Sustainable products are receiving significant attention worldwide from customers, industries, and governments. Companies that can efficiently respond with more sustainable products may recover more long-term value from their operations. Flexibility measures response value in an environment of price uncertainty. We consider a company that has the flexibility of producing both ordinary and more sustainable "green" products, and is striving to improve its overall quality. We present a model to evaluate the optimal strategies that will maximize the expected profit using real options analysis. We illustrate the use and sensitivity of the model for desktop computer production. Our approach gives decision makers a way to choose the appropriate
strategies to maximize the expected profit when there is flexibility of producing ordinary and green products under price uncertainty and switching costs between strategies. We discuss future sustainable product quality attributes and their product life cycle management implications for the electronics industry.

12.1 SUSTAINABLE PRODUCTION IN FLEXIBLE SYSTEMS

Recent reports show that corporations are reporting sustainable development activities at an increasing rate (KPMG International 2005). Consequently, research and development efforts have produced new tools to help manufacturers consider environmental attributes in product design (see, e.g., Simon 1992; Stuart 2001; Mangun and Thurston 2002; Tien et al. 2005; Donnelly et al. 2006; Rossi et al. 2006; Ny et al. 2006; Byggeth et al. 2007; Boks and Stevels 2007). Accordingly, so-called green products that are more sustainable are receiving significant attention from customers, industries, and governments around the world. However, there remains a gap between the increasing number of companies reporting awareness of sustainable development principles and the impact on product design and operations (Rondinelli 2007).

Another indicator of the focus on environmental quality is the emergence of the International Standards Organization (ISO) 14000 protocol, which specifies environmental management and standards and promotes sustainable development. While ISO 14000 builds upon the foundation of ISO 9000 for quality management to satisfy customer requirements, it also seeks to satisfy the general public (Morris 2004). An integrated set of requirements for both ISO 9001 and ISO 14001 provides organizations with the opportunity to prepare documentation for the combined system standards (Puri 1996). The ISO reports that its ISO 9000 and ISO 14000 standards are implemented by over 1 million organizations in 161 countries (ISO 2008).

From a management strategy viewpoint, it is important for an organization to determine when it can benefit from responding to the market’s changing demand for more sustainable “green” products. In a complex system, one necessity is the ability to react to events as they unfold. Thus for the organization, as the demand for a particular green product increases or decreases, it becomes obvious that the flexibility to modify production must hold some value. In this chapter, we apply the real options approach to determine the optimal strategies between green and ordinary production, and we estimate the expected value of such flexibility over ordinary production. When the production system is flexible, the company can switch production mode among ordinary products, green products, and a combination of both products. The key advantage and value of real options analysis are to integrate managerial flexibility into the valuation process and thereby assist in making the best decisions (Dixit and Pindyck 1994; Trigeorgis 1999; Amram and Kulatilaka 1999; Schwartz and Trigeorgis 2001; Brach 2003). Motivated in part by the attention to joint implementation or the integration of ISO 9000 and ISO 14000 (see, e.g., Prakash 1999; Renzi and Cappelli 2000; Strachan et al. 2003), we incorporate the aspect of ongoing quality control and improvement using a time series model. We demonstrate that by using the real options approach, a company can determine the optimal strategies and the resulting maximum value of flexibility in a system.
12.2 SUSTAINABLE PRODUCT QUALITY MANAGEMENT
ISSUES IN DESIGN AND MANUFACTURING
IN THE ELECTRONICS INDUSTRY

As noted in the introduction, green products are emerging from the demand-pull of many constituents with new attitudes toward environmental values (Ottman 1992). In this chapter, we specifically consider the supply chain for desktop computers, which represents a significant global industry. Worldwide sales for personal computers, which include desktop and portable computers, exceeded 230 million in 2007 (Gartner 2008; IDC 2008). Product design decisions impact this supply chain, which begins with material choice, then flows to the supplier, manufacturer, retailer, and consumer; the supply chain is extended with a demanufacturing infrastructure to recycle materials (see Figure 12.1). Demanufacturing may include product remanufacturing, component recovery, and/or materials recycling (Maslennikova and Foley 2000; Williams 2006).

Many factors affect the environmental quality of the product across this supply chain. A green product design may include attributes such as recycled material content (U.S. Environmental Protection Agency [EPA] 2005; Qu et al. 2006; Williams 2007) or reduced energy consumption during use (Energy Star 2005; Tuite 2006; IVF 2007; Aoe 2007). The EPA Energy Star Computer Program has been a catalyst for hardware and software design that includes component and circuit configuration, intelligent sensors, and power management software (Eren 2004; Perry 1995; Lapujade and Parker 1995; Liu 1994). An added benefit to designing for lower equipment power consumption is increased reliability from reduced heat dissipation (Bensen 1996).

