Market Impact on IT Security Spending

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Traditionally, IT security investment decisions are made in isolation. However, as firms that compete for customers in an industry are closely interlinked, a macro perspective is needed in analyzing the IT security spending decisions and this is a key contribution of the paper. We introduce the notions of direct- and cross-risk elasticity to describe the customer response to adverse IT security events in the firm and competitor, respectively, thus allowing us to analyze optimal security investment decisions. Both symmetric and asymmetric cases are examined for a duopoly in a continuous-time Markov chain (CTMC) setting. We demonstrate that optimal IT security spending, expected firm profits and willingness of firms to cooperate with competitors to improve security are highly dependent on the nature of customer response to adverse events, especially whether customer response to adverse security events in the competitor increases or decreases firm demand.

Key words: IT Security, Regulation, Continuous-time Markov Chain, Direct and Cross-risk Elasticity of Demand

1. Introduction

In the context of IT security, we use the terms direct-risk and cross-risk elasticity of demand to describe the customer demand effects of adverse IT security events. Our model addresses both direct- and cross-risk elasticity of demand, just as changes in price are traditionally related to demand. Direct-risk elasticity of demand is used to describe the percentage change in demand due to an adverse IT security event experienced directly by the firm, while cross-risk elasticity of demand is used to describe the percentage change in demand due to the cross-over effect of an adverse IT security event at a competitor firm. Our paper models this context in a continuous-time setting, incorporating both the direct- and cross-risk elasticity of demand. The firm's IT security spending reduces the frequency of adverse IT security events experienced by the firm, thus affecting customer demand for the firm's products. Also, due to the cross-risk elasticity between firms, IT security spending by competitor firms will affect customer demand for the firm's products, either positively or negatively. This paper addresses the impact of many types of adverse events (such as well-publicized security breaches, distributed denial of service attacks, and significant computer virus outbreaks) on IT security spending.

We show that the nature of the cross-risk elasticity is crucial to understanding how firms will behave when making spending decisions. We show that under certain conditions, it is possible for both firms to increase profits if they cooperate and increase IT security spending, even though the individually rational choice is to not increase IT security spending. Our model allows us to answer the question: "Under what conditions will an opportunity for mutually increasing profits through cooperation exist?" Further, we demonstrate that even if regulations are weak or non-existent, customers will still force the firms involved to meet a certain level of security by making buying decisions that affect demand, allowing us to answer the question: "What is the impact of cross-risk elasticity where regulations or voluntary security standards exist?"

This research contributes to the literature by specifically considering how customer purchasing decisions and adverse IT security events for all firms have an impact on IT security spending. In particular, we examine the importance of understanding the indirect impact on a firm's demand due to adverse IT security events experienced by competitors. We find that there are significant changes to the optimal IT security spending for a firm when there are cross-over effects on customer demand when compared to the neutral case with no cross-over. Furthermore, this research also contributes to the literature by examining the dichotomous impacts of negative and positive cross-over effects.

The remainder of this paper is examines this cross-risk elasticity of demand and how it may be used to explain several phenomena that we observe. The paper proceeds as follows. Section 2 reviews prior literature; Section 3 presents a model for the two-firm case. The next sections analyze specific model results: security spending (Section 4); expected profit (Section 5); the impact of regulations on firm profits (Section 6); alternate forms for the risk function (Section 7); and the asymmetric model (Section 8). Finally, conclusions are presented in Section 9.

2. Prior Literature

Researchers have considered investment decisions for a single firm (Gordon and Loeb 2002), finding that it is not always the case that a firm should increase security investment as the vulnerability of the information being protected increases. When considering the interaction between competitors, each firm's choices to share information and invest in security interact in interesting ways. Costs change when information sharing occurs between firms (Gal-Or and Ghose 2005, Gordon et al.

2003), but the nature of those changes depends on how the cost of a breach is viewed. Gordon et al. (2003) consider a fixed loss for the breach of a specific information set and show that when two firms coordinate by sharing information, it is possible that they can achieve the same level of security they had prior to information sharing, but at a reduced cost.

Prior literature has examined cases where no firm interaction was considered (single firm) (Gordon and Loeb 2002), where firm interaction, but not cross-over effects of customer demand changes, was considered (Gordon et al. 2003), and where firm interaction with positive cross-over effects with some customers switching to the unaffected firm (Gal-Or and Ghose 2005, Cezar et al. 2009) were considered. We extend this customer reaction to include the case where a firm which has not experienced an adverse IT security event loses demand as a result of a competitor's adverse IT security event (our complements in loss case). As we are using a CTMC rather than a periodic model, we can also analyze the effects of time between successful attacks and the duration of the effects of successful attacks. Further, we examine the asymmetric case where customer reactions may be different for the firms.

Gal-Or and Ghose (2005) introduce demand changes as a customer reaction to spending and sharing decisions by both the firm and its competitor. Under their model's assumptions, the competitor's spending has a direct negative effect on the firm's demand and an indirect beneficial effect, moderated by information sharing. In this case, when one firm has a security breach, at least some of its customers will switch to the competitor. Cezar et al. (2009) use a game theoretic model to explore outsourcing the security function to a managed security service provider (MSSP) in a case where a firm's demand is affected by security breaches; when both firms have breaches they both lose demand but if only one firm is breached, the unbreached firm may gain demand. Using backward induction, the authors find the Nash equilibrium for the outsourcing game where the firms maximize their own payoffs. The case not considered by either Gal-Or and Ghose (2005) or Cezar et al. (2009) occurs when one firm has a security breach and both firms lose demand to varying degrees.

Several researchers show that there is a clear benefit to firms in sharing their security strategy as well as information about the success of that strategy in warding off attacks (Cavusoglu et al. 2008, Gal-Or and Ghose 2005, Gordon et al. 2003). Whereas these researchers focus on information sharing, we focus on the security investment aspects of the problem. Sharing information has a cost and we have incorporated it into the per-unit cost of security in our model. Thus, an increase in cost in our model represents not only a direct monetary investment in technology to reduce adverse events such as security breaches, but also any costs for sharing information, if the firms choose this as one of their methods to reduce the probability of having a security breach.

