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Predicting the diffusion of LCD TVs by incorporating price in the extended Gompertz model

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ABSTRACT

In addition to reflecting how price decline stimulates consumption behavior, an effective diffusion model of liquid crystal display televisions (LCD TVs) featured by coexistence of multi-generational LCD TVs could also forecast accurately LCD TV sales under a market segmentation framework. As technological advances have led to a substantial decline in the price of LCD TVs, the diffusive prediction of LCD TVs based on prior conventional models, which neglect how price affects the LCD diffusions, must be biased. Based on anchoring and adjustment theory, this work develops extended Gompertz models that incorporate the consumers' comparison of the initial prices with the later reduced prices to analyze the purchasing decisions of consumers for various sized LCD TVs from psychological perspectives. The effective ranges of market penetration rate are located under which the estimated parameters conform to the theoretical assumptions of product diffusion. Their forecasting accuracy is examined by further comparing prediction errors of the conventional Gompertz model and the extended Gompertz model. Empirical results indicate a significantly positive correlation between price reduction and LCD TV sales. Additionally, the market penetration rate is higher for smaller-sized LCD TVs than for larger-sized ones, implying that smaller-sized LCD TVs have reached market saturation, while larger-sized LCD TVs still have remaining market potential. Furthermore, the comparison results demonstrate that the effectiveness of the extended Gompertz model in predicting future shipment orbits of LCD TVs is superior to that of the conventional Gompertz model, since the extended model incorporates price factors.

1. Introduction

Determining the diffusion of hi-tech products has become increasingly essential to marketing, production, and operational strategies. As hi-tech products, liquid crystal display televisions (LCD TVs) hold numerous advantages over conventional TVs. For instance, LCD TVs are slimmer and lighter, as well as have a higher resolution and a larger screen size than conventional TVs. Moreover, LCD TVs are brighter, have a higher contrast, and consume less power as well [1]. Notably, LCD TVs are rapidly replacing conventional TVs in households [2], explaining why consumers increasingly view LCD TVs as durable products. LCD TVs are both durable products and technological commodities whose prices decline as the technology matures and production expands. Smaller and larger-sized LCD TVs are commercially available. The capital intensive nature of the thin film transistor (TFT)-LCD industry explains why manufacturers must decide when and how they can recover R&D and production costs. Therefore, forecasting the market potential, namely, the total number of potential LCD TV adopters, and future shipments of multi-generational LCD TVs is of worthwhile interest when making investments and operational decisions.

Studies involving multi-generational high-tech products have suggested that next-generation products may replace dynamic random access memory (DRAM) [3]. Previous studies viewed the product characteristics and functions of DRAM and flash memory in various generations as homogeneous, explaining the rapidly diminishing market for previous product generations. In

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contrast to such homogenous products, the attributes and functions of LCD TVs vary across generations. LCD TV purchasers use these TVs in different locations (e.g., public spaces, living rooms and bedrooms) have different size preferences. Consumer demand for various sizes of LCD TVs is typically heterogeneous. Larger-sized LCD TVs are not as commercially available as smaller ones, explaining why the larger ones in successive generations fail to fully replace smaller ones in previous generations. Distinctive consumer groups in favor of different sizes of LCD TVs behave according to the market segmentation hypothesis of Smith [4] and Kotler [5]. The commercial availability of various sizes of LCD TVs simultaneously differs from the generational substitutions of technological products containing a homogeneous property among multiple generations. Forecasting the sales of LCD TVs is biased if a previous substitution model constructed for homogenous technological products. Because academic literature still lacks the research concerning sales forecasting for heterogeneous products, this work presents a novel model to forecast the sales of LCD TVs, which incorporates the qualities of durable products and high-technological commodities, under the market segmentation framework.

Most of the above studies applied the conventional diffusion theory to elucidate market dynamics [6,7]. Bengisu & Nekhili [8] forecasted the trends of 20 emerging technologies by using the conventional Gompertz model. Lee and Lee [9] analyzed the growth patterns of telecommunication services by using the typical logistical S-curve. In the setting of the original growth model, product diffusion is assumed to remain unaffected by prices [10–12]. To our knowledge, above studies fail to explore the market dynamics of specific products characterized as both “durables” and “high-technological commodities” under the market segmentation framework, while considering price effect as well.

However, retail prices of LCD TV panels have decreased as their production has expanded, leading to a decline in the unit cost owing to economies of scale. Given the continuous reduction in retail prices of LCD TV panels, the successive consumers are more encouraged by the favorable responses of consumers having already purchased LCD TVs positively influence potential customers. An immediate reduction in retail prices is likely to cause the diffusive growth of different sizes of LCD TV panels. In particular, the extent of price reductions is greater for larger-sized LCD TV than for smaller ones, explaining why price declines generally accelerate the pace of market saturation for larger-sized LCD TVs at a higher speed than for smaller ones. Therefore, estimating LCD TV diffusion is likely to be biased when using the restrictive Gompertz model because the model disregards price effect. Owing to the lack of empirical evidence on how prices affect sales with different generations coexisting commercially, this work is the first to develop and apply an extended Gompertz model incorporating price factors to address the diffusion patterns of a product with dual property- durable and high-tech products. While relaxing the restrictive assumptions that prices do not impact the LCD TV diffusion to purchase LCD TVs, this work hypothesizes that the diffusion of each generation of LCD TVs is a function of its price reduction. Under this hypothesis, each generation of LCD TVs occupies its own market share independently under market segmentation framework. In particular, the proposed model follows the anchoring and adjustment heuristic findings of Tversky and Kahneman [13]. The anchoring and adjustment heuristic theory of Tversky and Kahneman [13] assumes that consumers regard the initial price of a new style LCD TV, upon its market launch, as the “reference point”. When the price drops, consumers compare the new price with the “reference point”. A more price declines imply a greater inclination of successive adopters to purchase LCD TVs. In other words, deciding to purchase a LCD TV depends on consumers’ comparison of the initial price with the later reduced price around the purchasing time. From such psychological viewpoints of consumers' comparison of the initial price with the later reduced price, this work applies anchoring and adjustment heuristic theory to explore how the price declines of LCD TV increase consumer purchasing inclinations.

In addition to the price effect, this work examines the range of market penetration rate for multi-generational LCD TVs. Calculated through dividing cumulative shipments by market potentials, market penetration rate refers to the number of active LCD TV adoptions within the upper demand bound for LCD TVs. This work estimates the model for various market penetration rates and, then, selects the rate that most accurately forecasts the future shipment orbits for three reasons. First, parameters estimated under various levels of market penetration rates can respond to environmental changes. The economic environment and technology production skills of the hi-tech industry fluctuate continuously. Hi-tech products have a short life cycle, and a breakthrough in product technology affects the market potential of existing products. As mentioned earlier, market penetration rate is calculated by dividing cumulative shipments with market potential, explaining why the market penetration rate fluctuates. That is, a sudden technological breakthrough shrinks the market potential of products originally circulating in the market, subsequently inducing the market penetration rate to rise. Second, the demand and receptiveness of consumers for hi-tech products fluctuate as well, which also increases the market potential and market penetration rate of technological products. For instance, LCD panels have quickly replaced cathode ray tubes (CRTs), subsequently curtailing the potential market size of CRTs and shrinking the market for CRTs. Market prospects for the CRT industry are pessimistic, owing to the development of LCD panel technology. Third, Trappy and Wu [12] also assessed the diffusion of products of a short life cycle with a fluctuating penetration rate. As is widely suggested in academia, a forecasting model should consider the uncertainty of market potential, a feature of short life-cycle products. When the sales volume of LCD TVs is forecasted using the Gompertz curve, the upper limit of the curve represents the market potential for a product. Caution must be taken to include the actual situation when setting the market potential in both optimist and pessimist circumstances in order to forecast the shipments of short life cycle LCD TV [8]. Therefore, estimating the parameters and evaluating the forecasting accuracy under various levels of market penetration rates can accurately forecast the market potential of hi-tech technological products in both a optimist and a pessimist environment, thus providing managerial implication for the TFT-LCD industry, as well as for academia. However, if the proposed model assumes that the economic environments and manufacturing technology skills remain constant and set the potential market size of the LCD TV product as a fixed value, parameters estimated by the proposed nonlinear least squares (NLS) model fail to respond to environmental changes. Therefore, based on statistical simulation, this work estimates parameters based on various levels of

market penetration rates and then identifies the effective ranges of the market penetration rate. The parameter subsequently generated conforms to the theoretical assumptions of product diffusion. Effective levels of market penetration rate allow LCD TV manufacturers not only to evaluate total profits gained from investing capital and resources in LCD TVs, but also to anticipate the time needed to recover R&D and production costs.