The determinants of the consumer's purchase decision for recycled products may include the price, believed quality, and psychological benefit (Bei and Simpson 1995). A quality-based model has been developed to analyze the strategic demand and supply as well as policy issues concerning the development of products with conflicting traditional and environmental attributes (Chen 2001). Stuart and Sommerville (1998) summarized the literature for life cycle design guidelines for six specific life cycle characteristics. Since some key life cycle parameters may be uncertain, several

FIGURE 12.1 Current supply chain for desktop computers.
authors propose Monte Carlo simulations to evaluate the sensitivity of parameters in their design tools, which consider both costs and wastes at the material and component acquisition, primary and secondary assembly, and disassembly stages of the product life cycle (Bras and Emblemevag 1996; Sandborn and Murphy 1999). A structured methodology for formulating end-of-life strategies using specific examples from consumer electronics products is presented in Rose et al. (2002). Quotes for environmentally weighted recyclability (QWERTY) is a more comprehensive approach to evaluate a product design by determining an environmentally weighted recycling score in comparison to a weight-based recycling score (Huisman et al. 2003).

At present, product design evaluation tools that consider sustainability factors continue to evolve, but primarily involve checklists and environmental impact scoring (Keoleian and Menerey 1994; Alting and Legarth 1995; Stuart and Sommerville 1998; Lenox et al. 2000; Byggeth and Hochschorner 2006; Ge and Wang 2007). These approaches can effectively compare the outcome of a product in the absence of uncertainty, but offer no means by which to design products for global sustainability in the face of uncertainty. Deterministic design and infrastructure decision tools provide opportunities for sensitivity analysis but do not directly address uncertainty (Clegg et al. 1995; Stuart et al. 1999; Bennett and Yano 2004).

In our work, we integrate real options into the supply chain framework for more sustainable electronic products in order to enhance the understanding of the value of flexibility regarding decision making in this domain context.

12.3 REAL OPTIONS FOR THE FLEXIBLE SUPPLY CHAIN

In the present work, to evaluate the value of flexibility to enhance the sustainability of product manufacturing operations, it is useful to view system control as the ability to switch between states of operation (e.g., corresponding to different combinations of supplier levels, product mixes, and processors). These states may be discrete (e.g., an open or closed plant) or continuous (e.g., operating at different levels of capacity). From this viewpoint, the value of the sustainable materials' quality, energy consumption, or waste generation implications of product design and product life cycle management decisions will typically depend on the underlying uncertainties in a nonlinear fashion. In the real options literature, there are various examples of switching between different operating states (as in Brennan and Schwartz 1985; Triantis and Hodder 1990; Hodder and Triantis 1993).

Two classes of models arise from the option to switch between states over time: when a cost does not occur due to a switch in the decision and when a cost does occur. Real options without switching costs have the distinguishing feature of time separability, making them easier to value. These real options can be treated as a bundle of European options (i.e., one that can be exercised only on the expiration date) with different maturities and then valued using numerical procedures such as the binomial lattice (Cox et al. 1979; Boyle et al. 1989), the pentanomial lattice (Kamrad and Ritchken 1991; Nembhard et al. 2002), or Monte Carlo simulation (Hull 2008; Nembhard et al. 2003). Valuing a real options problem with switching costs is, of course, more difficult than valuing one without switching costs. Switching costs capture the additional expenditure to change a decision. For example, a switching cost
may stem from drawing up a new contract if the manufacturer seeks to change to recycled plastic materials (Xu et al. 2002; Kuswanti et al. 2002; Rios et al. 2003) or from eliminating components and modifying the assembly process if the manufacturer seeks to change the product's power supply design (Directron 2005).

When there are switching costs, options exercised in successive time periods have connections with each other, because a current decision influences the later ones through the extra outlay. In other words, we cannot separate the problem into time periods where the decisions are independent from each other, so we cannot use the feature of time separability. Analytic solutions to real options with switching costs are not attainable if there is more than one state variable; hence, the need for numerical methods arises. Kogut and Kulatilaka (1994) and Huchzermeier and Cohen (1996) presented numerical methods to value multiple options with switching costs. Tades et al. (1998) proposed to use neural networks to value options with switching costs, and demonstrated their method by valuing flexibility for a costly production switch among several products. Broadie and Glasserman (BG; 1997) developed a simulation algorithm for estimating the prices of American-style assets. Aktan et al. (2003) combine dynamic programming with the BG approach to develop a simulation procedure to value real options problems with switching costs. Nembhard et al. (2005) take this important step further and address valuation when there is an implementation time lag between the time a decision is made and when it can be implemented. They show that without considering the time lag impact, the value of the operational flexibility could be significantly overestimated.

