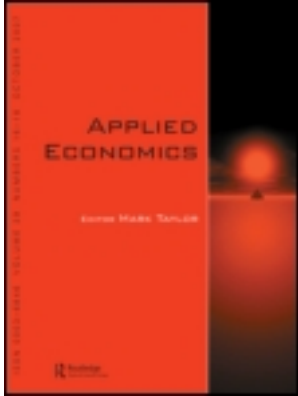


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# Modelling competition in global LCD TV industry

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This work analyses global shipments of Liquid Crystal Display Televisions (LCD TVs) by considering mutualism among multiple generations of LCD TVs. In applying the revised Lotka–Volterra equations, this study analyses the dynamic competitive relationship among producers of 26-, 32- and 37-inch LCD TVs. Equilibrium analysis is used to evaluate whether future shipment orbit could converge to equilibrium status. The prediction abilities of Bass growth model and Lotka–Volterra model are further compared to examine whether the Lotka–Volterra model, which incorporates the mutualism among multi-generation LCD TVs, performs better. The result shows that the relationships between 26- and 32-inch LCD TVs, and 37- and 32-inch LCD TVs are commensal. Sales of 32-inch LCD TVs are promoted by increased sales of 26- or 37-inch LCD TVs. Results of the equilibrium analysis indicate that competition among various sizes of LCD TVs will not be stable. The interactions among multiple generations of LCD TVs will influence each other, leading to great fluctuations in sales. Since this study incorporates the interactive relationships among various sizes of LCD TVs in the proposed Lotka–Volterra equations, the ability of the Lotka–Volterra model to predict the market evolution of LCD TVs is superior to that of the Bass model.

## I. Introduction

As the popularity of Liquid Crystal Display Televisions (LCD TVs) has increased markedly in recent years, diffusion growth has become progressively crucial to management, marketing, investment, production and operational strategies. In 1997, LCD TV output values, which account for 46% of the total value of Thin Film Transistor (TFT)-LCD industry, reached US \$33.6 billion. Notably, LCD TVs have numerous advantages over conventional TVs. For example, LCD TVs are slimmer, lighter and have higher resolution and a larger screen size.

Furthermore, LCD TVs are brighter, have better contrast and consume lesser power than conventional TVs (Hung, 2006). Notably, LCD TVs are rapidly replacing conventional TVs in households (Teo *et al.*, 2003); thus, consumers now view LCD TVs as durable consumer products. LCD TVs are products with dual property of consumer durables and technological products. The 20-, 26-, 32- and 37-inch LCD TVs have been successively marketed and competition likely exists between smaller and large next-generation LCD TVs.

In terms of multi-generational high-tech products, studies have determined that Dynamic Random

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Access Memory (DRAM) or flash memory may be replaced by next-generation products (Norton and Bass, 1987; Li and Chiang, 2007). In these studies, the product characteristics and functions of DRAM and flash memory in various generations are treated as homogeneous; thus, the market for previous product generations diminishes rapidly. In contrast to such homogenous products, LCD TV attributes and functions differ among various generations. Varying household space requirements are associated with different sizes of LCD TVs. Additionally, those who purchase LCD TVs use these TVs in different locations, such as public spaces, living rooms and bedrooms, and thus have different size preferences. Although small LCD TVs are not as common as large ones in the marketplace, large LCD TVs cannot fully replace small ones. The division of the LCD TV market into distinct buyer groups that prefer different sizes of LCD TVs is called 'market segmentation'. Many studies have examined market segmentation (Wendell, 1956; Kotler, 2000). Consumer demand for various sizes of LCD TVs is typically heterogeneous, but homogeneous for consumers who prefer the same sizes of LCD TVs. The coexistence of different sizes of LCD TVs has resulted in collaboration and competition in the TFT-LCD industry, which affects the potential market dynamics of the multiple-generation LCD TVs. Nosella *et al.* (2008) emphasize that critical technological advances can have a significant impact on a company's operation and potential market size. It is essential to predict the potential market dynamics of various generations of LCD TVs, so we can determine which potential technologies that LCD TV companies should adopt to maintain their profitability.

Most studies applied conventional diffusion theory to determine market dynamics *via* logistical diffusion model (Gruber, 1998; Tishler *et al.*, 2001; Lee and Lee, 2009). Lee and Lee (2009) applied the Bass (1969) model and a typical logistical S-curve to analyse the growth patterns of telecommunication services. Tsai *et al.* (2010) also employed the Bass model to examine the trend in which LCD TV adopters have caused potential LCD TV adopters to purchase LCD TVs. However, the Bass model assumes a monopolistic market (Bass, 1969; Liberatore and Breem, 1997; Teng *et al.*, 2002; Bass, 2004), such that reciprocal cooperation or competition among different sizes within the LCD TV industry is ignored. No study has considered the effects of reciprocal interactions in the LCD TV industry. This work focuses on 32-inch LCD TVs and explores technological substitution of 32-inch LCD TVs for other sizes of LCD TVs. We, for the first time, apply the Lotka–Volterra model to address the

effects of interactive cooperation on a product with dual property of consumer durables and technological products.

The Lotka–Volterra model was developed to model interaction between two competing species based on the logistic curve (Chakraborty *et al.*, 2007; Delgado and Suárez, 2007) and extended to analyse technological diffusion in competitive or collaborative markets (Watanabe *et al.*, 2003; Tang and Zhang, 2005; Castiaux, 2007). Castiaux (2007) utilizes the Lotka–Volterra model to demonstrate that predation relationship is the most relevant to acquire new knowledge from partners and thus allow radical innovation. Tang and Zhang (2005) quantitatively analysed the quarterly revenues of Advanced Micro Devices (AMD) and Intel using Lotka–Volterra equations. Their research focused on competition between two vendors of Central Processing Units (CPUs). Watanabe *et al.* (2003) apply the Lotka–Volterra equations to analyse the optimal orbit for Japan's transition from analogue to digital TV broadcasting.

Since our investigation analyses LCD-based products that are subject to various market segments and technology levels for multiple product generations, competitive or collaborative interactions exist among multiple product generations. It is reliable to employ Lotka–Volterra models to forecast the LCD TV diffusions. The Lotka–Volterra model can capture competition or collaboration among market segments for multi-generational technologies. In particular, equilibrium analysis using the Lotka–Volterra model for LCD TVs may benefit the strategic planning and operational management of enterprises.