This work investigates the dynamic diffusion of 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch, and 46-inch LCD TVs by incorporating time-varying price decline factors into the extended Gompertz model. Effects of price elasticity, and market penetration on LCD TV shipments are systematically analyzed based on statistical examinations. This work also forecasts the future orbits of global LCD TV shipments and, then, compares the accuracy of the conventional Gompertz model with that of the proposed extended Gompertz models. In doing so, whether the proposed model, which identifies price reduction, performs better than the conventional Gompertz model is determined. Analysis results indicate that the Gompertz equation explains cumulative sales increases exponentially over time for multiple generations of LCD TVs. Our results further demonstrate that larger-sized LCD TVs continue to have many potential consumers, while sales for smaller-sized LCD TVs are approaching market saturation. In particular, this model illustrates how reducing the retail price of LCD TVs stimulates the diffusion of LCD TVs. Owing to the statistical significance of the modeled price effect in LCD TV diffusions, the proposed model more accurately forecasts the price impact than the conventional one does.

This work significantly contributes to technology management in several ways. First, this work adopts a market segmentation framework to forecast the sales volume of products as Tsai et al. [14]. This work emphasized the critical role of segmentation in devising marketing strategies aimed at potential adopters, leading to the general consensus that enterprises should coordinate technological, forecasting and marketing strategies concerning consumer segmentation simultaneously. Second, this work attempts to explain the product life cycle of hi-tech products by using the Gompertz curve, because Gompertz curve corresponds to the shipment distribution of hi-tech products. The Gompertz curve can generally be divided into two non-symmetrical parts based on the inflection point; the left-hand section where the curvature is positive before the inflection point and the right-hand section where the curvature is negative after the inflection point. This pattern of Gompertz curve represents a situation in which consumer appeal to hi-tech products creates a tremendous demand for such products during the early stage of the product life cycle. The demand quantity of such products decrease over time as the related hype has diminished. In particular, the left-hand section accounts for a relatively smaller portion of the entire whole graph than the right-hand section does. This phenomenon reflects the fact that the early stage of a product life cycle in which sales grow dramatically persists shorter than the later stage when sales decline. Third, the anchoring and adjustment heuristic theory adopted here illustrates how price affects the purchasing behaviors of LCD TV consumers. Based on psychological viewpoints, the proposed model accentuates the role of consumers in comparing the current price with the initial price at the first launching of LCD TVs. LCD TV diffusions are thus specified as the function of such price comparison in our extended Gompertz model to forecast the global adoptions of multi-generational LCD TVs, which is in contrast to the assumptions in previous studies of no price effect [15–17]. Although previous studies highlight the role of price in determining market dynamics [18–20] in the growth model, products combining the attributes of durables and hi-technological products based on anchoring and adjustment heuristic theory have received little attention. To our knowledge, this work applies for the first time an extended Gompertz model that combines the role of price in the purchasing behaviors of potential consumers to explain the diffusion of a specific commodity with durable and high-tech attributes. Fourth, in addition to simulating the effective ranges of market penetration rates for multi-generational LCD TVs, this work analyzes the adoptive features of LCD TVs under such effective market penetration levels. Unexpected technological advances and fashion trends affect the total adoption number of LCD TVs, thus inducing the market penetration rate variant. Parameter simulation under both optimistic and pessimistic market scenarios allows LCD TV manufacturers to make precise decisions under uncertain economic circumstances, highlight the diffusion characteristics of LCD TVs and review the feasibility of their marketing strategies.

The remainder of this paper is organized as follows. Section 2 provides a background of LCD TV industry. Section 3 summarizes the conventional Gompertz model and extended Gompertz models with the price effects in our research. Section 4 gives the empirical results of coefficient estimations, market potential evaluations, and forecast accuracy. Section 5 provides the additional testing of alternative forecasting models. Finally, conclusions are given in Section 6.

2. Background

Fig. 1 depicts the coexistence of cumulative shipment for 15-inch, 20-inch, 26-inch, 37-inch, 40-inch, 42-inch, and 46-inch LCD TV panels. It is clearly observed from Fig. 1 that the curve of 15-inch and 20-inch LCD TVs changes from being concave upwards (positive curvature) prior to inflection point to concave downwards (negative curvature) subsequent to inflection point. 15-inch and 20-inch LCD TVs nearly approach market saturation, while the curvatures of 40-inch, 42-inch and 46-inch LCD TVs appear positive; briefly, their quarterly shipment volumes still grow increasingly. The slope of shipment curve for 40-inch and 42-inch LCD TVs are still getting steeper with time even after 46-inch LCD TVs have been entered into markets. Since varying household space requirements are associated with different sizes of LCD TVs, the attributes and functions LCD TVs is heterogeneous among various generations. Hence, larger-sized LCD TVs in successive generations hardly substitute for the smaller-sized LCD TVs in previous generations. Distinctive consumer groups prefer different sizes of LCD TVs under market segmentation framework. This coexistence of various sizes of LCD TVs in the market is different from the generation substitutions of technological products that contain homogeneous characteristics among multiple generations.

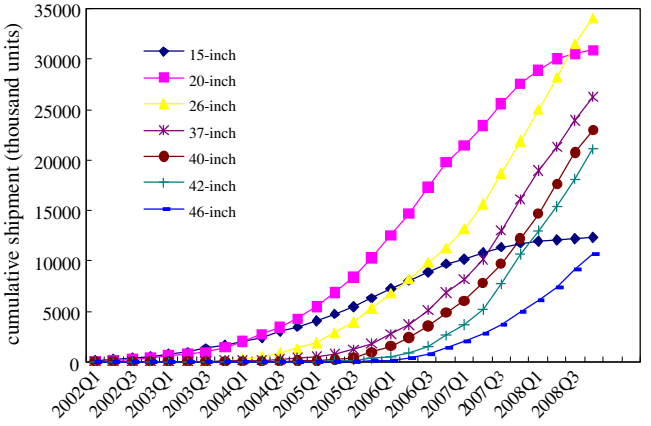


Fig. 1. The distribution of cumulative shipment for 15-inch, 20-inch, 26-inch, 37-inch, 40-inch, 42-inch, and 46-inch LCD TV panels (Data source: DisplaySearch databases). The cumulative shipment of 32-inch LCD TVs is approximately four times of the cumulative shipments of other sizes of LCD TVs by the fourth quarter of 2009. To report the curvature clearly for other sizes of LCD TVs, 32-inch LCD TVs is not included in Fig. 1.

More specially, technology progress and industrial competition of LCD TV manufacturers enhance the cost down of LCD TV production, reducing the price of LCD TVs. The price of various size levels of LCD TVs has been standardized in terms of average prices per square meters and denoted the in Fig. 2. Prices of LCD TV panels decrease with time as their degrees of productivity expands, leading unit cost to drop due to economy of scale. In particular, Fig. 2 exhibits the differential patterns of price reduction among multiple generations of LCD TVs. The accumulated price reduction was 4,805 US dollars (per square meters) for a 26-inch LCD TV from its debut in the fourth quarter of 2004 to the fourth quarter of 2009, while the accumulated price reduction was only 3,088 US dollars (per square meters) for a 15-inch LCD TV from its launch in the first quarter of 2002 to the fourth quarter in 2009. The price reduction for 26-inch LCD TVs is almost one and half times of that for 15-inch LCD TVs. Also, the price of 42-inch and 46-inch LCD TVs keep dropping to the lowest point due to the technical maturity after their appearance in the market. The unit price appeared greater for larger-sized LCD TV panels than smaller ones as the LCD TV panels newly entered the markets. Briefly, only when the productivity of each size level finally reaches the economy of scale, does the unit price of various size levels of LCD TV panels converge to be approximately the same. Combining the shipment pattern in Fig. 1 and price trend in Fig. 2, the diffusive growth of different sizes of LCD TV panels accompany the immediate advent of lower prices. Particularly, the extent of price reductions is more immense for larger-sized LCD TV than for smaller ones, so price declines accelerate the pace of market saturation for larger-sized LCD TVs at higher speed than small ones.

