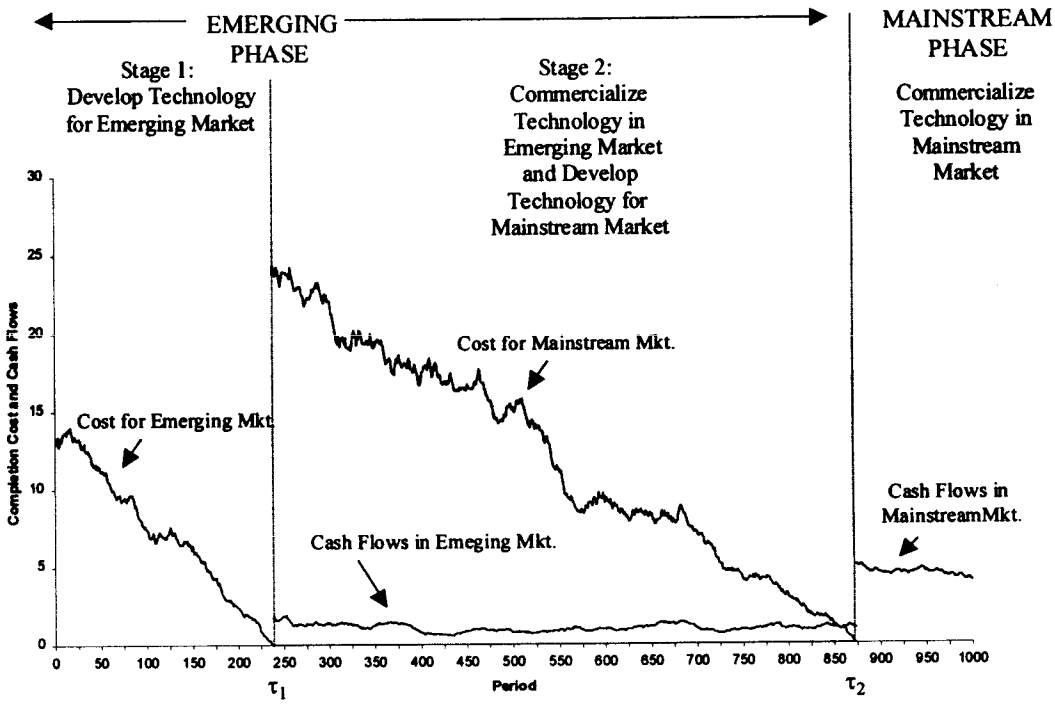

Figure 4: Evolution of Completion Costs and Cash Flows in a Simulation Run

6 Example and Results

Suppose that a group of technicians of *High Tech Corp.* (HTC) has just developed a prototype of a technology that allows them to store and retrieve data from a crystal using optical technology. The potential market for this type of application has not yet been identified; however, they foresee that data storage devices using this technology will be less subject to failure than conventional magnetic storage devices because they would have no moving parts. Furthermore, the data stored in the crystal may be retrieved in parallel instead of being read in a sequential manner, leading to faster access times. However, the most profitable customers of the company have said that they are not interested in this type of technology because its cost per megabyte stored is substantially higher than the cost of magnetic storage devices.

At the moment of the assessment, the group of technicians is uncertain about the costs that will be needed in order find a market for this technology and starting its commercialization. Also, they are uncertain about the time in which the technology will be ready for launching since all they have at this moment is a prototype device. However, they believe that this technology might be potentially

disruptive to some of the data storage technologies currently being used by the organization to supply the needs of its current customers, and that some other markets such as the military or the airlines might be interested in having safer and faster devices. Therefore, they decide to prepare a presentation to senior managers with some preliminary figures, in the understanding that these assumptions will be tested during the development of the project. Table 1 shows the preliminary figures used for the initial valuation of the project (Base Case)

Table 1. Parameters for the Example of *High-Tech* Corp. (Base Case)