Customer demand is affected by concerns for the safety of a product (Conz 2008, Crawford 2008, Smed and Jensen 2005). Duh et al. (2002) discuss the need for control (which they define as "expectational equilibrium between what participants do and what others expect of them") in eCommerce as a necessary component for building customer trust in order to increase business activity. The authors also examine how third party assurance services such as TRUSTe and BBB Online can help with risk mitigation. We see from this that customer demand is affected by industry security standards.

3. Model

In this section, we present the details of our model. We examine how the firm's optimal spending is affected by: (1) spending by competitors to prevent adverse events in their respective firms, (2) the internalization of adverse events into the customer demand, both for the firm and its competitors, (3) the arrival rate and duration of adverse events, and (4) industry standardization or regulation. For the remainder of the paper, we use the terms *successful security related attack* and *adverse event* interchangeably.

We consider a game theoretical approach with two profit maximizing firms (duopoly) − firm 1 and firm 2. In our model, firms decide their own IT security spending level and with this they can alter the frequency of experiencing an adverse event, to a point. In this context, let:

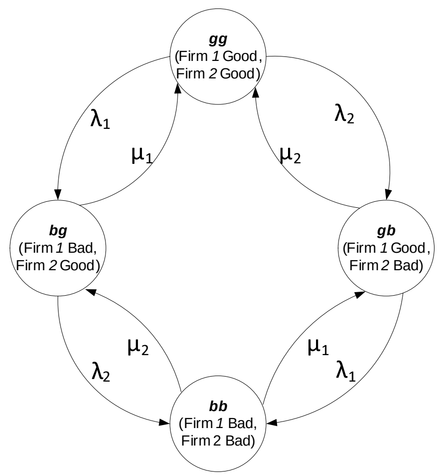
$$c_i = \text{Firm } i\text{'s per product spending on IT security, where } i = 1, 2.$$

We use a CTMC process to model the evolution of the state in which firms operate. In our model, successful security related attacks follow a Poisson process and they happen with rate λ_i for firm $i = 1, 2$, independent of the adverse events at the other firm. To a point, each firm $i = 1, 2$ can alter the arrival rate of successful attacks on itself, λ_i, by adjusting its security spending level, c_i; making λ_i a function of c_i. Every time firm $i = 1, 2$ experiences an adverse event, the effects last for a stochastic duration of time that has an exponential distribution with expected length $1/\mu_i$. In Section 3.2, we detail the effects of adverse events to firms.

Let $\{S(t), t \geq 0\}$ be the state process for the firms with $S(t) = (S_1(t), S_2(t))$ denoting the state of each firm at time t. At any point in time, each firm can either be in a "bad" state, where the firm is still under the effects of an adverse event it has experienced, or in a "good" state, where the firm is no longer under the negative effects of its most recent adverse event. We adopt the notation

$S_i(t) \in \{g, b\}$ for each firm $i = 1, 2$, where g denotes a *good* state and b denotes a *bad* state. As we have two firms, we have four possible states: $S(t) = \{gg, gb, bg, bb\}$ (Note that we simplify notation by using gg instead of (g, g), etc.). The possible states are shown in Figure 1. Besides the states, Figure 1 also displays all the possible transitions between states and corresponding transition rates.

Figure 1 State Diagram.



Note. Each firm can either be in a *bad* state, where the firm is still under the effects of an adverse event it has experienced, or in a *good* state, where the firm is no longer under the negative effects of its most recent adverse event.

As shown in Figure 1, in state gg none of the firms are experiencing an adverse event. From the state gg, an adverse event happening for firm 1 (firm 2) moves the system to the state bg (gb), where firm 1 (firm 2) is in a bad state and the other firm is in a good state. If the system is at either of these two bad event states, bg or gb, and an adverse event occurs for the other firm, then the system will move to the state bb, where both firms are simultaneously in a bad state.

3.1. State Probabilities

To find the equilibrium spending level that maximizes the long-run expected firm profits, we obtain the steady-state probabilities of being in each state shown in Figure 1. Let P_s denote the steady-state probability of being in state $s \in S = \{gg, gb, bg, bb\}$. With this notation, P_{gg} is the probability that both firms are in a *good* state, P_{bg} (P_{gb}) is the probability that firm 1 (firm 2) is in a *bad* state and the other firm is in a *good* state, and lastly P_{bb} is the probability is that both firms are in a *bad* state.

As we have modeled the system as a CTMC, the steady-state probabilities, P_s, for the system in Figure 1 can be obtained from the following equations:

$$P_{gg}(\lambda_1 + \lambda_2) = P_{bg}\mu_1 + P_{gb}\mu_2 \tag{1}$$

$$\begin{aligned} P_{bg}(\lambda_2+\mu_1) &= P_{bb}\mu_2+P_{gg}\lambda_1 && (2)\\ P_{bb}(\mu_1+\mu_2) &= P_{bg}\lambda_2+P_{gb}\lambda_1 && (3)\\ P_{gb}(\mu_2+\lambda_1) &= P_{gg}\lambda_2+P_{bb}\mu_1 && (4)\\ \sum_{P_i, i\in S} P_i &= P_{gg}+P_{bg}+P_{gb}+P_{bb}=1 && (5) \end{aligned}$$

where (1)-(4) are state balance equations and (5) normalizes the probabilities to 1.

In our model, the arrival rate of adverse events, λ_i, for the firm $i=1,2$ is a function of the base arrival rate for the firm, Λ_i, and the security spending c_i; in particular, we let $\lambda_i=\Lambda_i/c_i$. As our focus in this paper is not risk-free environments, we are only interested in cases where $\Lambda_i>0$. This functional form provides two important properties: (1) the arrival rate of the successful adverse events is decreasing in security spending, and (2) the returns to security spending are decreasing. In section 7 we show that our main results are not dependent on this specific functional form, $\lambda_i=\Lambda_i/c_i$, by repeating the analysis for alternative functions including the ones used in Gordon and Loeb (2002).