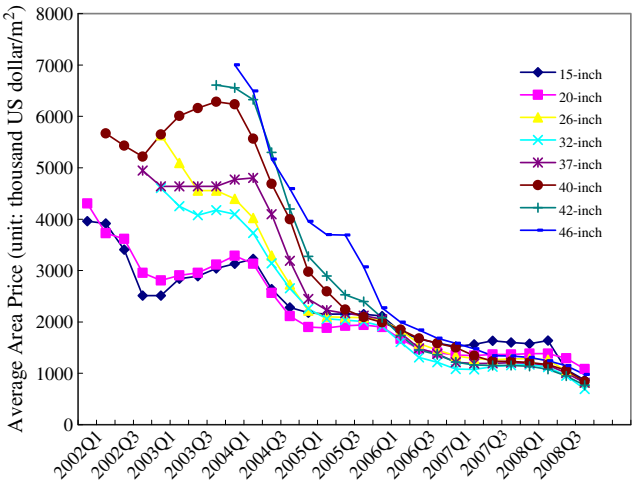


Fig. 2. The distribution of average price per square meters for 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch, and 46-inch LCD TV panels (Data source: DisplaySearch databases).

3. Methodology

3.1. Gompertz Model

The Gompertz model was first used to calculate mortality rates in 1825 and has been widely applied to the technology forecasting [21]. Different from the simple logistic curve, Gompertz curve is not symmetric about the inflection point. The Gompertz model reaches the point which occurs early in the growth trend and is expressed as:

$$y_t = Le^{-ae^{-bt}}, \tag{1}$$

where y_t is the cumulative shipments of LCD TVs. L is the upper bound which means the potential market size and should be set before estimating the parameters a and b. Natural logarithms are used to transform the original Gompertz model to linear equation:

$$Y_t = \ln(\ln(L/y_t)) = \ln(a) - bt. \tag{2}$$

The distribution of Gompertz model follows s-shape curve. The Gompertz curve is not symmetrical about the inflection point which occurs at $t = (\ln(a)/b)$, where $y_t = L/e$. There are two examples for Gompertz function tracking in Figs. 3 and 4 and both figures set upper bound L at 12,392, which means the potential market size for technological products is 12,392 if Figs. 3 and 4 are applied to describe the sale for technological products. The inflection point occurs at 4,757.344 thousand units, at which the curvature changes sign. The curve changes from being concave upwards prior to inflection point to concave downwards subsequent to inflection point. In brief, the curvature is positive before the inflection point, while negative after the inflection point. The features of Gompertz curve properly explains the life cycle of high-technology products. At the beginning stage when high-technology products go on shelves, consumers flock in to purchase them. Demand quantity for LCD TVs surges, so the marginal growth rate of shipment is thus positive in the early stage of product life cycle. However, as the hype fades, high-technology products have less appeal to consumers, so the demand quantity decreases over time. Thus, the marginal growth rate of shipments turns to be negative, and the cumulative shipments curve tends smooth, whose pattern is the same as the long and smooth tail of the Gompertz curve. In addition, the right-hand asymptote of the Gompertz function is approached much more gradually by the curve than the left-hand asymptote, in contrast to the logistic function in which both asymptotes are approached by the curve symmetrically. The characteristics of Gompertz curve can account for the shipment concentration of high-technology products in the short period at the early stage of product life cycle. Because LCD TVs contain the property of durables and technology products, Gompertz model is employed to forecast the diffusion of LCD TVs in our studies.

Fig. 3 clearly indicates that the change in coefficient b affects the shape yet does not affect the location. In the Gompertz equation, y_t refers to the positive function of coefficient b when both upper bound L and coefficient a are fixed as constants. Also, parameter b denotes the growth rate of the logarithm of the reciprocal of penetration rate $\frac{y_t}{L}$, which indicates the speed by which the cumulative shipment y_t gradually approach market potential L. In Eq. (2) $Y_t = \ln(\ln(L/y_t)) = \ln(a) - bt$,because the operator before parameter b is a minus. This finding suggests that if parameter b is positive, the speed by which the cumulative shipments y_t approach market saturation decreases progressively. According to Fig. 3, when parameter b is positive, the closer the Gompertz curve approaches market potential L implies a slower product diffusion. When the Gompertz curve is used to explain a product shipment, a larger parameter b implies an earlier period that the market reaches saturation; in addition, the curve becomes flatter and closes in to market potential L in later stages. This finding suggests that the speed at which a shipment is made slows down at the end of the product cycle.

Conversely, the change in coefficient a affects the location only and does not affect the shape. Parameter a is the logarithm of the reciprocal of the penetration rate, $\frac{y_t}{L}$. A smaller parameter a implies a larger penetration rate when the product is launched, implying that potential consumers immediately purchase a product upon its market entry. Fig. 4 clearly reveals that y_t refers to the negative function of coefficient a when upper bound L and coefficient b are fixed as a constant in the Gompertz equation. If the market evolutions of LCD TVs are stated using the Gompertz equation, cumulative shipment y_t decreases with parameter a.

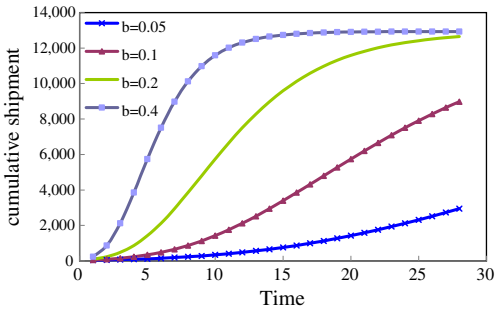


Fig. 3. The incremental effect of the parameter b on the Gompertz curves. The four Gompertz curves set the same value of the upper bound L and the parameter a (L = 12,392 and a = 6). The parameter b affects mainly the magnitude of adoptions per period.

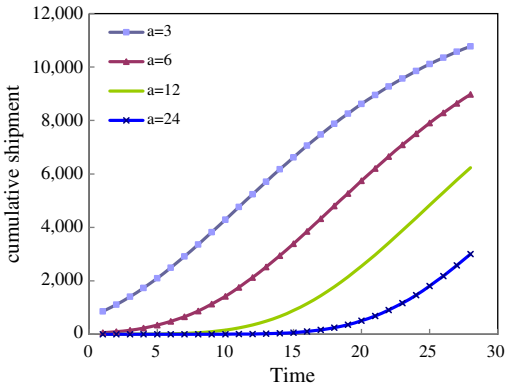


Fig. 4. The incremental effect of the parameter a on the extended Gompertz curves. The four Gompertz curves set the same value of the upper bound L and the parameter b ($L=12{,}392$ and $b=0.1$). The coefficient a affects mainly the intercept of the diffusive curve, and the necessary time to reach the maximum number of adoptions L. The smaller parameter a is, the sooner the diffusive curve reaches L.

From Eq. (1), the Gompertz model has definite limitations (upper bound L), when used to forecast high-technological products with shorter product lifecycles than durable commodities. Because it is almost impossible to estimate the correct upper limit for a new product when it is first introduced to the market. This paper statistically simulates parameters based on different levels of market penetration rates. The market penetration rate of LCD TV is a term generally used to describe the number of active LCD TV adoptions within the upper demand bound for LCD TV products, so it can be calculated by dividing the cumulative shipment volumes by the potential market size. In our study, the parameters are simulated based on the market penetration rate datasets of 10%, 20%, 30%, 50%, 70%, 80%, 90%, and 95%. Then, this investigation determines under what level of market penetration rate the parameters can be reasonably estimated. In theory, the coefficients a and coefficients b are presumed to be positive in Gompertz model concerning the dynamic diffusion of LCD TV panels. If the parameters estimated are negative under a certain market penetration level, the chosen market penetration rate could be inferred to be invalid. Hence, this investigation locates the effective ranges of market penetration rates, under which the coefficients are estimated positive, to be the predictive level of market penetration rate. Next, we calculate the potential market size, which means the upper bound of LCD TV product demand, by dividing the current cumulative shipments by the predictive market penetration rate.

3.2. The Extended Gompertz Model that Incorporates Price Effect

Aforementioned conventional Gompertz models are assumed unaffected by price reductions. However, as LCD TV prices drop, more and more potential consumers are likely to shop for LCD TVs in response to the persuasions of previous adopters. Prior articles emphasized the impact of price on market potential dynamics of products [22–24]. It is inferred that the LCD TV diffusion should be sensitive to price reduction. The assumptions of no price effect in conventional Gompertz model violate the real situations. In practice, the decreasing prices of LCD TVs can strongly encourage the successive consumers to buy LCD TVs. The unit price of LCD TVs declines in high speed after LCD TVs are first to be promoted on sale. In Fig. 2, unit prices of various types of LCD TVs in 2005 decrease to half of that in 2003. Price reduction is the key factor to strengthen the purchasing behaviors of potential LCD TV adopters, so this study relaxes the restrictive assumption of ignoring internal price elasticity.