This study highlights the dependence of 32-inch LCD TVs on other sizes of LCD TVs as shipments of 32-inch LCD TVs have been highest since 2005. This study selects to product pairs; one pair comprises 26- and 32-inch LCD TVs, and the other pair comprises 32- and 37-inch LCD TVs. The Lotka–Volterra model is applied to investigate the reciprocal influence in the two pairs. If the shipment values of one pair have an increasing lead-lag relationship, then product substitutions and complementarities may be explicitly proved to exist among multiple generations of LCD TVs. This study also forecasts trends of global LCD TV shipments, and compares the accuracy of the Lotka–Volterra and Bass models; that is, this research determines whether the Lotka–Volterra model, which identifies inter-industrial reciprocal competition, performs better than the Bass model. Finally, characteristics of the dynamic collaborative relationships in the LCD TV industry are examined, including the existence of an equilibrium point and its

**Table 1. Multi-mode competitive relationship according to the signs of interaction parameters**

$c_1$	$c_2$	Type	Explanation
+	+	Pure competition	Both species suffer from each other's existence.
+	-	Predator-prey	One of them serves as direct food to the other.
-	-	mutualism	It is the case of symbiosis or a win-win situation.
+	0	Amensalism	One suffers from the existence of the other, who is impervious to what is happening.
-	0	Commensalism	One benefits from the existence of the other, who nevertheless remains unaffected.
0	0	Neutralism	There is no interaction.

stability in terms of estimated functions. Analytical results show that commensalism defines the relationship between 26- and 32-inch LCD TVs: that is, sales of 26-inch LCD TVs stimulate the sales of 32-inch LCD TVs; however, sales of 26-inch LCD TVs are not significantly affected by increased sales of 32-inch LCD TVs. Additionally, commensalism defines the relationship between 37- and 32-inch LCD TVs; that is, sales of 37-inch LCD TVs increase the sales of 32-inch LCD TVs; however, sales of 37-inch LCD TVs are not significantly affected by sales of 32-inch LCD TVs. The 32-inch LCD TV will remain the most common size in the future LCD TV market. Competition will not converge to equilibrium for the two pairs (26- and 32-inch LCD TVs, and 32- and 37-inch LCD TVs); namely, the state in these two pairs will not stabilize over time. The interactions among multi-generation LCD TVs influence each other, which leads to the great fluctuations of their shipment orbits. This suggests that if one size level of LCD TVs cannot keep with their opponent (another size level of LCD TVs), the severe competition in LCD TV industry will wipe them away from the market. Since this study incorporates interactive relationships among various sizes of LCD TVs in the proposed Lotka–Volterra equations, the prediction ability of the Lotka–Volterra model is superior to that of the Bass model.

The remainder of this article is organized as follows. Section II describes study methodology and the sample. Section III presents analytical results from dynamic competition analysis and equilibrium analysis. Finally, Section IV presents conclusions.

## II. Methodology and Sample

### Lotka–Volterra model

The Lotka–Volterra model uses the logistic equation and a term that accounts for the interaction with the

other species (Watanabe *et al.*, 2003). The interaction between two species can be expressed by the following two differential equations:

$$\frac{dX}{dt} = (a_1 - b_1X - c_1Y)X = a_1X - b_1X^2 - c_1XY \quad (1)$$

and

$$\frac{dY}{dt} = (a_1 - b_1Y - c_1X)Y = a_1Y - b_1Y^2 - c_1YX \quad (2)$$

where  $X$  and  $Y$  are the populations of two competing species at time  $t$ ;  $X^2$  and  $Y^2$  are the same species interacting with itself;  $XY$  and  $YX$  are different species interaction;  $a_i$  is the logistic parameter of geometric growth for species  $i$  when it is living alone;  $b_i$  is the limitation parameter of the niche capacity for species  $i$ ; and  $c_i$ , generally called the coupling coefficient, is the parameter for interaction with the other species. Equations 1 and 2 contain all the fundamental parameters that affect the growth rate of both species. The multi-mode form of competition can be captured by coefficient  $c_i$  for two species. The competitive roles are assigned according to the sign of  $c_i$ ; thus, the multi-mode form can be determined for the case with two species (Table 1).

To use discrete time data, one must convert the continuous Lotka–Volterra model into a discrete time version. Equations 1 and 2 can be transformed into the following difference equations (Leslie, 1957):

$$X(t + 1) = \frac{\alpha_1 X(t)}{1 + \beta_1 X(t) + \gamma_1 Y(t)} \quad (3)$$

and

$$Y(t + 1) = \frac{\alpha_2 Y(t)}{1 + \beta_2 Y(t) + \gamma_2 X(t)} \quad (4)$$

where  $\alpha_i$  and  $\beta_i$  are logistic parameters for single species  $i$  when it is living alone, and  $\gamma_i$  is the magnitude of effects one species has on the growth rate of the other. The relationship between coefficients in the Lotka–Volterra model, and that of

transformed difference in Equations 3 and 4, are as follows:

$$a_i = \ln \alpha_i \quad (5)$$

$$b_i = \frac{\beta_i \alpha_i}{\alpha_i - 1} = \frac{\beta_i \ln \alpha_i}{\alpha_i - 1} \quad (6)$$

$$c_i = \gamma_i \frac{b_i}{\beta_i} = \frac{\gamma_i \beta_i \ln \alpha_i}{\beta_i \alpha_i - 1} = \frac{\gamma_i \ln \alpha_i}{\alpha_i - 1} \quad (7)$$

where  $\gamma_i$  must be the same as the sign of  $c_i$  since  $\frac{\ln \alpha_i}{\alpha_i - 1}$  is always positive when  $\alpha_i > 0$  and  $\alpha_i \neq 1$  in Equation 7. Thus, the competitive roles (Table 1) can be determined according to the sign of  $\gamma_i$ .

### Assumptions

We assume that the market evolution of global LCD TVs corresponds to the original condition in the Lotka–Volterra model. Since no study has determined whether competition exists among 26-, 32- and 37-inch LCD TV panels, this study determines the competitive influence of 26- or 37-inch LCD TVs on the diffusion of 32-inch LCD TVs. This work groups shipments of the three LCD TVs into two pairs: 26- and 32-inch LCD TVs, and 32-inch and 37 LCD TVs. Two system equations, Equations 3 and 4, are applied separately to determine the mutual impacts of sales volumes in the LCD TV industry for the two pairs. In Equations 3 and 4,  $X$  and  $Y$  are the cumulative shipments of LCD TVs of different sizes;  $\alpha_i$  and  $\beta_i$  are logistic parameters for one industry;  $\gamma_i$  is the magnitude of the effects that one size level's shipment has on the growth rate of the other.