From (1)-(5), we obtain the steady-state probabilities as follows:

$$\begin{aligned} P_{gg} &= \frac{\mu_1\mu_2c_1c_2}{(\mu_1c_1+\Lambda_1)(\mu_2c_2+\Lambda_2)}, \qquad & P_{bb} &= \frac{\Lambda_1\Lambda_2}{(\mu_1c_1+\Lambda_1)(\mu_2c_2+\Lambda_2)}\\ P_{bg} &= \frac{\mu_2c_2\Lambda_1}{(\mu_1c_1+\Lambda_1)(\mu_2c_2+\Lambda_2)}, \qquad & P_{gb} &= \frac{\mu_1c_1\Lambda_2}{(\mu_1c_1+\Lambda_1)(\mu_2c_2+\Lambda_2)} \end{aligned} \tag{6}$$

Let ρ_i be the base arrival rate times the expected duration of an adverse event for the firm:

$$\rho_i=\frac{\Lambda_i}{\mu_i}, \qquad \text{for firm } i=1,2. \tag{7}$$

Thus, for a higher base arrival rate, Λ_i, the environment is more risky and ρ_i will be higher. Likewise, for a longer expected duration the environment is also riskier and thus ρ_i is higher. Unlike traditional risk measures which are between zero and one, $\rho>0$ and provides an indication of how dangerous the firms' operating environment is.

Using the relationship (7), the probabilities in (6) simplify to

$$\begin{aligned} P_{gg} &= \frac{c_1c_2}{(c_1+\rho_1)(c_2+\rho_2)}, \qquad & P_{bb} &= \frac{\rho_1\rho_2}{(c_1+\rho_1)(c_2+\rho_2)}\\ P_{bg} &= \frac{\rho_1c_2}{(c_1+\rho_1)(c_2+\rho_2)}, \qquad & P_{gb} &= \frac{\rho_2c_1}{(c_1+\rho_1)(c_2+\rho_2)} \end{aligned} \tag{8}$$

3.2. Modeling Demand

When a firm experiences an adverse event, consumers may change their purchasing decisions for a period of time. Let $D_{i,s}$ denote the demand rate for the product of firm $i=1,2$ in state $s\in\{gg,bg,bb,gb\}$. Also, let $Q_i>0$ denote the demand rate for the product of firm i in the absence of an adverse event, i.e., when both firms are in a good state, $D_{i,gg} = Q_i$. When firm i experiences an adverse event, the demand for its product will decrease by β_{i1}, e.g., $D_{1,bg} = Q_1 - \beta_{11}$. When firm j experiences an adverse event, the demand for the product of firm i $(i \neq j)$ will change by β_{i2}, e.g., $D_{1,gb} = Q_1 - \beta_{12}$. Note that, $D_{1,gb}$ $(D_{2,bg})$ may be greater than Q_1 (Q_2), if the firm gains demand when the competitor faces an adverse event. Finally, when both firms experience adverse events, firm i's demand will change by both β_{i1} and β_{i2}, resulting in $D_{i,bb} = Q_i - \beta_{i1} - \beta_{i2}$. To summarize, we have the following:

$$
\begin{aligned}
D_{i,gg} &= Q_i, & D_{i,bb} &= Q_i - \beta_{i1} - \beta_{i2}, \quad \text{for } i = 1,2 \\
D_{1,bg} &= Q_1 - \beta_{11}, & D_{1,gb} &= Q_1 - \beta_{12}, \\
D_{2,gb} &= Q_2 - \beta_{21}, & D_{2,bg} &= Q_2 - \beta_{22}.
\end{aligned} \tag{9}
$$

Let $X_i(t)$, be a binary variable indicating an adverse event in firm $i = 1,2$ at time t:

$$
X_i(t) = \begin{cases} 1 \text{ Firm } i = 1,2 \text{ is under the effects of an adverse event at time } t, \\ 0 \text{ otherwise.} \end{cases}
$$

Then, the demand for firm i's product at time t can be expressed as follows:

$$
D_i(t) = Q_i - \beta_{i1} X_i(t) - \beta_{i2} X_j(t) \qquad \text{for } i = 1,2 \text{ and } j \neq i. \tag{10}
$$

The cross-effect term, β_{i2}, allows the model to capture the alternative ways that firm $i = 1,2$ may be affected by an adverse event in the other firm j $(j \neq i)$. During the time firm j is under the effects of an adverse event, firm i may gain market share by picking up demand, if some of the customers switch from firm j to firm i. This case happens when $\beta_{i2} < 0$. Alternatively, when $\beta_{i2} > 0$, firm i loses market share temporarily as customers either find substitutes for the product offered by both firm i and j or choose not to buy the product due to the adverse event. Lastly, when $\beta_{i2} = 0$, firm i's demand is unaffected by adverse events at firm j.

We now focus on the symmetric duopoly case. Results for asymmetric cases are discussed in section 8. In the symmetric setting, we can drop the index i from Q_i, β_{i1}, β_{i2} and ρ_i. Next, we normalize the demand functions by dividing (9) by Q. The normalized demand functions for firm i in the symmetric setting are provided below:

$$
\begin{aligned}
&D_{i,gg} = 1, \qquad D_{i,bb} = 1 - Z_1 - Z_2, \qquad \text{for } i = 1,2 \\
&D_{1,bg} = D_{2,gb} = 1 - Z_1, \qquad D_{1,gb} = D_{2,bg} = 1 - Z_2.
\end{aligned} \tag{11}
$$

where $Z_1 = \frac{\beta_1}{Q}$ is the percentage change in demand due to an adverse event in own firm and $Z_2 = \frac{\beta_2}{Q}$ is the percentage change in demand due to an adverse event in the other firm. In this setting, Z_1 is the *direct-risk elasticity of demand* and Z_2 is the *cross-risk elasticity of demand*. The normalized version of the demand function in (10) is:

$$D_i(t) = 1 - Z_1 X_i(t) - Z_2 X_j(t) \qquad \text{for } i = 1,2 \text{ and } j \neq i. \tag{12}$$