Both the absolute change in the level of prices and the ratio of price changes are specified as the price decline indicators in our proposed models because this work attempts to explain the consumer receptiveness towards the initial price of a new style of LCD TV by using anchoring and adjustment heuristic theory of Tversky and Kahneman [13]. The extended Gompertz model which incorporates the absolute price changes and the change ratio of prices are defined here as “extended Gompertz models with the absolute price change value” and “extended Gompertz models with the change ratios of prices”. LCD TV diffusion is specified as the function of price decline expressed as Eqs. (3) and (4):

$$b_{1t} = b_1 \exp[\gamma_1 \times (P_0 - P_{t-1})]. \tag{3}$$

$$b_{2t} = b_2 \exp\left[\gamma_2 \times \frac{(P_0 - P_{t-1})}{P_0}\right]. \tag{4}$$

In Eqs. (3) and (4), P_t is the price at time t. We set up the time 0 as the time point when a new style of LCD TV initially launch in the market, so P_0 is the initial price. The styles for LCD TVs are classified by their size, including 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 42-inch and 46-inch LCD TVs. Obviously, the term $(P_0 - P_{t-1})$ and $\frac{(P_0 - P_{t-1})}{P_0}$ in Eqs. (3) and (4) represents the price gap in the interval [0, *t-1*], from the time point when a new style of LCD TV is first to be promoted on sale ($t=0$) to time (*t-1*). Because price reductions enhance the growth rate of LCD TV consumptions, the coefficient b_{1t} and b_{2t} varies with LCD TV panel prices over time and is stated as a function of price reduction during period (*t-1*). The parameters of price elasticity γ_1 *and* γ_2 denote the

marginal effect of price reduction on the sales growth of LCD TVs. For this reason, we put the Eqs. (3) and (4) into Eq. (2) and it can be rewritten as Eqs. (5) and (6):

$$y_t = Le^{-a_1 e^{-b_1 \exp\left[\gamma_1 \times (P_0 - P_{t-1})\right]t}}. \tag{5}$$

$$y_t = Le^{-a_2 e^{-b_2 \exp\left[\gamma_2 \times \frac{(P_0 - P_{t-1})}{P_0}\right]t}}. \tag{6}$$

Natural logarithms are used to transform the conventional Gompertz model to linear equation:

$$Y_t = \ln(\ln(L/y_t)) = \ln(a_1) - b_1 \exp[\gamma_1 \times (P_0 - P_{t-1})]t. \tag{7}$$

$$Y_t = \ln(\ln(L/y_t)) = \ln(a_2) - b_2 \exp\left[\gamma_2 \times \frac{(P_0 - P_{t-1})}{P_0}\right]t. \tag{8}$$

Eqs. (5) to (8) explain the LCD TV shipments during time period t by using the product's price gap in the interval [0, *t-1*]. Restated, during period t, consumers have already observed the price decline from period 0 to period (t-*1*), explaining why they decide to purchase a LCD TV during period t. With such an adjustment, shipment volumes of LCD TV during period t do not affect the margin of the price decline during period *t-1*, thus excluding the endogeneity problem with the model.

Both the absolute change in the level of prices and the ratio of price changes are specified as the price decline indicators in our proposed models because this work attempts to explain the consumer receptiveness towards the initial price of a new style of LCD TV by using anchoring and adjustment heuristic theory of Tversky and Kahneman [13]. Fig. 5 denotes that the coefficients of price affect the shape. The positive price elasticity coefficient illustrates how the price decline accelerates the diffusions of LCD TV panels. Greater price elasticity coefficient represents larger impact of price decline on consumers' purchasing decisions, so it is clearly observed that price elasticity coefficients are increasing with LCD TV diffusion.

3.3. Forecasting

The forecasting accuracy of "extended Gompertz models with the absolute price change value" , "extended Gompertz models with the ratios of price changes" and conventional Gompertz models are compared in this section. Our sampled data is divided into two periods; one is the training period and the other is the test period. All the prediction models are developed by using the training sample, which ranges from the initial periods for various sizes of LCD TVs in our sample to the fourth quarter in 2008, and their levels of accuracy are compared with the test sample from the first quarter of 2009 to the fourth quarter of 2009. We apply the estimated parameters calculated from training sample to evaluate shipment orbits in test sample.

To verify whether the extended Gompertz model performs better than conventional Gompertz model, the accuracy comparison of the forecasting orbit in test sample is conducted between Gompertz model and our extended Gompertz models incorporating price factors. As for the prices used in the extended Gompertz models to predict cumulative shipments during the test period, three price indicators are adopted: 1. the last known real price during the training period, i.e. the price in the fourth quarter of 2008; 2 the actual prices from the first to the fourth quarter of 2009; and 3. the estimated price computed by the price

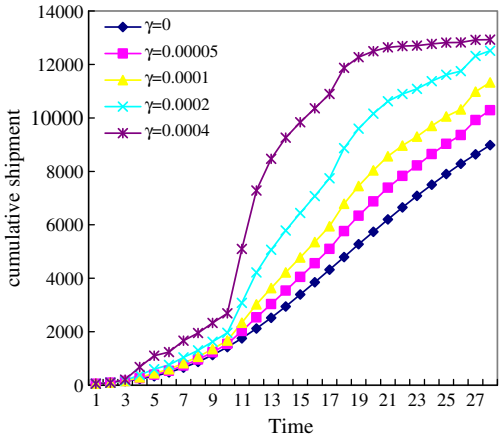


Fig. 5. The incremental effect of the price elasticity coefficients γ on the extended Gompertz curves. The five extended Gompertz curves set the same values of the upper bound L, the parameter a and the parameter b ($L = 12{,}392$, $a = 6$ and $b_1 = 0.1$). In the situation of price declines, $(P_0 - P_t) > 0$, the positive price elasticity coefficient γ enlarges the coefficient b_t . Thus, the slope of the Gompertz model considering price reductions ($\gamma > 0$) is higher than that of the conventional Gompertz model ($\gamma = 0$). The greater the price elasticity coefficient γ is, the faster the sale volumes reach the maximum L.

prediction model (Eq. (9)) which is constructed with data in the training period from the first quarter of 2002 to the fourth quarter of 2008. The price reduction prediction model can be expressed as Eq. (9):

$$(P_0 - P_t) = \alpha + \beta t \tag{9}$$

In Eq. (9), price decline is time-variant. After the accuracy between conventional and extended Gompertz models as well as the collected data is compared and validated in the test sample, this research verifies whether the extended Gompertz model, which specifies the price factors, performs better than the conventional one. We choose mean absolute percentage error (MAPE), mean absolute deviation (MAD), and the root mean squared error (RMSE) of the cumulative quarterly shipments in the test sample to compare the forecasting capability of the modified model with the conventional one. The calculated errors could manifest the results which method is more efficient. The MAPEs are computed by $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t - \hat{Y}_t|}{Y_t}$. The MADs are computed by $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t - \hat{Y}_t\right|$. The RMSEs are computed by $RMSE = \sqrt{\frac{\sum_{t=1}^{n}\left(Y_t - \hat{Y}_t\right)^2}{n}}$.

Table 1
The parameter estimation for the extended Gompertz models with the absolute price change value under the market penetration rate levels of 70%, 80%, 90%, and 95% for various size of LCD TVs.