12.4 FORMULATION OF A MODEL TO EVALUATE THE VALUE OF FLEXIBILITY TO PRODUCE ORDINARY, GREEN, OR BOTH PRODUCT DESIGNS

Specifically, we consider a company that has three production strategies to select from at a number of decision points that employ the status quo or introduce a more sustainable green product design. We assume the company has the flexibility to switch between the three strategies at each decision point. These three strategies are defined as follows.

**Strategy 1: Ordinary production.** This is the status quo strategy where only an ordinary product design is employed to make a quantity of \( N \) items per time interval.

**Strategy 2: Green and ordinary production.** Under this strategy, part of the capacity is allocated for the more sustainable green product design. The company produces \( N = n_o + n_g \) items per time interval, where \( n_o \) is the amount of ordinary items, and \( n_g \) is the amount of green items produced.

**Strategy 3: Green production.** Under this strategy, only the more sustainable green product design is employed to make a quantity of \( N \) items per time interval.

The strategies are based on the company’s material choices and sources, such as recycled versus new, as well as the product design. For example, under the green strategy, the manufacturer may select a cover composed of recycled high-impact polystyrene and a product design with power phase modes to conserve energy.
A company that is concerned with environmental quality may also be concerned with overall quality. Many technical tools of quality improvement may be deployed, such as process monitoring, experimental design, and process control. A goal of such efforts is to drive down the rate of defective items produced, which, in general, can be represented by time series models (Box et al. 1994; Montgomery et al. 1990). We assume that the rate of defective items produced is expected to decrease according to the following first-order autoregressive time series model:

\[ z_{ot} = \varnothing_o z_{ot-1} + a_{ot} \]

and

\[ z_{gt} = \varnothing_g z_{gt-1} + a_{gt} \]

where \( z_{ot} \) and \( z_{gt} \) are rates of defective ordinary and green items produced in time interval \( t \), \( \varnothing_o \) and \( \varnothing_g \) are constant terms representing the reduction factors for the ordinary and green products' defect rate (\( \varnothing_o < 1 \), and \( \varnothing_g < 1 \)), and \( a_{ot} \) and \( a_{gt} \) are random shocks.

In order to model the profit over time, we define the following set of parameters and variables:

- \( p_{ot} \) = price of the ordinary product in time interval \( t \)
- \( P_gt \) = price of the green product in time interval \( t \)
- \( c_{ot} \) = unit production cost of the ordinary product in time interval \( t \)
- \( c_{gt} \) = unit production cost of the green product in time interval \( t \)
- \( S_{ij} \) = cost of switching from strategy \( i \) to strategy \( j \)
- \( \sigma_o \) = volatility of the price of the ordinary product
- \( \sigma_g \) = volatility of the price of the green product
- \( \rho \) = correlation for \( p_{ot} \) and \( p_{gt} \)
- \( r \) = risk-free interest rate

Prices of the ordinary and the green products, i.e., \( p_o \) and \( p_g \), change over time. The company selects a strategy at a number of decision time points. During time interval \( t \), the company makes a profit \( P_t \) which is defined as follows:

- \( P_t = (p_{ot} - c_{ot})N - c_{ot}z_{ot}N \), if the preceding and current strategies are Strategy 1;
- \( P_t = (p_{pt} - c_{pt})N - c_{pt}z_{pt}N - S_{1i} \), if the preceding strategy was Strategy \( i \) (\( i = 2 \) or \( 3 \)), and the current strategy is Strategy 1;
- \( P_t = (p_{ot} - c_{ot})n_o + (p_{gt} - c_{gt})n_g - c_{ot}z_{ot}n_o - c_{gt}z_{gt}n_g \), if the preceding and current strategies are Strategy 2;
- \( P_t = (p_{pt} - c_{pt})n_o + (p_{gt} - c_{gt})n_g - c_{ot}z_{ot}n_o - c_{gt}z_{gt}n_g - S_{12} \), if the preceding strategy was Strategy \( i \) (\( i = 1 \) or \( 2 \)), and the current strategy is Strategy 2;
- \( P_t = (p_{gt} - c_{gt})N - c_{gt}z_{gt}N \), if the preceding and current strategies are Strategy 3; and
- \( P_t = (p_{gt} - c_{gt})N - c_{gt}z_{gt}N - S_{13} \), if the preceding strategy was Strategy \( i \) (\( i = 1 \) or \( 2 \)), and the current strategy is Strategy 3.
The goal of the company is to maximize the expected total discounted profit by selecting the appropriate strategies at each decision point, considering the switching costs between strategies. The prices $p_o$ and $p_g$ change over time as