We now talk about about ranges and assumptions on elasticity parameters Z_1 and Z_2. In our model, demand cannot be negative and a firm cannot gain demand from its own adverse event. Therefore, we are interested in cases where $Z_1 \in [0,1]$ (corresponding to $\beta_1 \in [0,Q]$). Likewise, the firm cannot gain more than the other firm's demand or lose more than its own demand when other firm has an adverse event and thus we are interested in cases where $Z_2 \in [-1,1]$ (corresponding to $\beta_2 \in [-Q,Q]$). We only consider the cases with $Z_1 + Z_2 \leq 1$, which ensures that $D_{i,bb} \geq 0$ holds. Also, we focus on the parameter region where $D_{i,bb} \leq 1$, since we do not find it realistic to think that demand for firm i will be greater after it has experienced an adverse event, even if it takes demand from the other firm. Hence, in this paper, we analyze the cases with $Z_1 + Z_2 \geq 0$, which ensures that $D_{i,bb} \leq D_{i,gg} = 1$ holds. Lastly, we are interested in the cases where the impact of events at a firm is greater than the impact from events at the competitor. Therefore, we consider the cases with $Z_1 \geq Z_2$. Our assumptions are listed below:

Assumption 1. $0 \leq Z_1 + Z_2 \leq 1$

Assumption 2. $Z_2 \leq Z_1$

4. Security Spending

We now derive the best response functions and the equilibrium security spending for the firms. In our model, each firm maximizes its long-run average profit. All firms are price takers; price and profit per unit, excluding security spending, are fixed. The long-run average profit for firm i, $E[\Pi_i]$, is given as:

$$E[\Pi_i] = lim_{t\to\infty} E\Big[\frac{1}{T}\int_0^T D_i(t)(\pi - c_i)Qdt\Big] \tag{13}$$

where $\pi > 0$ denotes the per product profit, excluding the security spending, c_i. In this paper we require $\pi - c_i > 0$ as a long-run participation constraint, as otherwise the firm would not be willing to produce the product. By using $D_i(t) = 1 - Z_1 X_i(t) - Z_2 X_j(t)$, we can write (13) in its steady-state form as follows,

$$E[\Pi_i] = E[D_i](\pi - c_i)Q = \sum_{s\in S} P_s D_{i,s}(\pi - c_i)Q \tag{14}$$

$$E[\Pi_i] = (P_{gg}D_{i,gg} + P_{bg}D_{i,bg} + P_{gb}D_{i,gb} + P_{bb}D_{i,bb})(\pi - c_i)Q \tag{15}$$

where, $E[D_i]$ is the expected demand rate for firm i. By substituting the probabilities in (8) and demand functions in (11) into (15), we obtain the firm's profit as:

$$E[\Pi_i] = \left(1 - \frac{Z_1\rho}{c_i+\rho} - \frac{Z_2\rho}{c_j+\rho}\right)(\pi - c_i)Q \qquad \text{for } i=1,2, \text{ and } j\neq i. \tag{16}$$

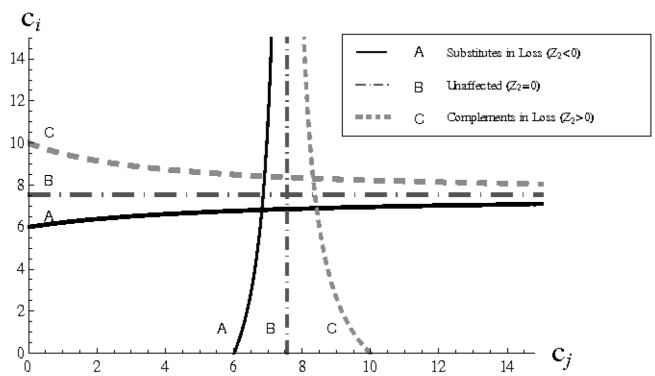
From the first-order conditions, we find the best response of firm i, c_i^*, below:

$$c_i^* = \rho\left(\sqrt{\frac{Z_1(\pi+\rho)(c_j+\rho)}{\rho(c_j+\rho-Z_2\rho)}} - 1\right) \qquad \text{for } i=1,2, \text{ and } j\neq i. \tag{17}$$

4.1. Best Response Spending Curves

An intuitive way to discuss the effects of competition on the security spending levels is to examine the different possible response curves. In this section, i denotes the firm under consideration and j denotes the other firm. Figure 2 shows the response curves for optimal spending for firm i under different effects of adverse events on the other firm j. Different curves in Figure 2 correspond to different values of Z_2 in the best response function provided in (17).

Figure 2 Best Response Curves.



Note. Response curves are generated with the parameters $Z_1 = .3, \pi = 100, \rho = 5$ and $Z_2 = \{-0.3, 0, 0.3\}$.

As the partial derivative of c_i^* with respect to c_j, shown below in (18) demonstrates, when the cross-risk elasticity of demand, Z_2, is less than 0, firm i should increase spending as the other firm increases spending. This is because Z_1 is non-negative and π and ρ are positive in our model. Conversely, when $Z_2 > 0$, firm i should decrease spending as the other firm increases spending.

$$\frac{\partial c_i^*}{\partial c_j} = -\frac{Z_1 Z_2 \rho(\pi+\rho)}{2\sqrt{\frac{Z_1(c_j+\rho)(\pi+\rho)}{\rho(c_j+\rho-Z_2\rho)}}(c_j+\rho-Z_2\rho)^2} \qquad \text{for } i=1,2, \text{ and } j\neq i. \tag{18}$$

When the cross-risk elasticity, Z_2, is such that there is no change in consumer demand for firm i's products when firm j experiences an adverse event, we call this "unaffected" ($Z_2 = 0$). In this case, as firm j spends more on security, firm i's optimal security spending does not change (see horizontal line B in Figure 2 and equation (18)). Similarly, the vertical line B in Figure 2 illustrates firm j's optimal security spending when the cross-risk elasticity, Z_2, is zero. Hence, when $Z_2 = 0$, regardless of the other firm's spending level, optimal spending for the firm is unchanging. As observed in (17), when $Z_2 = 0$, the optimal spending levels for each firm are independent of each other and $c_i^* = \rho(\sqrt{\frac{(\pi+\rho)}{\rho} Z_1} - 1)$ for $i = 1, 2$.