Size	Penetration Rate	70%		80%		90%		95%	
		Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
15	a_1					4.9936	15.18***	5.0290	10.59***
	b_1					0.1038	9.68***	0.0953	6.97***
	γ_1		X		X	0.0001	3.69***	0.0002	4.28***
	L					13,650		12,932	
	R^2					0.9912		0.9855	
	$Adj\ R^2$					0.9904		0.9843	
20	a_1	6.4206	28.82***	6.2287	19.35***	5.8719	10.36***	5.4478	7.05***
	b_1	0.0741	11.22***	0.0651	7.44***	0.0475	3.67***	0.0307	2.19**
	γ_1	0.0001	5.02***	0.0002	5.25***	0.0004	4.32***	0.0005	3.74***
	L	44,063		38,555		34,271		32,467	
	R^2	0.9969		0.9945		0.9846		0.9698	
	$Adj\ R^2$	0.9966		0.994		0.9834		0.9673	
26	a_1			7.8838	8.15***	6.2452	7.19***	5.2715	6.93***
	b_1			0.0758	2.66***	0.0229	1.52	0.0052	1.05
	γ_1		X	0.0001	1.73*	0.0004	2.93***	0.0008	3.64***
	L			42,526		37,801		35,812	
	R^2			0.9801		0.9608		0.9427	
	$Adj\ R^2$			0.9781		0.9569		0.9370	
32	a_1	9.6457	11.34***	9.1330	1.1342	8.1342	5.97***	7.1369	5.28***
	b_1	0.0802	4.27***	0.0649	0.0232	0.0376	1.67*	0.0164	1.12
	γ_1	0.0001	2.31**	0.0002	0.000092	0.0004	2.46**	0.0006	2.62***
	L	143,145		125,252		111,335		105,475	
	R^2	0.9871		0.9756		0.9519		0.9149	
	$Adj\ R^2$	0.9858		0.9732		0.9471		0.9064	
37	a_1	7.0139	14.37***	6.4754	12.51***	5.8733	10.39***	5.3623	9.07***
	b_1	0.0225	2.93***	0.0130	2.16**	0.0048	1.43	0.0011	0.97
	γ_1	0.0004	4.94***	0.0006	4.97***	0.0009	4.86***	0.0013	4.74***
	L	37,465		32,781		29,139		27,605	
	R^2	0.983		0.9753		0.9611		0.9467	
	$Adj\ R^2$	0.9814		0.9729		0.9574		0.9416	
40	a_1	8.4939	19.12***	7.980949	17.3***	7.4600	13.92***	7.0802	11.28***
	b_1	0.0115	3.13***	0.006368	2.48**	0.0024	1.73*	0.0008	1.23
	γ_1	0.0005	7.18***	0.000649	7.34***	0.0009	6.97***	0.0011	6.39***
	L	32,783		28,685		25,498		24,156	
	R^2	0.9857		0.9812		0.9713		0.9586	
	$Adj\ R^2$	0.9844		0.9796		0.9688		0.955	

Notes: 1.*Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. The measurement unit of potential market size L is thousand units.
4. Because market penetration rate in the fourth quarter of 2008 is equal to the proportion of cumulative shipment in the fourth quarter of 2008 to the potential market size, market potential L can be calculated by dividing the cumulative shipments with the market penetration rate.

3.4. Sample and Data

The units of global quarterly shipment of LCD TV panels and the prices of global LCD TV panels in this study are obtained from DisplaySearch databases. According to the definition of the DisplaySearch database, the global shipments and shipment price refer to shipments from all LCD TV panel manufacturers in the world and the average price of their shipment price. The global LCD TV panel shipments data include all countries. The "price" is defined as the average price of the quoted price from all LCD TV panel manufacturers in the world, including taxes and transportation costs. The period, which contains 32 quarters in our sample, ranges from the first quarter in 2002 to the fourth quarter in 2009. Because various sizes (15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch and 46-inch) of LCD TV begin to be available to the market in different periods, the actual units of shipment are collected from the first quarter in 2002, the first quarter in 2002, the first quarter in 2003, the first quarter in 2003, the fourth quarter in 2002, the second quarter in 2002, the fourth quarter in 2003, and the first quarter in 2004 for 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch and 46-inch LCD TVs, respectively. Therefore, we contain 32, 32, 28, 28, 29, 31, 25 and 24 observations for 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch and 46-inch LCD TVs, respectively.

4. Results and Discussion

4.1. The Results of Parameter Estimation

We use the actual market and price data of 15-inch, 20-inch, 26-inch, 32-inch, 37-inch, 40-inch, 42-inch and 46-inch LCD TV panels to fit the extended Gompertz model (Eqs. (5) and (6)) to optimize the model parameters of each size of LCD TV panels (Tables 1 to 4). The effective ranges of market penetration rate are located under which the estimated parameters conform to the theoretical assumptions of product diffusion. Theoretically and practically, the diffusion of new product contains non-negative intercept and growth rates of LCD TV diffusion in extended Gompertz model ($a_1, a_2 > 0$ and $b_1, b_2 > 0$). According to the statistically results of parameter estimation, the coefficients are estimated positive under 95% market penetration rate for 15-inch LCD TVs. The coefficient signs of intercept and growth rates are also positive as the market penetration rate is higher than 70% for 20-inch and 32-inch LCD TVs, implying the sale of smaller-sized LCD TV is almost close to the upper limit of the market size. On the other hand, the coefficients are theoretically valid under the low level of market penetration rates for larger-sized LCD TV panels. The effective market penetration rate is higher for smaller-sized LCD TVs than for larger-sized ones, implying that smaller-sized LCD

Table 2
The parameter estimation for the extended Gompertz models with the absolute price change value under the market penetration rate levels of 10%, 20%, 30% and 50% for 37-inch, 40-inch, 42-inch, and 46-inch LCD TVs.

Size	Penetration rate	10%		20%		30%		50%	
		Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
37	a_1					8.9227	33.52***	8.0421	20.21***
	b_1					0.0510	9.44***	0.0409	5.24***
	γ_1		X		X	0.0001	5.17***	0.0002	4.97***
	L					87,418		52,451	
	R^2					0.9963		0.9918	
	$Adj\ R^2$					0.9959		0.991	
40	a_1	12.7049	32.69***	11.8623	29.15***	11.2133	25.47***	9.8232	20.61***
	b_1	0.0449	9.76***	0.0442	8.81***	0.0410	7.41***	0.0271	4.72***
	γ_1	0.0001	4.52***	0.0001	5.49***	0.0002	5.89***	0.0002	6.32***
	L	229,485		114742		76,495		45,897	
	R^2	0.9939		0.9942		0.9935		0.9905	
	$Adj\ R^2$	0.9934		0.9937		0.9929		0.9897	
42	a_1	9.6664	56.94***	8.8711	53.36***				
	b_1	0.0179	5.61***	0.0143	5.34***				
	γ_1	0.0003	8.32***	0.0003	9.92***		X		X
	L	211,010		105505					
	R^2	0.998		0.998					
	$Adj\ R^2$	0.9977		0.9977					
46	a_1					10.8302	42.83***	9.9480	39.07***
	b_1					0.0459	8.12***	0.0312	6.89***
	γ_1		X		X	0.0002	8.07***	0.0002	10.63***
	L					35,285		21,171	
	R^2					0.9988		0.9987	
	$Adj\ R^2$					0.9986		0.9985	

Notes: 1. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. The measurement unit of potential market size L is thousand units.
4.Regarding LCD TVs whose size is equal to or smaller than 32-inch, the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such low market penetration rate level (10%, 20%, 30% and 50%). Thus, only the parameter estimation of larger-sized LCD TVs simulated under low level of penetration rate are disclosed in this table.

Table 3
The parameter estimation for extended Gompertz models with the change ratios of prices under the market penetration rate levels of 70%, 80%, 90%, and 95% for various size of LCD TVs.