### Comparison with Bass model

To further demonstrate the performance of Lotka–Volterra model, this study also applies the Bass model. Under several assumptions (Tsai *et al.*, 2010), the dynamics of LCD TV growth for each size in Bass model is derived as

$$\frac{dN(t)}{dt} = (p + qN(t)(M - N(t))) \quad (8)$$

where  $N(t)$  is the cumulative shipment amount at time  $t$ ;  $M$  is the potential size of shipments of LCD TVs; parameter  $p$  is the coefficient of innovation and  $q$  is the coefficient of imitation. After the shipment amount is estimated by Bass or Lotka–Volterra model, the prediction ability of the Bass model is compared with that of the Lotka–Volterra model based on Mean Absolute Percentage Error (MAPE). The calculated errors can determine which model is the most efficient.

### Equilibrium analysis

Analysis of the competitive relationship using the Lotka–Volterra model provides information about the equilibrium state and illustrates the trajectory of change over time. Furthermore, the stability of equilibrium can be clearly identified. In equilibrium, Equations 1 and 2 must equal zero because no simultaneous changes exist over time for each industry; thus,

$$\frac{dX}{dt} = 0 \quad \text{and} \quad \frac{dY}{dt} = 0 \quad (9)$$

Applying condition (9) to Equations 1 and 2 yields the following system of equations:

$$\begin{aligned} a_1 X - b_1 X^2 - c_1 XY &= X(a_1 - b_1 X - c_1 Y) = 0, \text{ and} \\ a_2 Y - b_2 Y^2 - c_2 XY &= Y(a_2 - b_2 Y - c_2 X) = 0 \end{aligned} \quad (10)$$

Solving Equation 10 yields

$$X = \frac{a_1 - c_1 Y}{b_1} \quad \text{and} \quad Y = \frac{a_2 - c_2 X}{b_2} \quad (11)$$

The two lines,  $dX/dt=0$  and  $dY/dt=0$ , cross, implying a point of equilibrium. When the two straight lines in Equation 11 intersect in the first quadrant, the two series of LCD TVs reach equilibrium; otherwise, no equilibrium exists. This equilibrium point indicates that the pair of the LCD TVs can coexist without dynamic changes. In addition, the stability of the equilibrium state depends on coefficient values in the Lotka–Volterra model. In Equations 10 and 11, if  $X < \frac{a_1 - c_1 Y}{b_1}$ , then  $dX/dt > 0$ . Conversely, if  $X > \frac{a_1 - c_1 Y}{b_1}$ , then  $dX/dt < 0$ . Similarly,  $dY/dt > 0$  if  $Y < \frac{a_2 - c_2 X}{b_2}$ , and  $dY/dt < 0$  if  $Y > \frac{a_2 - c_2 X}{b_2}$ .

## III. Results and Discussion

### Competitive relationship analysis

The quarterly global LCD TV shipments are obtained from DisplaySearch databases. The study period is from the first quarter of 2003 to the second quarter of 2008 – 22 quarters in total. The shipments of the three sizes of LCD TVs from the first quarter of 2003 to the second quarter of 2008 are used to estimate the demand function, coefficients and related statistics (Table 2). For the 26- and 32-inch LCD TVs (pair one), the interaction parameter is significant and negative for 32-inch LCD TVs and insignificant for 26-inch LCD TVs. These analytical results demonstrate that sales of 26-inch LCD TVs

**Table 2. Coefficient estimation results of Lotka–Volterra model for 26, 32 and 37-inch LCD TVs**

Pair one	26-inch		32-inch	
	Coefficient	<i>t</i> -statistic	Coefficient	<i>t</i> -statistic
$\alpha$	1.406940	16.7289***	1.203191	17.59167***
$\beta$	0.000048	1.86984*	0.000015	2.50655**
$\gamma$	-0.000014	-1.67058	-0.000039	-2.09036**
$R^2$	0.999276		0.999416	
Pair two	32-inch		37-inch	
	Coefficient	<i>t</i> -statistic	Coefficient	<i>t</i> -statistic
$\alpha$	1.504670	25.99569***	1.456414	17.11386***
$\beta$	0.000033	3.23027***	-0.000012	-0.26394
$\gamma$	-0.000103	-2.98257***	0.000004	0.54632
$R^2$	0.999519		0.998978	
	Pair one		Pair two	
	26-inch	32-inch	32-inch	37-inch
$a_i$	0.341417	0.184977	0.408574	0.375977
$b_i$	0.000040	0.000014	0.000026	-0.000010
$c_i$	-0.000012	-0.000036	-0.000083	0.000006

Note: \*, \*\* and \*\*\* denote significance of *p*-value at 0.1, 0.05 and 0.01% levels, respectively.

significantly increases the subsequent sales of 32-inch LCD TVs; however, sales of 26-inch LCD TVs are unaffected by sales of 32-inch LCD TVs. In other words, a commensalism relationship exists between 26- and 32-inch LCD TVs. These analytical results may be interpreted as follows. Consumers purchase 26-inch LCD TVs when they are unfamiliar with LCD TVs. However, consumers who purchased 26-inch LCD TVs have knowledge of their advantages, such as slimness, lightness, high resolution, large image area, increased brightness and contrast, reduced glare and power saving functions. Since LCD TVs have met the needs of these consumers, these consumers then purchase relatively larger LCD TVs. The possible explanation is that 32-inch LCD TVs are placed in larger rooms and 26-inch ones in smaller rooms.

For 37- and 32-inch LCD TVs (pair two), the interaction parameter is significant and negative in 37-inch LCD TVs, and insignificant for 32-inch LCD TVs. These analytical results suggest that the sales of 37-inch LCD TVs significantly promote sales of 32-inch LCD TVs; however, sales of 32-inch LCD TVs are unaffected by sales of 37-inch LCD TVs. That is, a commensalism relationship exists between 32 and 37-inch LCD TVs. Thus, when consumers have purchased 37-inch LCD TVs and realized their advantages, they are likely to consider purchasing a

32-inch LCD TVs for another location in their house. However, consumers who cannot afford expensive household appliances or who only require one TV set will be expected to opt for a 32-inch LCD TV. Once they own a 32-inch LCD TV, these consumers are less likely to buy a 37-inch LCD TV. Few consumers responded actively to consumption decisions when 37-inch LCD TVs were introduced into the market. The market share for 32-inch LCD TVs has remained constant, and may increase, suggesting that the potential demand for 32-inch LCD TVs are time-varying and related to sales of 37- or 26-inch LCD TVs. In the marketing field, the market penetration index is defined as the current market demand relative to potential demand. From aforementioned results, market growth of 37- or 26-inch LCD TVs expand the potential market of 32-inch LCD TVs, so the market penetration index of 32-inch LCD TVs decreases with the sales of the 37- and 26-inch LCD TVs. The reductions of the market penetration index imply that price competition has reduced and the profit margin has increased for firms in manufacturing 32-inch LCD TVs.