When the cross-risk elasticity is such that consumers increase demand for firm i's product when firm j experiences an adverse event, we call this is a "substitute in loss" ($Z_2 < 0$). As firm j spends more on security, firm i's optimal security spending also increases (see horizontal response curve A in Figure 2 and equation (18)). Similarly, the vertical response curve A in Figure 2 illustrates firm j's optimal security spending when the cross-risk elasticity, Z_2, is smaller than zero. Optimal security spending is lowest under conditions of substitutes in loss because, everything else being equal, c_i^* for both firms in (17) is increasing in Z_2, when $Z_1 > 0$. This can be observed from the the partial derivative of c_i^* with respect to Z_2, which is provided below.

$$\frac{\partial c_i^*}{\partial Z_2} = \frac{\rho^2 \sqrt{Z_1 \frac{\pi+\rho}{\rho}(c_j + \rho)}}{2(c_j + (1 - Z_2)\rho)^{3/2}} \qquad \text{for } i = 1, 2, \text{ and } j \neq i. \tag{19}$$

Hence, under conditions of substitutes in loss, optimal spending is always less than the unaffected case and eventually converges to the unaffected spending level, as the other firm's spending level goes to infinity.

When the cross-risk elasticity is such that consumers decrease demand for firm i's products when firm j experiences an adverse event, we call this is a "complement in loss" ($Z_2 > 0$). As firm j spends more on security, firm i's optimal security spending decreases (see horizontal response curve C in Figure 2 and equation (18)). Similarly, the vertical response curve C in Figure 2 illustrates firm j's optimal security spending when the cross-risk elasticity, Z_2, is greater than zero. As (17) and (19) suggest, under conditions of complements in loss, optimal spending is always greater than the unaffected case and eventually converges to the unaffected spending level as the other firm's spending level goes to infinity.

4.2. Equilibrium Spending

We can find the equilibrium spending by replacing competitor's spending, c_j, in (17) by c_i and solving the resulting equation for c_i. Due to symmetry, the equilibrium spending will be the same for both firms. We will use c^e to denote equilibrium spending. We are only interested in the cases where equilibrium spending, c^e, is positive.

$$c^e = \rho \left(\frac{1}{2} \left(Z_2 + \sqrt{Z_2^2 + 4Z_1 (\pi + \rho)/\rho} \right) - 1 \right) \tag{20}$$

We now present our results regarding the effects of model parameters on the equilibrium spending, c^e.

LEMMA 1. *When $Z_1 > 0$, equilibrium spending, c^e, is*

(i) increasing in per unit profit, π, direct-risk elasticity of demand, Z_1, and cross-risk elasticity of demand, Z_2.

(ii) increasing in ρ when $\rho < \rho_t$, and decreasing in ρ when $\rho > \rho_t$, where ρ_t is given below:

$$\rho_t = \frac{\pi Z_1}{2[1-(Z_1+Z_2)] + \sqrt{(Z_2-2)^2[1-(Z_1+Z_2)]}}, \qquad when\ Z_1+Z_2<1 \tag{21}$$

Proof: All proofs are available from authors on request.

As stated in Lemma 1, the equilibrium spending, c^e, for the firm is increasing in per unit profit, π. Keeping everything else constant, higher per unit profit increases losses in an adverse event, motivating the firm to spend more to reduce the likelihood of such an event.

$$\frac{\partial c^e}{\partial \pi} = \frac{Z_1}{\sqrt{Z_2^2 + 4Z_1\frac{\pi+\rho}{\rho}}} \tag{22}$$

Furthermore, (22) shows that the effect of a change in the per unit profit, π, on the equilibrium spending increases when the cross-risk elasticity of demand, Z_2, decreases in magnitude.

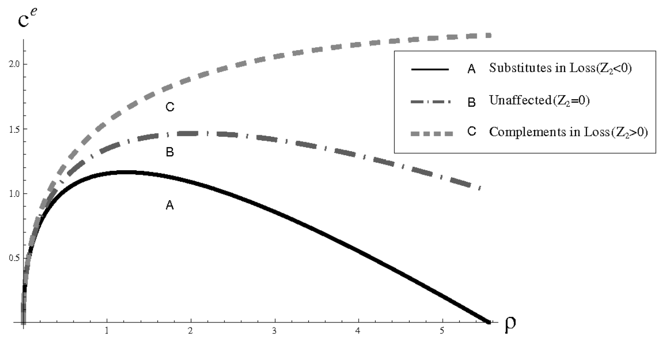
As stated in Lemma 1, the equilibrium spending, c^e, is increasing in ρ when ρ is below a certain threshold value, ρ_t provided in (21), and decreasing in ρ when ρ is above that threshold value. This effect is illustrated for different cross-risk elasticities of demand (Z_2) in Figure 3. The threshold values for curves A and B can be observed from Figure 3 but the threshold value for curve C ($\rho_t = 7.08$) is outside the figure range. This effect is interesting because it shows that after some point, the environment is so risky that the firm is nearly always in a bad state; decreased spending to save costs provides more benefit than spending more in an attempt to reduce the arrival rate of adverse events, λ. Our results echo the finding for single firms that security investment is not necessarily always increasing in vulnerability (Gordon and Loeb 2002).

Lemma 1 shows that the equilibrium spending, c^e, for the firm is increasing in direct-risk elasticity of demand, Z_1. Increased percentage losses from adverse events force the firm to increase the level of preventative measures.

$$\frac{\partial c^e}{\partial Z_1} = \frac{\pi+\rho}{\sqrt{Z_2^2 + 4Z_1\frac{\pi+\rho}{\rho}}} \tag{23}$$

As (23) shows, the change in the equilibrium spending with respect to a change in Z_1 increases when the cross-risk elasticity of demand, Z_2, decreases in magnitude or when the riskiness of the environment, ρ, increases.

Figure 3 Sensitivity of Equilibrium Spending to changes in ρ.



Note. Curves are generated with the parameters set to $Z_1 = .5, \pi = 10$, and $Z_2 = \{-0.4, 0, 0.4\}$.

As Lemma 1 shows, the equilibrium spending for the firm is increasing in cross-risk elasticity of demand, Z_2. The change in the equilibrium spending with respect to a change in Z_2 is as follows:

$$\frac{\partial c^e}{\partial Z_2} = \frac{1}{2}\left(1 + \frac{Z_2}{\sqrt{Z_2^2 + 4Z_1\frac{\pi+\rho}{\rho}}}\right)\rho \tag{24}$$

(24) shows that the change in the equilibrium spending with respect to a change in Z_2 increases when the direct-risk elasticity of demand, Z_1, decreases or when the riskiness of the environment, ρ, increases.