Initial Expected Completion Costs and Cash Flow Values		
Completion Cost for Developing and Launching the Technology in an Emerging Market	$K_1(0)$	13 million
Annual Net Cash Flow from Commercializing the Technology in an Emerging Market	$C_1(0)$	1 million
Cost Ratio (Total Completion Cost of Stage 2 / Total Completion Cost of Stage 1)	CostRatio	2 times
Cash Flow Ratio (Cash Flow in Mainstream Market / Cash Flow in Emerging Market)	CashRatio	5 times
Volatility, Drift and Correlation Parameters		
Volatility of Developmental Costs	β	0.3
Volatility of Cash Flows	ϕ	0.2
Drift of Cash Flows in Emerging Market	α_1	0.04
Drift of Cash Flows in Mainstream Market	α_2	0.10
Correlation of Costs and Cash Flow Changes	ρ	0.0
Investment Parameters		
Investment Rate during the Development of the Technology for an Emerging Market	I_1	5 million per year
Investment Rate during the Development of the Technology for the Mainstream Market	I_2	5 million per year
Other Parameters		
Risk-free rate	r_f	0.06
Risk premium on Cash Flow Value	η_c	0.08
Catastrophe Probability Rate for Developing and Launching the Technology in an Emerging Market	λ_1	0.3
Catastrophe Probability Rate for Developing and Launching the Technology in the Mainstream Market	λ_2	0.1
Fraction of Costs Subtracted from Benefits when computing the Abandonment Value	γ	From 0 to 1

After running the simulation for 100,000 times, the results shown in Table 2 were obtained for the case where no abandonment is allowed ($\gamma = 0$). The Value of the project is \$3.452 million when the technology is commercialized both in the emerging and in the mainstream market. In contrast,

the Value of the project is negative (- $4.707 million) if the organization decides only to develop (and commercialize) the technology for the emerging market. These results indicate that the main value of the disruptive technology developed by HTC will come precisely from the first-mover advantages it will provide to the company in the mainstream market of storage devices.

Table 2. Results for the Example of *High-Tech* Corp (Base Case) with no abandonment - millions

	Mean (μ)	Std Dev of Mean (σ_μ)
Value of the Project (Total)	$ 3.452	$ 0.043
Value of the Project (only Emerging Market)	-$ 4.707	$ 0.007

In order to study the impact of the cash flow and cost volatilities in the value of the investment project, we performed sensitivity analysis on various input parameters. Simulations were run for two scenarios depending on whether the organization has the option of abandoning the project once it has been started or not. For each simulation in which abandonment was allowed, we identified which *abandonment policy* was "optimal" by varying parameter γ from 0 to 1 in increments of 0.1. The results of this exercise are discussed below.

Effects of Different Abandonment Policies

The value of a project with an abandonment option is dependent upon the policy used for deciding whether to continue or not with the development of the disruptive technology. Figure 5 shows the expected value of the project for various abandonment policies represented by parameter γ. The policy of no abandonment occurs when parameter γ is zero. In this example, not abandoning the project gives better results than the policy in which the project is abandoned as soon as its expected NPV (ignoring sunk costs) becomes negative (γ=1). The best abandonment policy for our base case occurs when the company decides to abandon the project as soon as the present value of the benefits minus 70% of the costs (γ=0.7) is less than zero.

The value of the *option* to abandon can be estimated as the difference between the value with abandonment and the value without abandonment. As the figure shows, the option value can be an important component of the total value of the project, even if our pseudo-optimal abandonment strategy is followed. For instance, when γ=0.7 the option value ($3.986 - $3.452 = $0.534 million) represents 13.4% of the project value.