Figures 1 and 2 show the logarithm of the actual shipments and the total shipments simulated by the Lotka–Volterra model for the two pairs of LCD TVs, respectively. The estimated shipments have roughly the same trend as the collected shipment data,

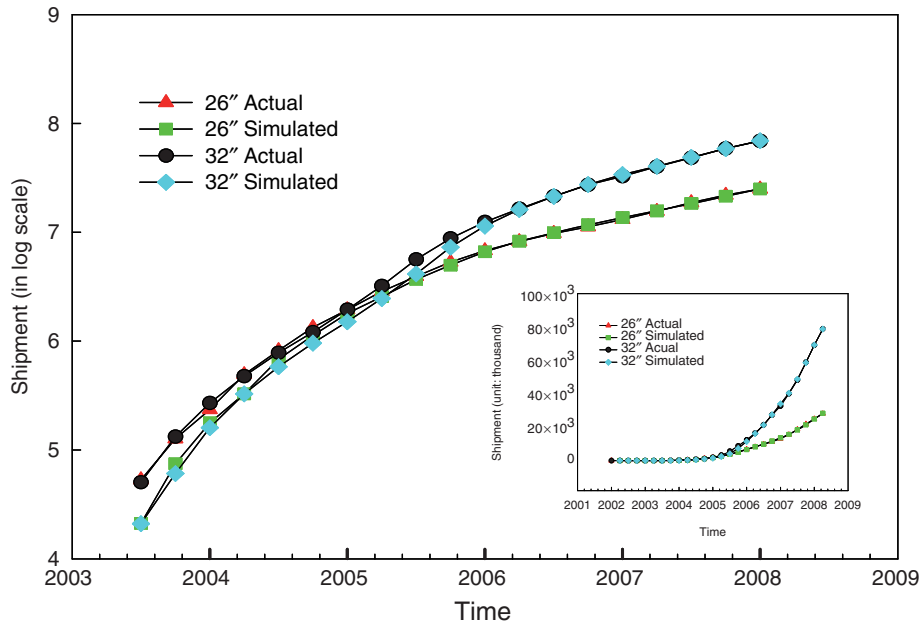


Fig. 1. Simulated and actual shipment amount for 26- and 32-inch LCD TVs based on Lotka–Volterra competition equation

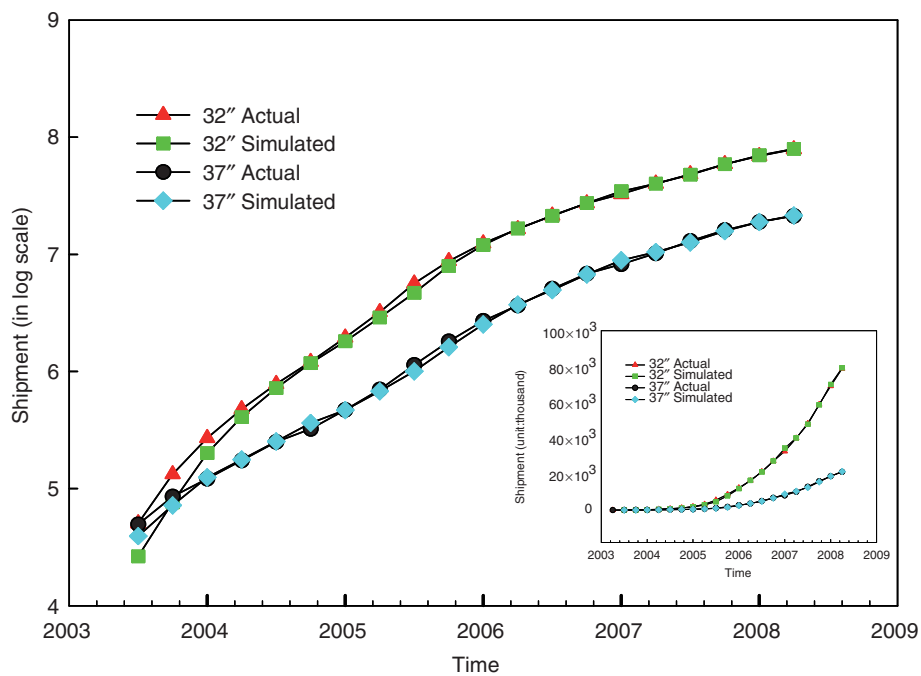


Fig. 2. Simulated and actual shipment amount for 32- and 37-inch LCD TVs based on Lotka–Volterra competition equation

indicating that the Lotka–Volterra model can explain the diffusive evolution process of LCD TVs. Since interactive relationships exist among various sizes of LCD TVs, the proposed Lotka–Volterra model accurately predicts the trajectory of LCD TVs. In terms of the time-series pattern of LCD TV

shipments, LCD TV shipments are assessed to aggressively increase with time. Particularly, based on the slope of total LCD TV shipments, the marginal growth rate of 26-, 32- and 37-inch LCD TV shipments is continuously increasing. Shipments of LCD TVs have not yet reached the saturation

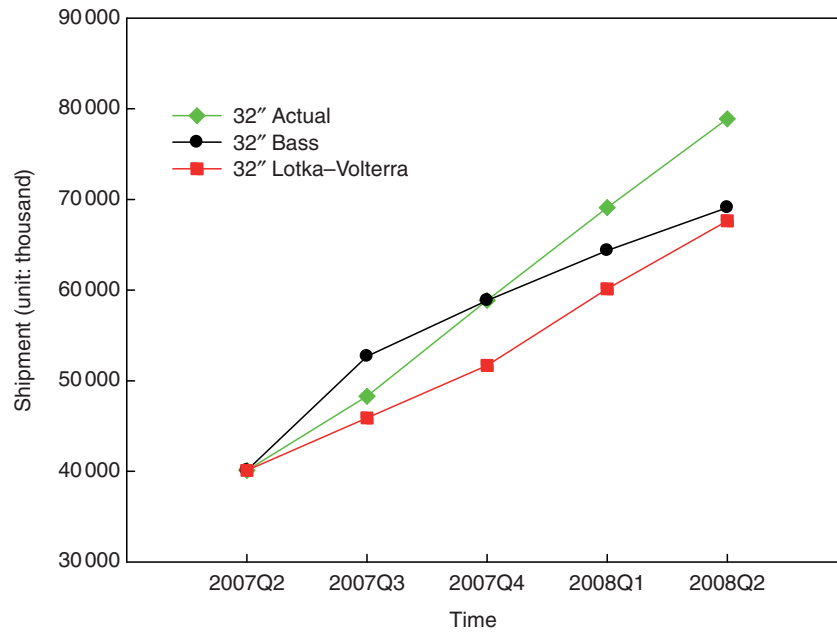


Fig. 3. Comparison among the actual shipments, Bass simulated result and Lotka–Volterra simulation results of 32-inch LCD TVs based on the pair of 26- and 32-inch LCD TVs

point; thus, their market diffusion will continue to increase in the future.