Size	Penetration rate	70%		80%		90%		95%	
		Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
15	a_2			5.1760	19.99***	5.2893	13.80***	5.3281	10.10***
	b_2			0.1195	12.89***	0.1167	9.76***	0.1072	7.44***
	γ_2		X	0.0413	0.41	0.3492	2.58***	0.6654	3.72***
	L			15356		13650		12931	
	R^2			0.9923		0.9886		0.9831	
	$Adj\ R^2$			0.9917		0.9877		0.9817	
20	a_2	6.6304	23.79***	6.4659	16.54***	6.0809	9.92***	5.5354	7.48***
	b_2	0.0799	9.22***	0.0705	6.39***	0.0499	3.55***	0.0294	2.33**
	γ_2	0.4754	3.42***	0.8162	4.02***	1.4977	4.02***	2.3751	4.10***
	L	44,063		38,555		34,271		32,467	
	R^2	0.9955		0.9925		0.9831		0.9711	
	$Adj\ R^2$	0.9951		0.9919		0.9816		0.9687	
32	a_2	9.0457	14.49***	8.2774	11.56***	7.2053	9.82***	6.4158	9.22***
	b_2	0.0604	4.53***	0.0397	3.19***	0.0164	2.20**	0.0057	1.74*
	γ_2	0.9486	3.71***	1.5602	4.21***	2.7740	5.04***	4.1698	5.96***
	L	143,145		125,252		111,335		105,475	
	R^2	0.9902		0.9832		0.9720		0.9637	
	$Adj\ R^2$	0.9892		0.9815		0.9692		0.9600	
37	a_2	7.0046	16.53***	6.5374	15.03***	5.9933	13.34***	5.5841	12.35***
	b_2	0.0183	3.14***	0.0107	2.57**	0.0041	2.00**	0.0013	1.66*
	γ_2	2.2921	5.95***	3.0719	6.46***	4.4318	7.19***	5.9294	7.97***
	L	37,465		32,781		29,139		27,605	
	R^2	0.9854		0.9813		0.9755		0.9716	
	$Adj\ R^2$	0.984		0.9795		0.9732		0.9688	
40	a_2	8.6167	22.11***	8.1871	21.08***	7.7015	18.67***	7.3322	16.44***
	b_2	0.0098	3.61***	0.0058	3.22***	0.0024	2.64***	0.0009	2.17**
	γ_2	2.9753	8.92***	3.7227	9.89***	4.9536	10.74***	6.2369	11.11***
	L	32,783		28,685		25,498		24,156	
	R^2	0.9885		0.9872		0.9844		0.9811	
	$Adj\ R^2$	0.9875		0.9861		0.9830		0.9794	
42	a_2	8.1718	20.49***	7.6019	14.67***	6.6696	10.53***	5.9648	8.74***
	b_2	0.0602	8.85***	0.0500	5.72***	0.0308	3.21***	0.0163	2.09**
	γ_2	1.1059	8.55***	1.4434	7.03***	2.1823	5.77***	3.0769	5.20***
	L	30,144		26,376		23,445		22,211	
	R^2	0.9942		0.9894		0.9778		0.9626	
	$Adj\ R^2$	0.9935		0.9881		0.9752		0.9582	
46	a_2	11.2691	21.24***	10.8211	14.15***	10.0373	8.26***	9.2320	5.78***
	b_2	0.1105	15.53***	0.1048	10.13***	0.0913	5.50***	0.0755	3.46***
	γ_2	0.5937	7.85***	0.7753	6.58***	1.0954	4.92***	1.4461	3.99***
	L	15,122		13,231		11,761		11,142	
	R^2	0.9957		0.9916		0.9788		0.9593	
	$Adj\ R^2$	0.9952		0.9906		0.9761		0.9542	

Notes: 1. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. The measurement unit of potential market size L is thousand units.
4. Because market penetration rate in the fourth quarter of 2008 is equal to the proportion of cumulative shipment in the fourth quarter of 2008 to the potential market size, market potential L can be calculated by dividing the cumulative shipments with the market penetration rate.

TVs have reached market saturation, while larger-sized LCD TVs still have remaining market potentials. Remaining market potential is defined as market potential minus cumulative shipment units. Regarding the *t*-statistic test results, all the coefficients, including price elasticity coefficients are statistically significantly at the 10% level, suggesting the enhancement of price decline on LCD TV diffusions.

Referring to the goodness of fit analysis, the adjusted R^2 is higher for smaller-sized LCD TV panels at the high level of market penetration rate while it is higher for larger-sized LCD TV panels at the low level of market penetration rate for both conventional Gompertz and extended Gompertz models. This concludes that smaller-sized LCD TVs reach the market saturation, while the larger-sized LCD TVs contain a remaining market potential. Comparing the adjusted R^2 of conventional Gompertz model (Eq. (1)) with that of the extended Gompertz models, which incorporate the impact of price reductions (Eq. (5) and (6)), the latter is higher than the former. The extended Gompertz model performs superior to the conventional Gompertz model in predicting LCD TV diffusions.

In regards to the extended Gompertz model incorporating price factors, price elasticity coefficients (γ_1 and γ_2 are all positive for multi-generational LCD TVs. To our expectation, price decline of LCD TV stimulates consumption caused by the price declines will accelerate the diffusions of LCD TV panels. The empirical results suggest that previous consumers who have adopted LCD TVs

Table 4
The parameter estimation for extended Gompertz models with the change ratios of prices based on the market penetration rate levels of 10%, 20%, 30% and 50% for 37-inch, 40-inch, 42-inch, and 46-inch LCD TVs.

Size	Penetration Rate	10%		20%		30%		50%	
		Coefficient	t-value	Coefficient	t-value	Coefficient	t-value	Coefficient	t-value
37	a_2	10.2867	41.85***	9.5155	34.43***	8.9649	27.98***	7.9659	20.19***
	b_2	0.0539	10.40***	0.0532	8.92***	0.0494	7.19***	0.0353	4.62***
	γ_2	0.2188	2.09**	0.4272	3.43***	0.6525	4.15***	1.2785	5.04***
	L	262,255		131,127		87,418		52,451	
	R^2	0.9964		0.9960		0.9963		0.9912	
	$Adj\ R^2$	0.9961		0.9957		0.9959		0.9903	
40	a_2	12.7962	26.07***	11.8240	23.32***	11.0242	21.83***	9.6202	21.9***
	b_2	0.0446	7.18***	0.0413	6.26***	0.0352	5.39***	0.0205	4.26***
	γ_2	0.5008	3.36***	0.7540	4.29***	1.0577	5.05***	1.8948	6.86***
	L	229,485		114,742		76,495		45,897	
	R^2	0.9914		0.9914		0.9909		0.9898	
	$Adj\ R^2$	0.9906		0.9907		0.9902		0.9889	
42	a_2	10.7208	40.36***	10.0279	41.84***	9.5920	43.27***	8.9209	36.18***
	b_2	0.0621	15.73***	0.0667	17.75***	0.0688	19.21***	0.0684	16.57***
	γ_2	0.3068	4.61***	0.4168	6.96***	0.5182	9.24***	0.7466	11.17***
	L	211,010		105,505		70,336		42,202	
	R^2	0.9953		0.9968		0.9976		0.9976	
	$Adj\ R^2$	0.9948		0.9965		0.9974		0.9973	
46	a_2	13.3959	26.93***	12.7892	26.58***	12.4197	27.4***	11.8677	29.37***
	b_2	0.0956	15.7***	0.1037	16.99***	0.1084	18.51***	0.1128	21.14***
	γ_2	0.0080	0.12	0.1025	1.56	0.1851	3.06***	0.3589	6.63***
	L	105,855		52,927		35,285		21,171	
	R^2	0.9917		0.9937		0.9952		0.9970	
	$Adj\ R^2$	0.9906		0.9929		0.9946		0.9966	

Notes: 1. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.
2. The measurement unit of potential market size L is thousand units.
3. Regarding LCD TVs whose size is equal to or smaller than 32-inch, the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such low market penetration rate level (10%, 20%, 30% and 50%). Thus, only the parameter estimation of larger-sized LCD TVs simulated under low level of penetration rate are disclosed in this table.

are more inclined to recommend potential consumers to successively buy LCD TVs as the prices of LCD TV panels drop. The comparison of the initial prices with the later reduced prices during period $(t\text{-}1)$ may induce successive consumers to purchase the LCD TVs. Purchasing a LCD TV based on the absolute change in the level of prices or the ratios of price declines verify that consumers' purchasing decisions follows Tversky and Kahneman's [13] anchoring and adjustment theory.

We further apply Eqs. (3) and (4) to calculate the time-variant coefficient b_t over time for multi-generational LCD TV panels. At 95% market penetration rate level, the pattern of time-variant growth coefficients of the extended Gompertz model with absolute price change values and the extended Gompertz with ratios of price changes (b_{1t} and b_{2t}) are denoted in Figs. 6 and 7, respectively. The result shows that the coefficients increase gradually for multi-generational LCD TV panels. Combining the price trend depicted in Fig. 2 and the growth fluctuations denoted in Figs. 6 and 7, the price reductions of LCD TV panels increased dramatically for multiple generations of LCD TVs surrounding 2004, so the diffusive growth rate is computed to drop. After 2004, the adoptions of LCD TV expand due to continuous price reduction. The decrease in price will promote the LCD TV sales. We then take the diffusion of 32-inch LCD TVs as an example, the price of the 32-inch of LCD TV panel has declined from 4,606 US dollars (per square meters) in the first quarter in 2003, the time when 32-inch LCD TV was newly available to the market, to 694 dollars (per square meters) in the fourth quarter in 2008. Meanwhile, the quarterly shipments of LCD TV panels have grown from 4,000 to more than 10,000,000 according to the statistics in DisplaySearch database. Consistent with our expectation, causal relations are also observed between LCD TV panel shipments and price reductions.