Figure 4 presents an enlarged section of Figure 2 highlighting the equilibrium points for the examples presented in Figure 2. In Figure 4, points A, B and C represent the equilibrium spending points. For example, point A in Figure 4 corresponds to the intersection (equilibrium) point of response curves A in Figure 2. As Lemma 1 shows, equilibrium spending levels increase with Z_2. Therefore, equilibrium spending is always lowest when firms are substitutes in loss (point A) and highest when firms are complements in loss (point C). In the unaffected case (point B), equilibrium spending is between the equilibrium spending for substitutes and complements in loss.

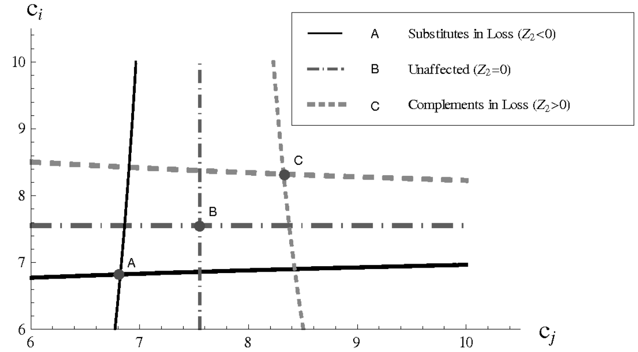
5. Expected Profit

In this section, we analyze the expected profit rate of a firm at the equilibrium security spending level, denoted as $E[\Pi^e]$. By substituting the equilibrium spending level, c^e, given in (20) into (16), we obtain expected profit rate for a firm at the equilibrium security spending level as:

$$E[\Pi^e] = \left(1 - \frac{\rho(Z_1 + Z_2)}{\rho + c^e}\right)(\pi - c^e)Q \tag{25}$$

Without loss of generality, we now focus on firm 1 with expected profit, $E[\Pi^e]$, at the equilibrium spending, c^e. However, let us consider what could happen if firm 2 spent an amount not at equilibrium, c_2^e. For a given spending level, c_2, of firm 2, if firm 1 follows its best response spending

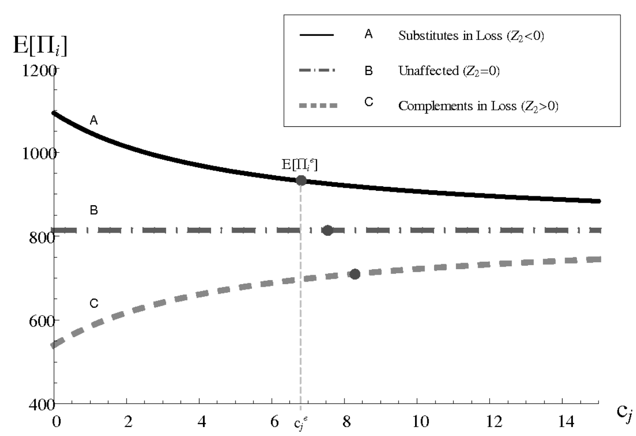
Figure 4 **Equilibrium Spending Points.**



Note. Response curves and equilibrium points are generated with the parameters $Z_1 = .3, \pi = 100, \rho = 5$ and $Z_2 = \{-0.3, 0, 0.3\}$.

level, c_1^*, as given in (17), then the profit curves of firm 1 as a function of firm 2 spending level would look like those presented in Figure 5. The differences are due to the nature of the parameter Z_2, that is, they depend on how firm 1's demand is affected by events in firm 2 (just as in the optimal spending cases). The equilibrium profit obtained at equilibrium spending, c^e, is shown on each case by a dot. For both the cases where firms are either substitutes in loss or complements in loss (when $Z_2 \neq 0$), if the other firm increases its security spending, the best response of the firm is to "move to the middle" (or "regress to the mean") in the sense that the firm's security spending approaches that of the unaffected case, where $Z_2 = 0$. This regression to the mean phenomenon can also be observed in Figure 5, functions A and C.

Figure 5 **Expected Profit Curves Under Best Response Spending.**



Note. Expected profit curves are generated with the parameters $Z_1 = .3, \pi = 100, \rho = 5$ and $Z_2 = \{-0.3, 0, 0.3\}$.

5.1. Sensitivity Analysis of Expected Profit at Equilibrium

In this section, we analyze the effects of model parameters on the expected profit at equilibrium, or equilibrium profit, $E[\Pi^e]$.

LEMMA 2. *When $Z_1 > 0$, equilibrium profit, $E[\Pi^e]$ is*

(i) increasing in per unit profit, π,

(ii) decreasing in direct-risk elasticity of demand, Z_1, and cross-risk elasticity of demand, Z_2,

(iii) decreasing in riskiness of the environment, ρ, when $Z_2 \geq 0$, or when $Z_2 < 0$ and $\rho < \rho_T$, and increasing in ρ when $Z_2 < 0$ and $\rho > \rho_T$, where ρ_T is given below:

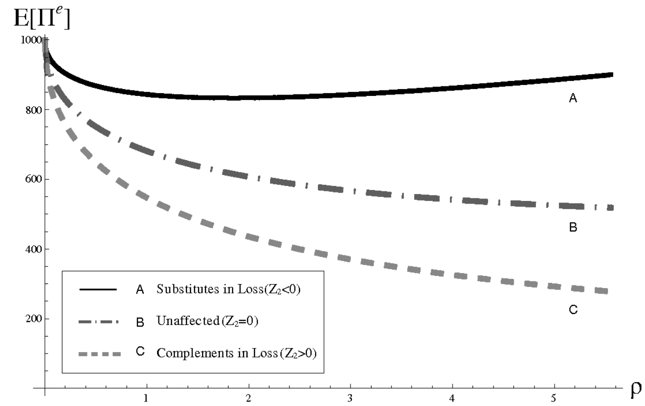
$$\rho_T = \frac{\pi(2Z_1 + Z_2)^2}{(4Z_1 + Z_2^2)(1 - (Z_1 + Z_2))}, \qquad \text{when } Z_1 + Z_2 < 1 \tag{26}$$

The equilibrium profit, $E[\Pi^e]$, for the firm is increasing in per unit profit, π. Keeping everything else constant, higher per unit profit increases the overall profit rate. The equilibrium profit, $E[\Pi^e]$, for the firm is decreasing in direct-risk elasticity of demand, Z_1. Increased percentage losses lead to fewer products being sold and thus decreased total expected profit.