#### Performance comparison

The ability of the Bass model and Lotka–Volterra model to predict LCD TV shipments is assessed. The parameters of both models are estimated using quarterly LCD TV shipments from the first quarter of 2003 to the second quarter of 2007. Forecasted quarterly LCD TV shipments from the third quarter of 2007 to the second quarter of 2008 are then compared with actual quarterly shipments. Figures 3–6 compare simulated and actual shipments. The actual shipments versus calculation for the Bass and Lotka–Volterra models are plotted. The forecast results computed by the Lotka–Volterra model have a trend similar to that of real time-series data. Conversely, the Bass model shifts away from the real data. Shipments simulated by the Lotka–Volterra model are closer to actual shipments than those simulated by the Bass model, particularly for 26- and 37-inch LCD TVs.

Moreover, forecasting error for each model is measured by MAPE (Table 3). The comparison results show that the MAPE of the Bass model is two times that of the Lotka–Volterra model for shipments of 37-inch LCD TVs. In addition, the MAPE of the Bass model is also higher for 26-inch LCD TV shipments than that of the Lotka–Volterra model. For 26- and

32-inch LCD TVs, the estimation of shipments by the Lotka–Volterra model is superior to that of the conventional Bass model. Although the MAPE of the Lotka–Volterra model is slightly higher than that of Bass model for 32-inch LCD TVs in the pair of 32- and 26-inch LCD TVs, the trajectory direction of the Bass model deviates from real data from the fourth quarter of 2007 for 32-inch LCD TVs. The comparison results suggest that prediction ability is improved dramatically as mutualism relationship among each size level is considered. We strongly recommended using a competitive diffusion model, such as the Lotka–Volterra model, when analysing LCD TV shipments under a multiple generation structure.

#### Equilibrium points

By substituting the values of  $\alpha_i$ ,  $\beta_i$  and  $\gamma_i$  (Table 2) into Equations 5–7, the values for  $a_i$ ,  $b_i$  and  $c_i$  can be derived (Table 2). Two linear functions for equilibrium analysis can be obtained by inputting the values  $a_i$ ,  $b_i$  and  $c_i$  into Equation 11. Figure 7 shows the equilibrium point for 26- and 32-inch LCD TVs. The two straight lines in Equation 11 intersect in the first quadrant; showing that there exists an equilibrium point for these two series of shipments. Based on coefficients  $a_i$ ,  $b_i$  and  $c_i$ , the equilibrium state does not comply with the Hritonenko and Yatsenko's (1999) stationary conditions. Thus, the unstable trajectory of



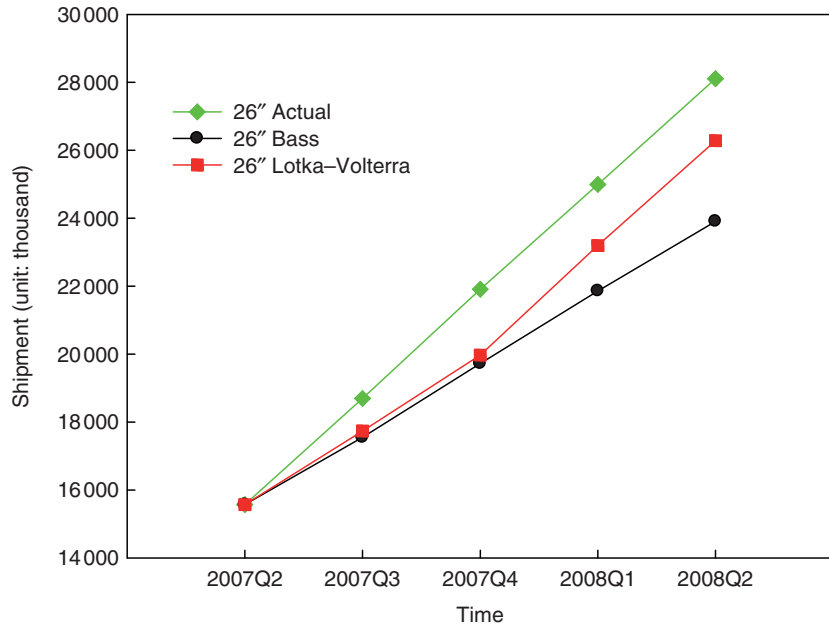


Fig. 4. Comparison among the actual shipments, Bass simulated result and Lotka–Volterra simulated results of 26-inch LCD TVs based on the pair of 26- and 32-inch LCD TVs

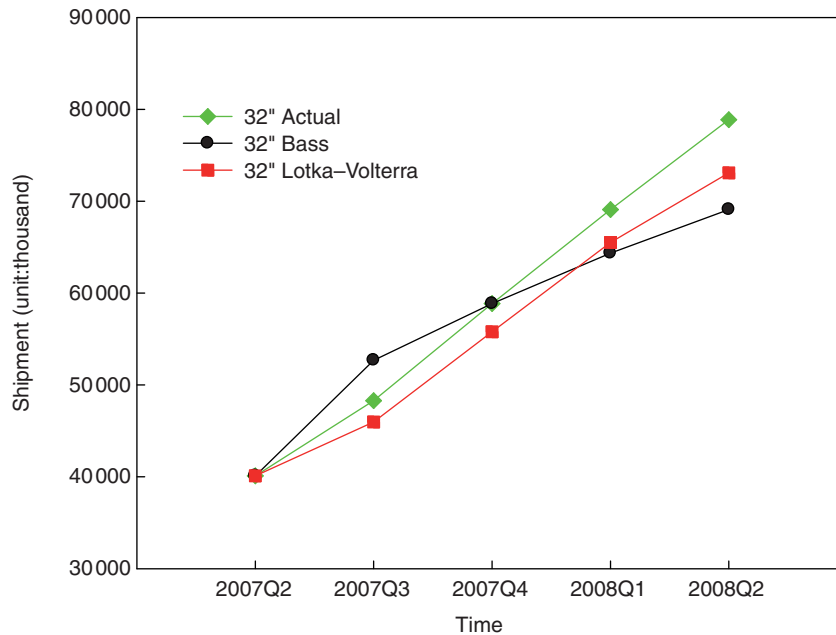


Fig. 5. Comparison among the actual shipments, Bass simulated result and Lotka–Volterra simulated results of 32-inch LCD TVs based on the pair of 32- and 37-inch LCD TVs