From Tables 1 to 2, we can also discover that the smaller-sized LCD TV panel's coefficient of growth rate (b_1 and b_2) is greater than the larger ones. Besides, the price elasticity coefficient (γ_1 and γ_2) of the larger-sized LCD TV panel has been found greater than that of the smaller ones. The diffusion of larger-sized LCD TV panels is more sensitive to the price reduction than smaller-sized ones. In Fig. 2, the price reduction is 4,805 US dollars (per square meters) from the first quarter in 2003, the time when a 26-inch LCD TV begins to be promoted on sale, to the fourth quarter in 2009, while the price reduction is only 3,088 US dollars (per square meters) from the first quarter in 2002, the time when a 15-inch LCD TV begins to be promoted on sale, to the fourth quarter in 2009. The price reduction to 26-inch LCD TVs is almost one and half times of that to 15-inch LCD TVs. The higher price elasticity coefficient γ and larger price reduction $(P_0 - P_t)$ enable the diffusion of larger-sized LCD TVs to become more obvious than smaller-sized ones. At 95% market penetration rate, the diffusive growth coefficient b_{1t} increase from 0.1 to almost 0.18 for 15-inch LCD TVs, while increase from 0 to almost 0.18 for 26-inch, 32-inch, 37-inch and 40-inch LCD TVs in the extended Gompertz model with absolute values of price changes. The diffusive growth increases smoothly for 15-inch LCD TVs, while

increases dramatically for LCD TV panels whose size is equal to or more than 26-inch. This suggests that the impact of price reduction on the sale is more profound for the larger-sized LCD TV panels than for the smaller ones. When the price of larger-sized LCD TVs drops, a great number of consumers are able to afford the larger-sized LCD TVs. A greater price reduction accelerates consumers to purchase larger-sized LCD TVs in a greater magnitude. Thus, the time-varying growth rate expands monotonously with the size of LCD TVs. Price reduction enhances the substantial diffusion of larger-sized LCD TV panels, curtailing the time of larger-sized LCD TV panels for reaching the inflection point or upper limit.

4.2. The Results of Forecasting

In this section, the ability of the conventional Gompertz model and our extended Gompertz model to predict LCD TV shipments is assessed. The parameters of both models are estimated by using quarterly LCD TV shipments in the training sample ranging from the initial period to the fourth quarter in 2008. This work chooses the market penetration rates that consistently have the lowest prediction errors among the three price indicators in the extended Gompertz model to depict their cumulative shipments in the test sample. The prediction error of 15-inch, 20-inch, 32-inch, and 46-inch TVs are consistently the lowest under 95%, 95%, 70% and 50% penetration rate among all the market penetration rates. Therefore, the shipments of these four sizes of LCD TVs under these four penetration rate were selected to be simulated by both the extended and conventional Gomprtz models.

Figs. 8 to 11 depict the actual shipments and the simulated shipments, as estimated by the extended and conventional Gomprtz models under 95%, 95%, 70% and 50% market penetration rate for 15-inch, 20-inch, 32-inch, and 46-inch LCD TVs, respectively. Forecasting results by the extended Gompertz models have a trend similar to that of actual time-series LCD TV diffusions. Conversely, the forecasted trend of LCD shipments by the conventional Gompertz model differs from actual shipments. Cumulative shipment units simulated by the extended Gompertz model are closer to actual shipments than those simulated by the conventional Gompertz model.

Forecasted quarterly LCD TV shipments from the first quarter in 2009 to the fourth quarter in 2009 are then compared with actual quarterly shipments. Forecasting errors for each model is then measured by MAPE, MAD, and RMSE. Tables 5 to 10 lists the forecast errors of extended Gompertz model which selects the three price indicators to predict cumulative shipments in the test period: 1. the last known real price, i.e. the price in the fourth quarter of 2008; 2. the estimated prices computed by the extended Gompertz model, and 3. the actual prices in the test period.

Regarding the extended Gompertz model in Table 6 and Table 9, the MAPE, MAD and RMSE is the smallest under 95%, 95%, 70%, 50%, and 30% level of market penetration rate for 15-inch, 20-inch, 32-inch, 37-inch, and 40-inch LCD TVs when actual price in the test period is used to predict shipments in the test period. The empirical results reveal that the extended Gompertz model with absolute change in the level of prices and the extended Gompertz model with the change ratio of prices have similar forecast accuracy. The findings suggest that consumers purchase LCD TVs based on the comparison of the initial price with the later reduced prices, a finding consistent with the anchoring and adjustment theory. Combining the aforementioned results of parameter estimation with the findings of forecasting errors in this section, the market penetration rate has been found diminishing with the size level of LCD TVs. Market penetration rate is high for the smaller-sized LCD TVs while the market penetration rates is low for larger-sized LCD TV panels. This reflects that most larger-sized LCD TVs do not reach the market saturation and still have a remaining market share. In addition, the findings show that 32-inch LCD TV panels contain the greatest market share (143,145 thousand units), implying its mainstream position in TFT-LCD industry. When the houses are large enough, consumers tend to purchase larger-sized LCD TVs in living rooms and 32-inch LCD TVs in bedrooms. In addition to the

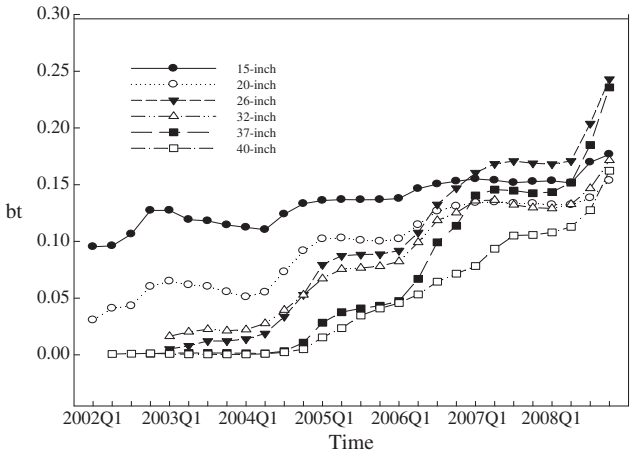


Fig. 6. The time-varying coefficient b_{1t} versus time for extended Gompertz models with the absolute price change value at the 95% market penetration rate. The coefficient b_t is calculated by $b_{1t}=b_1\ \exp[\gamma_1\times(P_0-P_t)]$.

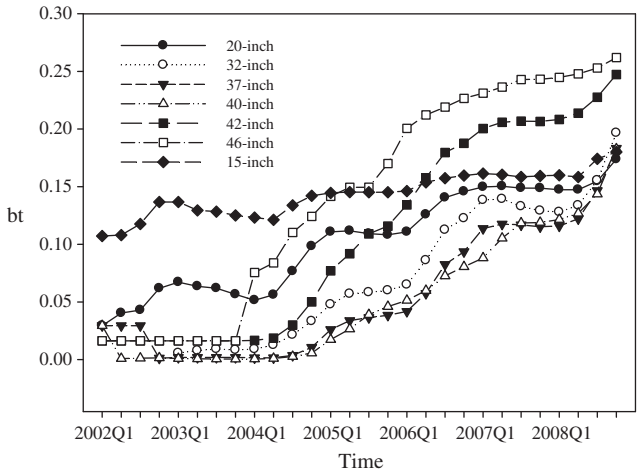


Fig. 7. The time-varying coefficient $b_t$versus time for extended Gompertz models with ratios of price changes at 95% market penetration rate. The coefficient b_t is calculated by $b_{2t} = b_2 \exp\left[\gamma_2 \times \frac{(P_0 - P_t)}{P_0}\right]$.

consumers who live in large houses, 32-inch LCD TVs are also favorable for those who in small houses for putting them in the living rooms. Thus, the potential market size is greatest for 32-inch LCD TVs.