$$dp_o = \mu_o p_o dt + \sigma_o p_o dz$$

and

$$dp_g = \mu_g p_g dt + \sigma_g p_g dz$$

where $\mu_o$ and $\mu_g$ are drift of the prices for the ordinary and the green products, respectively; $\sigma_o$ and $\sigma_g$ are the volatility of the prices of the ordinary and the green products, respectively, and $dz$ is a standard Wiener disturbance term.

Since there are two state variables (i.e., $p_o$ and $p_g$), we use a multinomial lattice approach to estimate the value of flexibility due to being able to switch between strategies. At each time interval, the two state variables can move up with the rate of $u_i$, move down with the rate of $d_i$ such that $d_i = 1/u_i$, or stay constant at each time interval. There are five possible movements, as shown in Table 12.1.

Probabilities of movements $p_1$ through $p_5$ are given as

$$p_1 = \frac{1}{4} \left\{ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( \frac{\mu_1}{\sigma_1} + \frac{\mu_2}{\sigma_2} \right) + \frac{\rho}{\lambda^2} \right\}$$

$$p_2 = \frac{1}{4} \left\{ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( \frac{\mu_1}{\sigma_1} - \frac{\mu_2}{\sigma_2} \right) - \frac{\rho}{\lambda^2} \right\}$$

$$p_3 = \frac{1}{4} \left\{ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( -\frac{\mu_1}{\sigma_1} + \frac{\mu_2}{\sigma_2} \right) + \frac{\rho}{\lambda^2} \right\}$$

$$p_4 = \frac{1}{4} \left\{ \frac{1}{\lambda^2} + \frac{\sqrt{\Delta t}}{\lambda} \left( -\frac{\mu_1}{\sigma_1} - \frac{\mu_2}{\sigma_2} \right) - \frac{\rho}{\lambda^2} \right\}$$

$$p_5 = 1 - \frac{1}{\lambda^2}$$

<table>
<thead>
<tr>
<th>Change in $p_o$</th>
<th>Change in $p_g$</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>$u_2$</td>
<td>$p_1$</td>
</tr>
<tr>
<td>$u_1$</td>
<td>$d_2$</td>
<td>$p_2$</td>
</tr>
<tr>
<td>$d_1$</td>
<td>$d_2$</td>
<td>$p_3$</td>
</tr>
<tr>
<td>$d_1$</td>
<td>$u_2$</td>
<td>$p_4$</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$p_5$</td>
</tr>
</tbody>
</table>
where \( \Delta t \) is the length of each time interval, \( \rho \) is the correlation for the two products' prices, and \( \lambda \geq 1 \) (Kamrad and Ritchken 1991). For \( \lambda = 1 \), \( p_5 \) is zero, and there are four movements with probabilities \( p_1 \) through \( p_4 \). The rate of up movement for the ordinary and the green products' prices are given as \( u_1 = e^{\lambda \sigma \sqrt{\Delta t}} \) and \( u_2 = e^{2\lambda \sigma \sqrt{\Delta t}} \), respectively.

A pentanomial lattice with two steps is shown in Figure 12.2. First and second elements in parentheses represent the changes in the first and second state variables, respectively.

In order to find the optimal set of strategies that maximizes the expected profit, we need to apply a dynamic programming approach in the lattice. If switching between the options is costless, the optimal decision at each node can be analyzed independently. Since we assume that there are switching costs between the options, decisions at the nodes are not independent. When applying the dynamic program, we need to determine the optimal strategy at each node for all immediately preceding possible strategies. The optimal strategies at each node are determined to maximize the expected total profit that will be obtained between that node and the last time interval. Selection of the optimal strategies begins from the last time interval, and moves one time interval at each step until the first node is reached. Then, the set of optimal strategies that maximize the expected total profit for each possible initial strategy can be determined by tracking the set of optimal decisions in the dynamic program.