shipment unit cannot reach the equilibrium point. Since the shipment trajectory for the following 13 quarters after the second quarter of 2008 is advanced to be predicted by the estimated parameters ( $a_i$ ,  $b_i$  and  $c_i$  in Equation 1) in this investigation, and to be depicted in Fig. 7, so the deviation of future shipment

trend from equilibrium point can be clearly observed in Fig. 7.

The area on the left side of Line 2 represents the region where 26-inch LCD TV shipments will increase ( $dX/dt > 0$ ). Similarly, the area on the bottom of Line 1 represents the region where

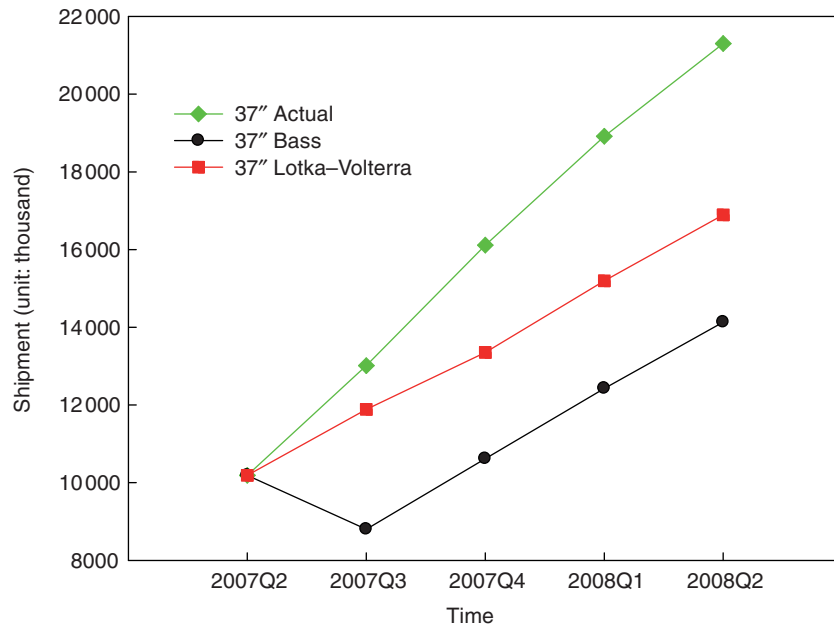


Fig. 6. Comparison among the actual shipments, Bass simulated result and Lotka–Volterra simulated results of 37-inch LCD TVs based on the pair of 32- and 37-inch LCD TVs

Table 3. MAPEs of Bass and Lotka–Volterra models from the third quarter of 2007 to the second quarter of 2008.

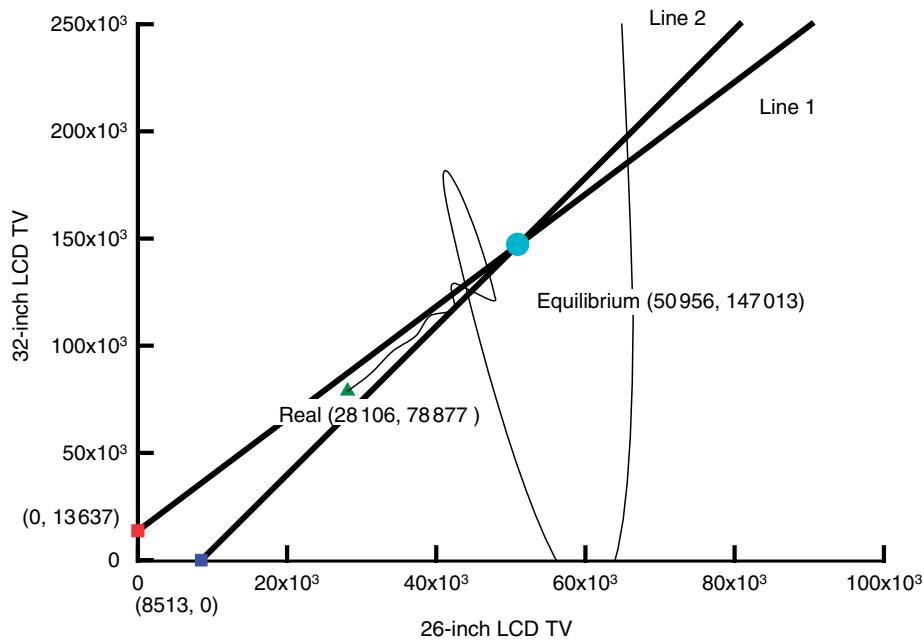
Size level	Bass	Lotka-Volterra	
		26- and 32-inch	32- and 37-inch
26-inch	0.1090	0.0691	
32-inch	0.0711	0.1109	0.0564
37-inch	0.3360		0.1654

Note: This MAPE is calculated by  $MAPE = \frac{1}{n} \sum_{t=1}^n \frac{|Y_t - \hat{Y}_t|}{Y_t}$ , where  $Y_t$  and  $\hat{Y}_t$  represent the realistic and predicted shipment of LCD TV panels at time  $t$ .

32-inch LCD TV shipments will increase ( $dY/dt > 0$ ). For the second quarter of 2008, 28 106 and 78 877 thousand 26-inch and 32-inch LCD TVs were sold, respectively. Those numbers correspond to a point where the two sized LCD TVs have not yet reached their equilibrium point (50 956 and 147 013, respectively). If the equilibrium state complies with the Hritonenko and Yatsenko (1999) stationary conditions, future shipments of 26- and 32-inch LCD TVs will increase and thus the two sized LCD TVs will converge to their equilibrium point. In other words, the market diffusion for both should be still expanding to the equilibrium point. However, their equilibrium does not satisfy with the Hritonenko and Yatsenko (1999) stationary conditions. The future trajectory on Fig. 7 suggests that 26-inch LCD TVs have only retained their market in the next 10

quarters subsequent to the second of 2008. The shipment orbit deviates from the equilibrium point in the eleventh quarter after the second quarter of 2008. Once more and more people own 26-inch LCD TVs, the cumulative shipment units ( $X$ ) approach the saturation levels. According to Equation 1, the limitation effect of the saturated market ( $b_1 * X^2$ ) on the growth rate of 26-inch LCD TV shipment ( $dX/dt$ ) will strongly work and apparently reduce the sales of 26-inch LCD TVs, especially subsequent to the eleventh quarter after the second quarter of 2008.