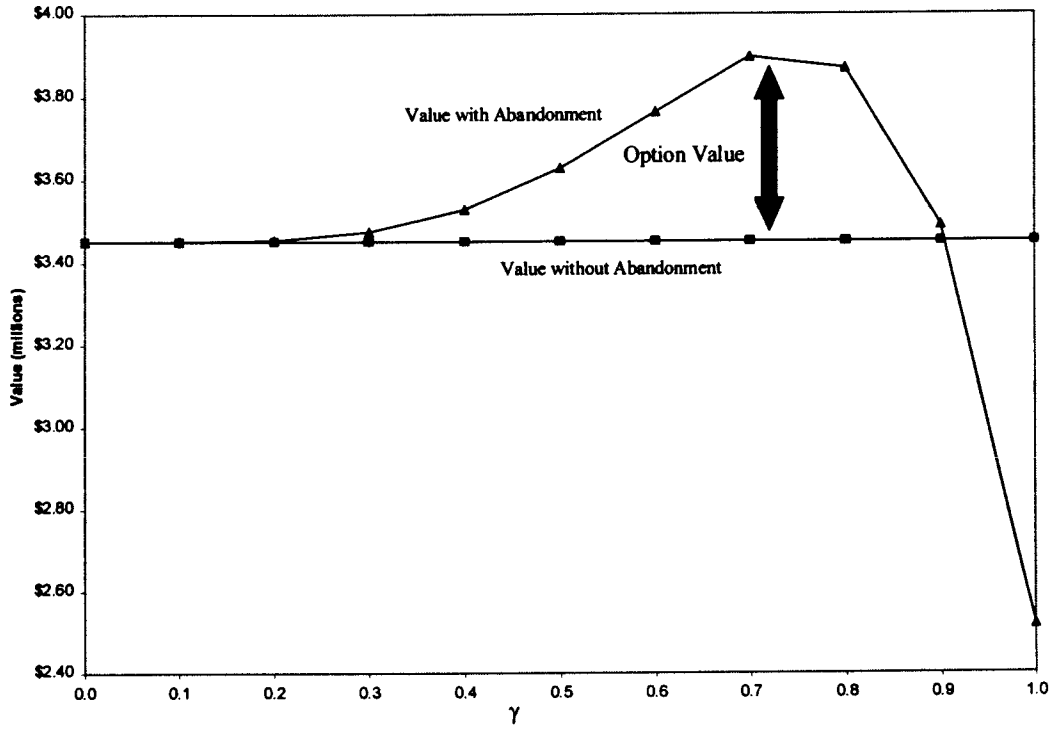

Figure 5: Effects of Different Abandonment Policies in the Value of the Project (Base Case)

As discussed earlier, the optimal abandonment policy is dependent upon the value of the input parameters. Figure 6 shows, for instance, the appropriateness of different abandonment policies for different values of the cost volatility β when all the other parameters remain constant. When β=0.1, optimal abandonment occurs when γ is set to 0.9. In contrast, when β=0.5, optimal abandonment occurs when γ is set to 0.4. These results indicate that projects with high volatilities should be abandoned only when the NPV becomes sufficiently negative. Note that in both cases, abandoning the project as soon as its NPV becomes negative (i.e. the traditional criteria represented by γ=1.0) gives worse results than not abandoning the project at all.

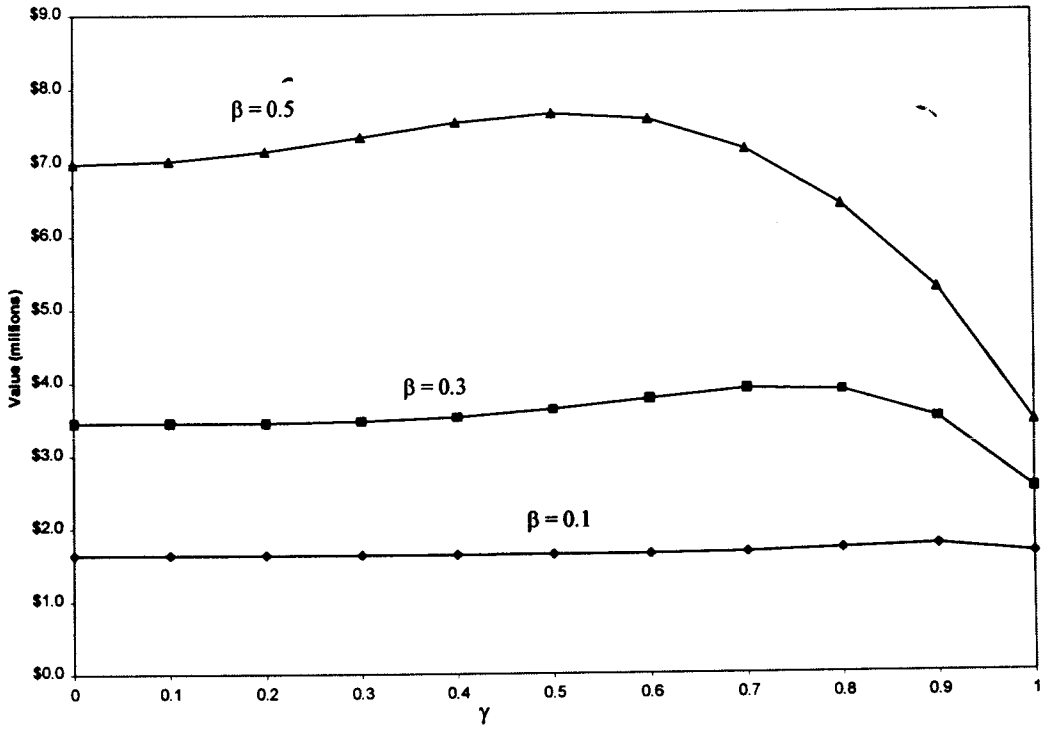

Figure 6: Effects of Different Abandonment Policies in the Value of the Project for Various Cost Volatilities

Effects of Cost Volatility

Figure 7 shows the value of the project with and without abandonment for different cost volatilities. The value of the project is higher when costs are more volatile. This is a consequence of the value being a convex function of costs and, due to Jensen's inequality (Dixit and Pindyck 1994, p. 49), the value of the expected costs is greater than the expected value of the project. For the case with abandonment, the option value also increases with volatility. Note that the value of the project with optimal abandonment is always higher than the value of the project without abandonment. This is true since the decision maker can always decide not to abandon the project by setting γ=0 whenever this policy happens to give better results.