In each state, the profit is maximized by selecting an option \( O_\rho \), given that option \( O_{\rho-1} \) was selected in the preceding time interval, and the vector of product prices at time \( t \) is \( e_\rho \). The value \( V \) of the total expected profit at time \( t \) and state \((e_\rho, O_{\rho-1})\) is defined with the following recursive equation:

\[
V_t(e_\rho, O_{\rho-1}) = \max_{O_\rho} E[P_t(e_\rho, O_{\rho-1}, O_\rho)] + e^{-\lambda \Delta t} V_{t+1}(e_{t+1}, O_\rho)
\]

where \( E[P_t(e_\rho, O_{\rho-1}, O_\rho)] \) is the expected profit during time interval \( t \).
12.5 REAL OPTIONS ANALYSIS OF ORDINARY AND GREEN DESKTOP PRODUCT DESIGNS

Since two important aspects of green design for computers are material selection and energy consumption during use, we illustrate the use of the real options to evaluate hypothetical ordinary versus green desktop computer designs that differ for these two criteria. For the green product in this example, energy consumption during use is a key design factor that is achieved through hardware and software design (Davis 1994; Liu 1994; Bensen 1996; Gianni et al. 1997; Korn et al. 2004), while material selection includes the use of recycled high-impact polystyrene for the desktop housing (Xu et al. 2002; Kuswanti et al. 2002). Assuming an average plastic desktop computer housing weighs 0.6 kg and that the average price reduction for recycled high-impact polystyrene is $0.30/kg, the production cost may be lowered only 0.002 percent (Rios et al. 2003; Williams et al. 2006). With respect to design modifications to lower energy consumption and heat dissipation (Davis 1994), we assume savings of approximately 6 percent through elimination of the cooling fan with its weight and volume (Directron 2005).

We assume that the levels of the problem parameters at the current time (i.e., $t = 0$) are as follows:

- current strategy = Strategy 1
- total time horizon = 1 year
- number of time intervals = 3
- risk-free interest rate ($r$) = 2 percent
- $N = 150,000$ (number of total items to be produced)
- $n_o/n_g = 2$ (rate between ordinary and green items produced if strategy 2 is selected)
- $p_{o0} = $100 (price of ordinary product at $t = 0$)
- $p_{g0} = $102 (price of green product at $t = 0$)
- $c_{ot} = 0.90* p_{ot}$ (unit production cost of ordinary product)
- $c_{gt} = 0.85* p_{gt}$ (unit production cost of green product)
- $\sigma_o = 0.3$ (volatility for the price of ordinary product)
- $\sigma_g = 0.3$ (volatility for the price of green product)
- $\rho = 0.7$ (correlation for the two products' prices)
- $z_{o0} = 3$ percent (rate of defective ordinary products at $t = 0$)
- $z_{g0} = 4$ percent (rate of defective green products at $t = 0$)
- $\varnothing_o = 0.95$ (discount factor for the number of defective ordinary products)
- $\varnothing_g = 0.93$ (discount factor for the number of defective green products)

The design and coordination of hardware and software to achieve energy savings and the identification of sources of recycled high-impact polystyrene require a switching cost (Murphy et al. 2001; Korn et al. 2004). While the power management software options on many desktop computers were not initially activated due to networked device management or software compatibility (Nordman et al. 2000; Christensen et al. 2004; Korn et al. 2004), recent research provides new approaches to effective network power management methods (Harris and Cahill 2005; Gunaratne...
et al. 2005; Anand et al. 2005). Switching costs among the three strategies are given in Table 12.2.

Using the above values in a quadrinomial lattice, we can obtain the expected profits and optimal set of strategies at all nodes in the lattice. Figure 12.3 shows the optimal set of decisions that maximizes the expected profit considering all possible levels of ordinary and green products’ prices throughout the three time intervals. In each node, there are four elements: the first element shows the preceding strategy, the second element in bold characters shows the strategy that should be applied in the current time interval, the third element shows the up (u) and down (d) movements that have been observed totally in the ordinary product’s price, and the last element shows the up or down movements that have been observed totally in the green product’s price. If there is a strategy change in a node, that node is colored gray. We see that a switch should be made in the first time interval (from strategy 1 to strategy 3), and a switch back from strategy 3 to strategy 1 should be made at one out of the nine possible nodes in the third time interval.

Figure 12.4 shows the decisions and all possible levels of ordinary and green product prices when there is no flexibility to change the strategy (i.e., strategy 1 is applied and cannot be changed at all three time intervals).