In addition to the pressure of market saturation, the 26-inch LCD TVs may face competition from 32-inch LCD TVs. The competitive relationships between 26- and 32-inch LCD TVs is commensalism, according to the significantly negative parameters of interaction term in the equation of 32-inch LCD TVs.



**Fig. 7. Equilibrium point between 26- and 32-inch LCD TVs (unit: thousand)**

Notes: Line 1:  $\frac{dX}{dt} = (0.3414147 - 0.000040X + 0.000012Y)X = 0.341417X - 0.000040X^2 + 0.000012XY$

Line 2:  $\frac{dY}{dt} = (0.184977 - 0.000014Y + 0.000036X)Y = 0.184977Y - 0.000014Y^2 + 0.000036YX$

X = shipment of 32-inch LCD TV

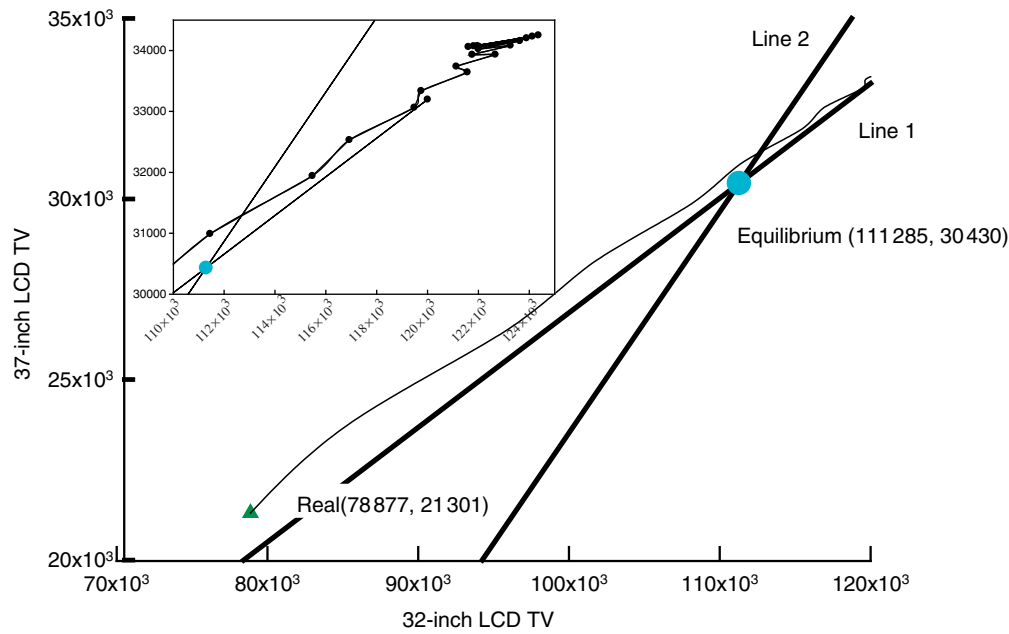
Y = shipment of 26-inch LCD TV.

The consumers who own small LCD TVs are familiar with their functions and, thus, they try to purchase 32-inch LCD TVs. 32-inch LCD TVs are likely to replace the smaller ones. Particularly, in the next eleventh quarter after the second quarter of 2008, 26-inch LCD TVs will completely leave the market and disappear.

Figure 8 shows the equilibrium point based on the relationship between shipments of 32- and 37-inch LCD TVs. The two straight lines in Equation 11 intersect in the first quadrant; thus, these two shipment series also have an equilibrium point. Since their coefficients do not satisfy Hirtonenko and Yatsenko (1999) conditions, the equilibrium point is unstable and their shipment series cannot, as a result, return to the equilibrium point. Since the shipment trajectory for the following 26 quarters after the second quarter of 2008 is advanced to be predicted by the estimated parameters ( $a_i$ ,  $b_i$  and  $c_i$  in Equation 2) in this investigation, and to be depicted in Fig. 8, so the deviation of future shipment trend from their equilibrium point can be clearly observed in Fig. 8.

The area on the right side of Line 1 represents the region where 32-inch LCD TVs will increase ( $dX/dt > 0$ ), while the area on the top of Line 2 represents the region where shipments of the 37-inch

LCD TVs will decrease ( $dY/dt < 0$ ). For the second quarter of 2008, 78 877 and 21 301 of 32- and 37-inch LCD TVs were shipped, respectively. Those numbers correspond to a point where the two LCD TV sizes have not yet reached their equilibrium point (111 285 and 30 430, respectively). If this equilibrium point is satisfied with the stability conditions, sales of 32-inch LCD TVs will increase, whereas sales of 37-inch LCD TVs will decrease and thus the shipment can return to the equilibrium point. However, their coefficients do not satisfy stability conditions (Hritonenko and Yatsenko, 1999). Figure 8 shows that, the 32- and 37-inch LCD TV market is still expanding during the period from the second quarter of 2008 to the fourth quarter of 2011. 32- and 37-inch LCD TVs are regarded as different size levels of LCD TVs from the viewpoints of consumers. When living rooms are sufficiently large, consumers tend to purchase 37-inch LCD TVs; otherwise, 32-inch LCD TVs are more favourable. Due to the persisting demand, 32- and 37-inch LCD TVs have retained their markets and the shipment trend is predicted to depart from the equilibrium point after the fourth quarter of 2009. Conversely, the shipment trend of 37-inch LCD TV fluctuates severely subsequent to the fourth quarter of 2011. The reason can be stated by the following two relations between 32- and 37-inch LCD TVs.



**Fig. 8. Equilibrium point between 32- and 37-inch LCD TVs (unit: thousand)**

Notes: Line 1:  $\frac{dX}{dt} = (0.408574 - 0.000026X + 0.000083Y)X = 0.408574X - 0.000026X^2 + 0.000086XY$

Line 2:  $\frac{dY}{dt} = (0.375977 + 0.000010Y - 0.000006X)Y = 0.375977Y + 0.000010Y^2 + 0.000006YX$

X = shipment of 32-inch LCD TV

Y = shipment of 37-inch LCD TV.