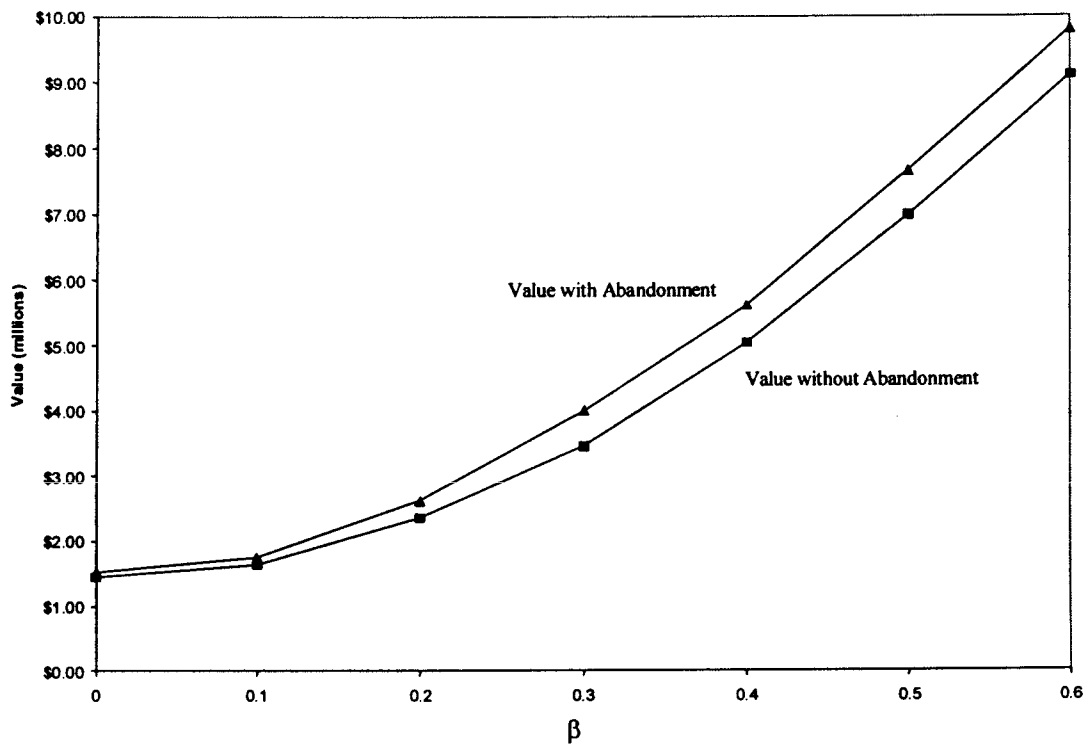

Figure 7: Effects of Cost Volatility in the Value of the Project

Effects of Cash Flow Volatility

Figure 8 shows the value of the project with and without abandonment for different cash flow volatilities. In contrast with cost volatility, cash flow volatility does not impact the value of the project when no abandonment is allowed. This occurs because the value of the project without abandonment is a linear function of the cash flows and, therefore, the volatility has no impact on the overall expected value of the project. Note, however, that the value of the project with optimal abandonment increases monotonically when more volatility is present. This is a consequence of the asymmetry associated with the abandonment option: those projects that are positively affected by the higher volatility will be continued but those that are negatively affected will be abandoned.