The equilibrium profit, $E[\Pi^e]$, for the firm is decreasing in the riskiness of the environment ρ when cross-risk elasticity is non-negative ($Z_2 \geq 0$; firms are unaffected or complements in loss). This effect is shown by curves B and C in Figure 6. The equilibrium profit, $E[\Pi^e]$ is also decreasing when cross-risk elasticity is negative ($Z_2 < 0$) and the riskiness is below the threshold given by (26). Above that threshold value, ρ_T, equilibrium profit is increasing in the riskiness for firms that are substitutes in loss. In that case, the environment becomes extremely risky and firms actually gain demand when their competitors have adverse events, therefore the profits can increase as each firm spends less on security. This effect is shown by curve A in Figure 6 where profits initially decrease but begin increasing when ρ is above the threshold value, ρ_T.

The equilibrium profit for the firm is is decreasing in cross-risk elasticity of demand, Z_2. Figure 5 presents the expected profits under best response spending levels, highlighting the equilibrium points for the example presented in Figure 2 for different values of cross-risk elasticity of demand, Z_2. In Figure 5, points on functions A, B and C represent the equilibrium profit under equilibrium spending. As Lemma 2 shows, equilibrium profit levels decrease with Z_2. Therefore, equilibrium profit is always highest when firms are substitutes in loss (point on function A) and lowest when firms are complements in loss (point on function C). In the unaffected case (point on function B), equilibrium profit is between the equilibrium profit for substitutes and complements in loss.

Figure 6 **Sensitivity of Equilibrium Profit to changes in ρ.**



Note. Curves are generated with the parameters set to $Z_1 = .5, \pi = 10, Q = 100$, and $Z_2 = \{-0.4, 0, 0.4\}$.

6. Profits under Regulation and Industry Standardization

In this section, we analyze the effects of binding regulation or industry standardization on expected profits of the firm. Let us define R as the minimum spending requirement per unit product that ensures that the firm satisfies the regulation or industry standardization conditions.

As long as the requirements of regulation or industry standardization dictate spending below equilibrium spending level, then each firm will spend their equilibrium amount. However, once the required spending, R, is above the equilibrium spending, then both firms will have to spend more than they would like. In this section, we are interested in cases where requirements are binding, i.e., required spending, R, is greater than or equal to the equilibrium spending, c^e.

Propositions 1 and 2 show that the effect of regulations or industry standards on firm profits is case dependent, varying by customer response to adverse security related events in competitor firms. Proposition 1 states that when firms are substitutes in loss or unaffected by an event at the other firm, binding regulation or industry standardization which improves industry security will decrease firm profits.

Proposition 1. *When the firms are substitutes in loss or unaffected by each other (that is, one firm's demand increases or is unaffected by an event at the other firm:* $Z_2 \leq 0$*), then profits decline for both firms when a binding regulation or industry standard is introduced.*

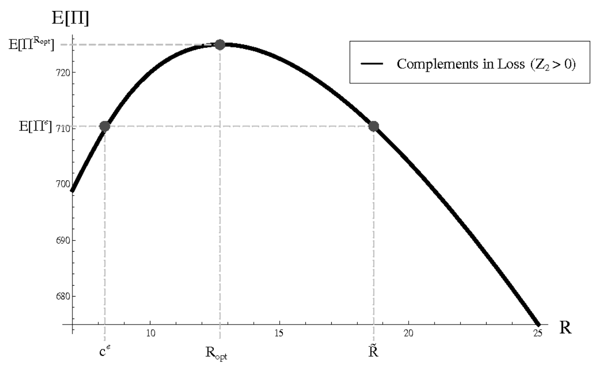
Proposition 2 states that when firms are complements in loss, there is a range of required spending beyond the market equilibrium over which firm profits will increase. This range is illustrated in Figure 7.

Proposition 2. *When the firms are complements in loss (that is, one firm's demand decreases due to an event at the other firm:* $Z_2 > 0$*), then there is a region in which profits increase under* *binding regulation or industry standardization. Profits will remain above the equilibrium profit, $E[\Pi^e]$, while the required spending, R, is between c^e and $\tilde{R}$ and will be maximized when required spending is at R_{opt}, where $c^e \leq R_{opt} \leq \tilde{R}$. Spending levels R_{opt} and $\tilde{R}$ are given as follows:*

$$R_{opt} = \sqrt{(Z_1 + Z_2)(\pi + \rho)\rho} - \rho \geq c^e \tag{27}$$

$$\tilde{R} = \rho \left(\frac{(Z_1 + Z_2)(\pi + \rho)}{c^e + \rho} - 1 \right) \geq R_{opt} \tag{28}$$

Figure 7 **Expected Profit for firm when $Z_2 > 0$, with regulation or industry standardization spending.**



7. Alternate Functional Forms

We examine alternate functional forms for the arrival rate, λ, such as $\lambda_i = \Lambda_i/(c_i+1)^\alpha$, where $\alpha > 0$. We must adapt our approach by using properties of our state probabilities to enable us to consider additional linear and non-linear functional forms. In all cases, we find that our results hold for these alternate forms. Our analysis suggests that the insights obtained in our model are not dependent on the functional form $\lambda = \Lambda/c$ but can be generalized to a broader class of security risk functions.