When there is flexibility to produce green and ordinary products, the expected total profit is estimated as $5,433,829. This estimated value is the output of the optimal set of strategies given in Figure 12.3. If we do not have the flexibility to produce
green products (i.e., no switching between strategies), the expected profit is estimated as $3,402,407. This estimated value is the output of strategy 1 given in Figure 12.4. Then, the value of green production flexibility is estimated as follows:

Estimated value of flexibility = $5,433,829 - $3,402,407 = $2,031,422

In other words, having the green production as an option in addition to the ordinary production provides an expected profit that is $2,031,422 greater than the expected profit of ordinary production. This can be defined as the value of having green production as an additional strategy to the current strategy of ordinary production.

An important part of the valuation analysis is sensitivity of the estimated option value against system parameters. We analyze the behavior of the estimated option value (the value of being flexible to produce the green product) against different levels of the risk-free interest rate ($r$), the initial price of the ordinary product ($p_o$), the initial price of the green product ($p_g$), the demand for the ordinary product ($n_o$), the demand for the green product ($n_g$), the price volatility of the ordinary product ($\sigma_o$), the price volatility of the green product ($\sigma_g$), and the correlation for the ordinary and the green products' prices ($\rho$).

Figure 12.5 shows the estimated option value against the risk-free interest rate. We see that the estimated option value drops with an increasing rate while the risk-free interest rate increases. This is an expected result since the interest rate has a negative effect on the present value of future cash flows.

Figure 12.6 shows the change of estimated option value against the ordinary and the green products' initial prices. We see that the value of flexibility increases with increasing price of the green product, and it decreases with increasing price of the ordinary product. If the price of the ordinary product is larger than the green product's price, it is more profitable to produce the ordinary product, and, therefore, there is not much value to have a flexibility of producing the green product. On the other hand, flexibility of producing the green product becomes more valuable when the price of the green product increases. As a result, the option value increases with increasing price of the green product.

Figure 12.7 shows the estimated option value against the demand for the ordinary product per time interval. We assume that the total demand for the ordinary and
Figure 12.5 Estimated option value versus risk-free interest rate.

Figure 12.6 Estimated option value versus initial prices of the products.

Figure 12.7 Estimated option value versus demand for ordinary product.
green products is stable at the level of 150,000 items per time interval. Flexibility of producing the green product has its maximum value when the whole demand is for the green product. The value of flexibility decreases with decreasing demand for the green product.

Figure 12.8 shows the estimated option value against the volatility for the ordinary and the green products' prices. It can be seen that both volatilities have similar small positive effects on the value of flexibility. It can be seen that the value of flexibility is more sensitive to the green product's price volatility when that volatility is between 0.5 and 0.7, and it is more sensitive to the ordinary product's price volatility when that volatility is between 0.7 and 1.0.

Figure 12.9 shows the effect of the correlation for ordinary and green products' prices on the estimated option value. While the correlation increases from -1 to 1, the value of flexibility decreases with a slowing speed. It can be seen that when the price correlation for the ordinary and the green products is negative, there is more value for being flexible to produce the green product.

**FIGURE 12.8** Estimated option value versus product price volatilities.

**FIGURE 12.9** Estimated option value versus correlation for the product prices.
12.6 SUMMARY

In this chapter, we considered a company that has the flexibility of producing ordinary products and more sustainable green products and is also striving to reduce its overall defective product rate through quality control and improvement efforts. The model we developed for the system used a real options valuation approach to estimate the additional value of flexible production over ordinary production. If the production is flexible, it is assumed that the company is able to switch among three production modes: producing only the ordinary product, producing only the more sustainable green product, or producing both the ordinary and green products.

Using the domain context of desktop computer design, we analyzed the decision to switch among production levels that would allow for better environmental quality. We assumed that switching among the three strategies is costly, and defined the switching costs in a matrix. We estimated the value of green production flexibility that is provided by the three strategies using a real options approach. We presented a complete set of optimal strategies that maximizes the expected total discounted profit and analyzes the sensitivity of the estimated option value against different levels of system parameters.

We believe that our approach shows that decision makers can choose appropriate strategies to maximize the expected profit when there is flexibility of producing ordinary and green products under price uncertainty and switching costs among strategies. For example, this approach could be used to help manufacturers evaluate the use of conventional nonrenewable materials versus biomaterials (Toensmeier 2004, 2007; IVF 2007). Future research opportunities include the interface of this model with product life cycle management and material selection tools. This new capability may help companies close the gap between recognizing the importance of sustainable design and deciding when to pursue the flexibility of producing more sustainable product designs.

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REFERENCES