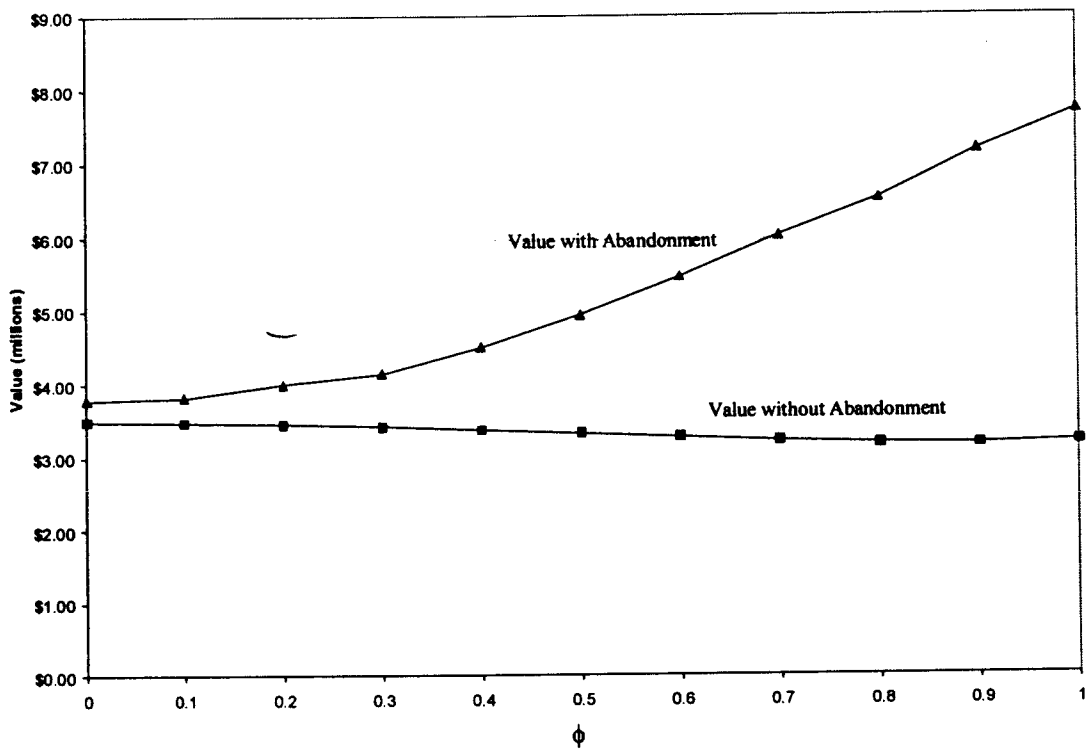

Figure 8: Effect of Cash Flow Volatility in the Value of the Project

Combined Effects of Cost and Cash Flow Volatilities

Since the value of the project without abandonment does not change with respect to the volatility of the cash flows but increases with respect to the volatility of the development costs, the combined effect of both types of volatilities will be to increase the overall value of the project. Similarly, since the value of the project with abandonment is always higher when cash flow or cost volatility increases, the combined effect of this type of uncertainty will be to increase the value of the project when abandonment is allowed.

Effects of Costs - Cash Flows Correlations

Figure 9 shows the effects of the correlation between completion costs and benefit cash flows on the value of the project. When these two variables are positively correlated, an unexpected increase in cash flows will be partially offset by an unexpected increase in costs. Conversely, when these variables are negatively correlated, an unexpected increase in cash flows will be associated with an unexpected decrease in costs and vice versa. Therefore, a positive correlation partially neutralizes the effect of uncertainty and a negative correlation enhances it. Since the value of the project with or without abandonment is higher when more volatility is present, a positive correlation will impact negatively the value of the project and vice versa.