8. Asymmetric Cases

In the asymmetric case, we allow the direct- and cross-risk elasticity of demand parameters (Z_1 and Z_2) to be different for each firm. Whereas the expected profit equation in the symmetric case was given by (16), the expected profit equation for the asymmetric case is:

$$E[\Pi_i] = \left(1 - \frac{Z_{i1}\rho}{c_i + \rho} - \frac{Z_{i2}\rho}{c_j + \rho}\right)(\pi - c_i)Q \qquad \text{for } i = 1, 2, \text{ and } j \neq i. \tag{29}$$

Likewise, while the optimal spending equation in the symmetric case was given by (17), the optimal spending equation for the asymmetric case is:

$$c_i^* = \rho \left(\sqrt{\frac{Z_{i1}(\pi + \rho)(c_j + \rho)}{\rho(c_j + \rho - Z_{i2}\rho)}} - 1 \right) \qquad \text{for } i = 1, 2, \text{ and } j \neq i. \tag{30}$$

Using numerical analysis (details are available from the authors on request), we are able to demonstrate that, depending on its own cross-risk elasticity of demand, each firm's best response curve will look like the corresponding best response curve in the symmetric case as illustrated in Figure 2. There are three possible combinations of cross-risk elasticity that are of interest: (a) one firm is a complement in loss while the other is a substitute in loss, (b) both firms are substitutes in loss, and (c) both firms are complements in loss.

In all cases, without loss of generality, we focus on the instance where equilibrium spending for firm 1, c_1^e, is greater than or equal to the equilibrium spending for firm 2, c_2^e. As a result, when the required spending, R, greater than market equilibrium is introduced, it will become binding on firm 2 before firm 1 (that is, a lower required spending will become binding on firm 2). When firm 1 is a complement in loss ($Z_{12} > 0$) while firm 2 is a substitute in loss ($Z_{22} < 0$), profits for firm 2 always decrease and profits for firm 1 increase for a range of R values. In this situation, firm 2 would oppose any move from firm 1 to increase the required spending level, R above c_2^e. When both firms are substitutes in loss ($Z_{i2} < 0$, for $i = 1, 2$), profits are reduced for both firm 1 and firm 2. In this situation, both firms would oppose any move to increase the required spending level, R above c_2^e. Finally, when both firms are complements in loss ($Z_{i2} > 0$, for $i = 1, 2$), profits for firm 1 increase for a range of R values. However, profits for firm 2 may or may not increase depending on the situation. Our analysis provided us with several general observations which illustrate that there is a significant range for which the insights from Proposition 2 hold when both firms are complements in loss, even in the asymmetric case.

Observation 1. *As direct-risk elasticity increases, the opportunity window for firm* 2 *to increase profit under required spending decreases, everything else being constant.*

Observation 2. *As cross-risk elasticity increases, the opportunity window for firm* 2 *to increase profit under required spending increases, everything else being constant.*

Observation 3. *The largest increases in profit for firm* 2 *occur when the firms are "more similar" in terms of both their direct- and cross-risk elasticity values.*

Thus, the more similar firms are, the better the opportunity for cooperation.

9. Conclusion

The novelty of this research is to explore how adverse IT security events at all firms have an impact on customer demand, IT security spending, and profits for a firm. By understanding how customers will react to a competitor's adverse IT security events, managers will have a better understanding of the appropriate IT security spending to maximize their firm's profits.

We have developed a rich and complex model for examining the interaction effects of firms' actions when customers react to any adverse IT security event by changing their demand for both firms' products. We not only model customer reaction in the case where a firm gains demand as a result of a competitor's adverse IT event, but also include the case where a firm loses demand as a result of a competitor's adverse IT security event, obtaining analytical results when firms are symmetric. Further, we examine the asymmetric case where customer reactions may be different for each firm. A significant contribution of our paper is to allow unique insights regarding customer demand changes in response to adverse IT security events, and the impact these demand changes have on security spending and profits.

We describe the impact between firms as the cross-risk elasticity of demand. The cross-risk elasticity of demand can be described in three ways: firms may be substitutes in loss, unaffected, or complements in loss. When firms are unaffected, there is no indirect effect on customer demand due to an adverse IT security event at another firm. In the symmetric case, when both firms are substitutes in loss, we show that equilibrium spending is lower (and equilibrium profit is higher) than it would be if both firms were unaffected. The gain in customer demand due to a competitor's adverse IT security event counteracts the direct losses in demand due to the firm's own adverse IT security events, resulting in a tolerance by the firm for a higher frequency of its own events. However, when both firms are complements in loss (again, in the symmetric case) we show that equilibrium spending is higher (and equilibrium profit is lower) than it would be if both firms were unaffected. Since a firm can only directly impact the frequency of its own adverse IT security events, it must decrease this frequency to off-set the additional indirect losses due to a competitor's adverse IT security events over which it has no control.

In addition, our model has shown how the direct- and cross-risk elasticities impact spending and profits for firms, pointing to the importance of including these parameters in IT security spending decision making. Governmental policy can encourage or require disclosure of security breaches which will help companies connect the dots, understanding how adverse events at other firms affect their demand.

Nevertheless, there are some limitations of this work:

- In this research, the arrival rates of adverse events are modeled as independent. In general, though, there are some types of attacks that are independent and some that are dependent, or correlated.
- As government policy begins to require breach disclosure, an area for future research is to actually connect those disclosures to changes in demand for other firms. Our research assumed

the elasticities of demand to be fixed, but the data may suggest a model where the direct- and cross-risk elasticities vary over time.

- Our model does not capture the possibility that some customers may have different risk seeking profiles, and this is an opportunity for future research. Some customers may be willing to accept a less secure product if it came at a discounted price, thereby allowing firms to choose their security posture (set their IT security spending level) and then price the product accordingly.

Despite these limitations, our model is successful in obtaining insights for different possible indirect effects of adverse IT security events on customer demand and firm IT security spending. IT security is not traditionally perceived as a mechanism to increase sales and we illustrate the competitive impact of IT security spending on customer demand changes resulting from adverse events. This paper lays the basis for further work to more fully understand the complex interaction of firms' actions and customer reactions to stochastic adverse events, IT security being our primary example. By understanding the nature of these customer reactions, managers can know when it is in their best interest to work together with others in the industry to increase the security posture of all firms in an attempt to increase overall customer demand - that is, rather than competing for a large piece of the pie, firms can cooperate to increase the size of the pie. Alternatively, our model also helps managers identify when it is not desirable to cooperate in this manner.

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