First, the positive interaction coefficient  $c_i$  of the competitor (32-inch LCD TV) in the 37-inch LCD TV Lotka–Volterra model implies that the substitution of 32-inch LCD TV for the 37-inch LCD TVs (Table 2). Prior to the fourth quarter of 2011, the amplitude of the opponent (32-inch LCD TV) reactions to 37-inch LCD TV market ( $c_2 * XY$ ) is not apparent because the opponent (32-inch LCD TV) market share ( $X$ ) is low. Subsequent to the fourth quarter of 2011, 32-inch LCD TV occupies the medium-sized market share, so the technology of 37-inch LCD TV will be deeply eroded by their competitors (32-inch LCD TV). The viewpoints of the consumers are different from those prior to the fourth quarter of 2011. Subsequent to the fourth quarter of 2011, consumers have changed to regard 32-inch and 37-inch LCD TVs as medium-sized LCD TVs, because larger LCD TVs successively enter the markets. The 37-inch LCD TVs hardly provide incremental functions if consumers have owned the 32- LCD TVs. Second, the communalism relation between 32- and 37-inch LCD TVs, which is derived from the significantly negative parameters of interaction term ( $c_i$ ) in the equation of 32-inch LCD TVs, are even getting stronger after the fourth quarter of 2011, in that time the sale growth of 37-inch LCD TVs will greatly stimulate the sale of 32-inch

LCD TVs, while consumers who purchase 32-inch LCD TVs do not necessarily replace their 32-inch LCD TVs with 37-inch LCD TVs.

Due to the aforementioned commensal and substitutive relations, once the 32-inch LCD TVs extend their market, they will initially substitute for the 37-inch LCD TVs. Namely, the subsequent shipment of 37-inch LCD TVs will further be eroded by the increasing 32-inch LCD TV shipments. This shrinkage in the shipment of 37-inch LCD TV will further reduce the subsequent 32-inch LCD TVs due to their commensalism relations. Because of the reduction of 32-inch LCD TVs, the erosion magnitude of 32-inch LCD TVs in 37-inch LCD TVs then becomes smaller. Thus, the shipment of 37-inch LCD TVs will rise again, and further enhance the sale of the 32-inch LCD TVs. As a result, shipments of 32 and 37-inch LCD TVs repeat affecting each other, so their shipment trends fluctuate a lot after the fourth quarter of 2011.

In the Bass model, sales of 37-inch LCD TVs are not corroded by another size level of LCD TVs because the Bass model does not consider the substitution of a new technology for an old technology. In contrast to the Bass model, the amplitude of interaction term,  $c_i$ , in the Lotka–Volterra denotes the interactions between 37- and 32-inch LCD TVs.

If 37-inch LCD TVs cannot keep up with 32-inch LCD TVs in time to satisfy consumers' needs, it will be wiped away. This work can state their severely competitive diffusive process in more detail, which implies that LCD TV manufacturers must increase their product lines by producing various sizes of LCD TVs. Restated, this 'line filing' strategy will enable LCD TV manufacturers to increase profit by selling multiple sizes of LCD TVs. The sale of 26 and 37-inch LCD TVs simultaneously expands the potential market of 32-inch LCD TVs. Moreover, this 'line filing', which maintains the profit through 32-inch LCD TVs, can resist the loss from the disappearance of 26 or 37-inch LCD TV markets and reduces the risk of LCD TV manufacturers. In addition to extending the potential market, the 'line filling' strategy also satisfies dealers who complain about lost sales because of a lack of suitably sized LCD TVs.

#### IV. Conclusions

Previous studies utilized Bass diffusion theory to analyse commodity diffusion. However, such Bass models cannot effectively interpret market evolutions of this commodity as the model ignores inter-level reciprocal effects on the product diffusion process. Thus, this study focuses on LCD TVs, which contain the properties of durable commodities and technological products. The primary purpose of this study is to quantify the relationships among various sizes of LCD TVs using global shipment data.

The Lotka–Volterra model was applied to investigate global LCD TV shipments deeply considering the mutual dependence among various sizes of LCD TVs. This work initially focuses on 32-inch LCD TVs, and investigates the relationships between 32-inch and larger-sized 37-inch LCD TVs or between 32-inch and smaller-sized 26-inch LCD TVs; thus, the reciprocal influence among shipments of these three size levels of LCD TVs can be captured by Lotka–Volterra models.

Analytical results demonstrate that LCD TV shipments will increase, supporting the prevalence of LCD TVs in households. The relationship between 26- and 32-inch LCD TVs or between 32- and 37-inch LCD TVs is generally commensalism, in which 32-inch LCD TV shipments are fundamentally driven by the sales of 26- or 37-inch LCD TVs, while 26 or 37-inch LCD TV shipments are only slightly affected by 32-inch LCD TV sales. These empirical results illustrate that those who purchased 26- or 37-inch LCD TVs will respond to functions of 32-inch LCD TVs; thus, the 'line filling' strategy

enables LCD TV manufacturers to profit by selling various sizes of LCD TVs. The market growth of 37- or 26-inch LCD TVs expands the subsequent sale for 32-inch LCD TVs.

The Lotka–Volterra model is superior to the Bass model in explaining the market dynamics of LCD TVs. The prediction ability is dramatically improved as industrial mutualism among various sizes of LCD TVs was considered. Furthermore, equilibrium analysis reveals that dynamic equilibrium points exist for shipments of the two pairs of LCD TVs; however, these shipments have not yet reached equilibrium. The interactions among various size levels of LCD TVs will influence each other, which leads to the great fluctuations in their sales. If one size level of LCD TVs cannot keep with their opponent (another size level of LCD TVs), the severe competition in LCD TV industry will wipe them away from the market. The findings of the equilibrium analysis suggest LCD TV manufacturers to engage in 'line filing' strategy. The persisting profit through 32-inch LCD TVs can make up for the loss from the disappearance of 26 or 37-inch LCD TV markets.

The framework in this study can be applied to other products that contain mutual dependence, and can accurately forecast the evolution process of products, paving the way for the establishment of efficient product marketing policies. However, the financial crisis in 2008 and 2009 may adversely affect the future markets of LCD TVs and other technological commodities. In further research, potential market size can be specified as a function of macro-economic factors for any financial crisis. Furthermore, future research can adopt the numerical simulation method to compute the parameters of Lotka–Volterra equations. Thus, the forecast capacity among the statistical methods in our models, numerical simulations in future research and collected data can be compared.

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