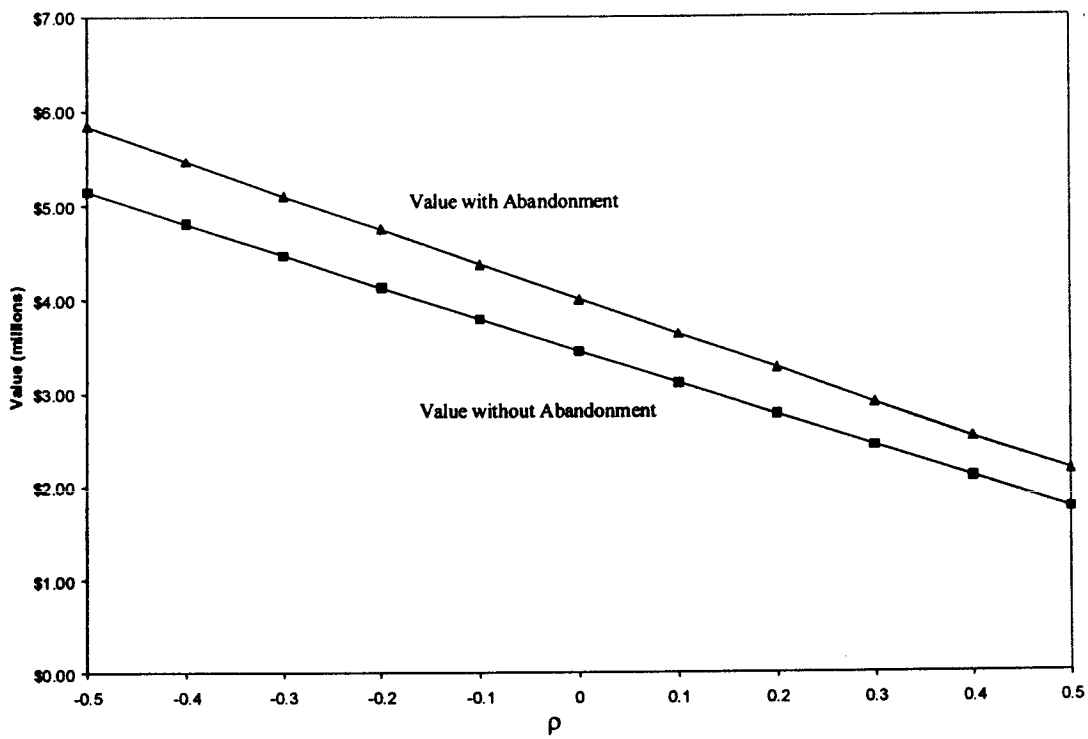

Figure 9: Effects of Cost – Cash Flows Correlation in the Value of the Project

7 Summary and Conclusions

In this paper we developed a computer simulation model for the valuation of investments in disruptive technologies. Based on the conceptual framework proposed by Christensen (1997) for explaining the Innovator's Dilemma phenomenon, an investment project is divided into two sequential phases representing the evolution of the disruptive technology from an emerging to a mainstream market. The model incorporates the effects of the uncertainty associated with the development costs, with the possibility that a catastrophic event causes the permanent abandonment of the project, and with the time required to complete each stage of the project. Also, the model accounts for the uncertainty associated with the net cash flows that an organization expects to obtain once the technology is commercialized in each of the markets and allows modeling the interaction between these cash flows and the development costs of each stage.

The application of the model to a hypothetical example provided some insights of the effects that cash flow and cost volatilities have on the overall value of this type of projects. When abandonment is allowed, higher cash flow or cost volatilities increase the value of the investment project. When no abandonment is possible, only cost volatilities have an effect in the expected value of the project. Also, a negative correlation between cash flow and cost changes increases the value of the project and vice versa.

We also discussed how to implement a pseudo-optimal policy for deciding whether to abandon or not a project once it has been started. For each set of the input parameters, an "optimal" percentage of the present value of the remaining completion costs is subtracted from the present value of the expected cash flows to determine an abandonment value. As shown in the example, the traditional criteria of stopping a project as soon as NPV becomes negative leads to a lower expected value of the project than the value obtained by other abandonment policies when cash flow or cost volatilities are considered.

The model described in the paper constitutes an attempt to develop a more formal methodology for evaluating investments in disruptive technology projects that, by their own nature, are characterized by a high degree of uncertainty in all their relevant variables. We believe that such an attempt is not in contraposition with the principles of disruptive innovation that Christensen recommends for dealing with this type of technologies. Modeling such a project does not mean that a company should not be cautious about keeping alive those ideas that their mainstream customers do not currently want. Neither does it mean that an organization will solve its growth needs by only developing such projects. Organizations need to treat projects of disruptive technologies as a new endeavor that might require the creation of new business processes and values that correspond to the size of the emerging market. However, they also need new tools that help the decision maker to account for the high uncertainty associated with this phenomenon.

Our model can be used to measure the effects of the various assumptions related to a particular *scenario*, including those related to the volatilities of cash flows and development costs, the probability of failure in each stage of development, the maximum investment rates that the organization can invest, the size of the jump in cash flows that occur when an organization is successful in moving up into the mainstream market, the risk-adjusted growth rates of the commercialization cash flows in each phase, and the risk-free rate. It also provides us with information related to the additional value coming from the flexibility that an organization has for abandoning the project once it has been started that traditional valuation tools such as the NPV method do not take into consideration. Therefore, the model can be used as a valuable input for other decision-making frameworks, such as discovery-driven planning (McGrath and MacMillan 1995), that help to identify what needs to be learned during the course of the project in order to solve for the uncertainties that characterize the phenomenon.

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