In regard to the prediction ability, MAPE of the conventional Gompertz model is listed in Table 11. The comparison results suggest that the prediction ability is improved dramatically as price reduction is considered for 26-inch and 32-inch LCD TVs. Price elements incrementally validate the predictions of LCD TV panel shipments. We strongly recommend for using a price-related diffusion model, such as the extended Gompertz model, when analyzing LCD TV shipments under a multiple generation structure. Although the predictive ability of the extended Gompertz model is not as good as that of conventional Gompertz model for 15-inch, 37-inch or 42-inch LCD TV panels under the optimal market penetration rate level, the simulated error difference is relatively minor. Martin and Witt [25] explained that the forecasting capacity of a model is "excellent" as MAPE is smaller than 10% (MAPE<10%). Forecasting capacity is "good" as MAPE locates in the interval [10%, 20%] (10%<MAPE<20%). Forecasting capacity is "reasonable" as MAPE is in the interval [20%, 50%] (20%<MAPE<50%). In the view of Martin and Witt [25] criteria, the forecast ability of the extended and conventional Gompertz models is "excellent" in predicting the cumulative shipments of 15-inch and 37-inch LCD TVs. The forecast ability of our extended Gompertz model also maintains to be "good" in predicting the cumulative shipments of 42-inch LCD TVs. The MAPE difference is minor when comparing conventional Gompertz and our extended Gompertz model. Conversely, the forecast ability of the extended Gompertz models with absolute price change values is "good" in predicting the cumulative shipments of 26-inch and 32-inch LCD TVs, while the forecast ability of the conventional Gompertz models is only "reasonable". Since 32-inch LCD TVs are the mainstreams and have the greatest market share in LCD TV industry, the improvement of the extended Gompertz model is worthwhile for LCD TV manufacturers in making investment and production decisions.

5. Additional Testing

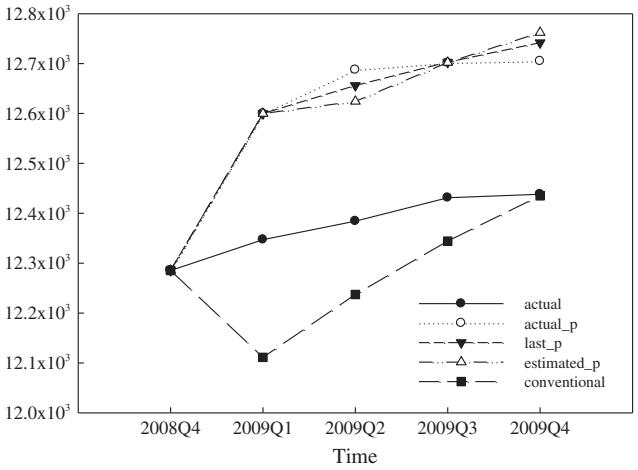
5.1. Multi-generational Gompertz Model Incorporating Price Factors

Previous constructed multi-generational models attempted to identify the substitutions of next generation products for previous generation ones [3, 26]. Owing to that similarly sized LCD TVs tend to replace each other, this work also constructs a multi-generational Gompertz model, which accumulates data of 37-inch, 40-inch, 42-inch and 46-inch LCD TVs to forecast LCD TV shipments. Price reductions are incorporated in specific multi-generational Gompertz models. Multi-generational Gompertz model are expressed as follows:

$$\begin{aligned} S_1(t) &= F_1(t)M_1[1-F_2(t-\tau_2)], \\ S_2(t) &= F_2(t-\tau_2)[M_2 + F_1(t)M_1][1-F_3(t-\tau_3)], \\ S_3(t) &= F_3(t-\tau_3)[M_3 + F_2(t-\tau_2)[M_2 + F_1(t)M_1]][1-F_4(t-\tau_4)], \\ S_4(t) &= F_4(t-\tau_4)[M_4 + F_3(t-\tau_3)[M_3 + F_2(t-\tau_2)[M_2 + F_1(t)M_1]]], \end{aligned} \tag{10}$$

where $S_i(t)$ denote the cumulative sales at period t. M_i refers to market potentials of the ith generation without considering market substitution of multiple generations. Generations of LCD TVs are classified by size. The 37-, 40-, 42-, and 46-inch LCD TVs represent the first, second, third, and fourth generation, respectively. Notably, τ_i refers to the time of introduction of successive product generations. Assume that $\tau_i = 0$ for the first generation. For comparisons of the aforementioned extended Gompertz

a) Extended Gompertz models with the absolute price change value



b) Extended Gompertz models with the change ratios of prices

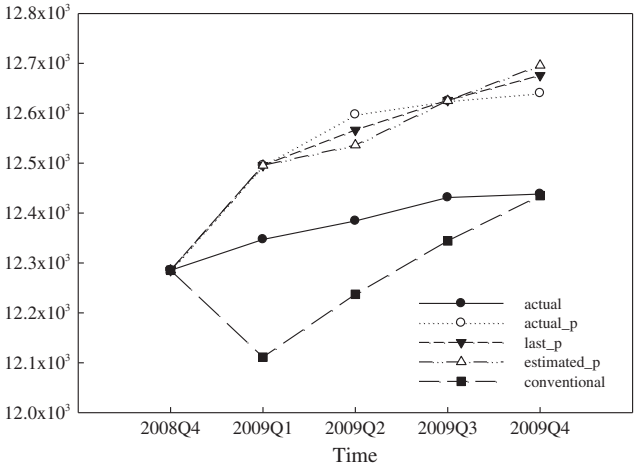


Fig. 8. Comparison of actual shipments of 15-inch LCD TVs with simulated values, by the conventional and extended models at 95% penetration rate level. "Actual," "conventional," "actual_p," "last_p" and "estimated_p" in the figure represent the three price indicators used to predict shipments in test periods: actual price in test prices, the last prices in the training period, and estimated price calculated by price prediction model (Eq. (9)).

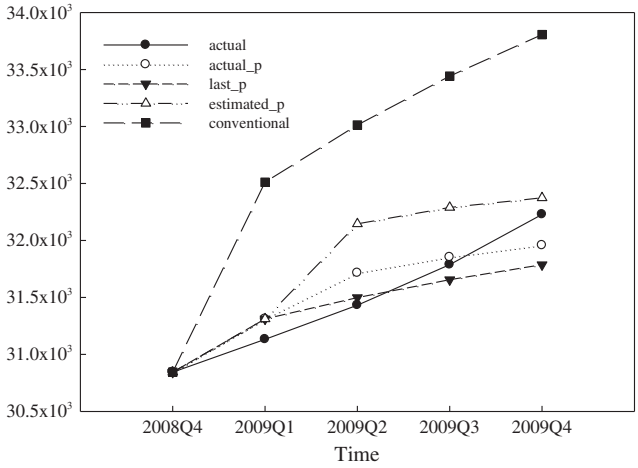
models, both the absolute price changes and the change ratio of prices are utilized to develop multi-generational models. The extended multi-generational Gompertz model which incorporates the absolute price changes and the change ratio of prices are defined here as "multi-generational Gompertz models with the absolute price change value" and "multi-generational Gompertz models with the change ratios of prices". Cumulative percentage of adoptions in multi-generational Gompertz models with the absolute price change value" and "multi-generational Gompertz models with the change ratios of prices" can be written as Eqs. (11) and (12), respectively:

$$F_i(t) = e^{-a_1 e^{-b_1 * \exp\left[\gamma_1 \left(p_{i,0} - p_{i,t-1}\right)\right]^t}}, t \geq 0. \tag{11}$$

$$F_i(t) = e^{-a_2 e^{-b_2 * \exp\left[\gamma_2 \left(\frac{p_{i,0} - p_{i,t-1}}{p_{i,0}}\right)\right]^t}}, t \geq 0. \tag{12}$$

Since such a multi-generational Gompertz model has four more parameter values, the parameter optimization fail to converge when this work utilize the statistical NLS methods to optimize parameters. Our proposed multi-general Gomertz models are estimated using a numerical method. This work iterates genetic algorithm simulations 1,000 times, subsequently generating

a) Extended Gompertz models with the absolute price change value



b) Extended Gompertz models with the change ratios of prices

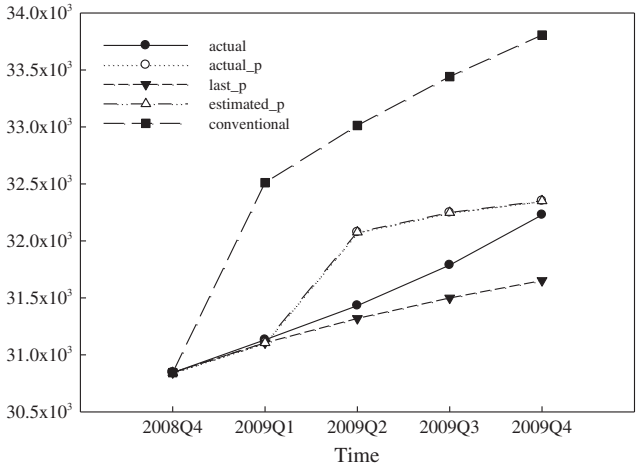


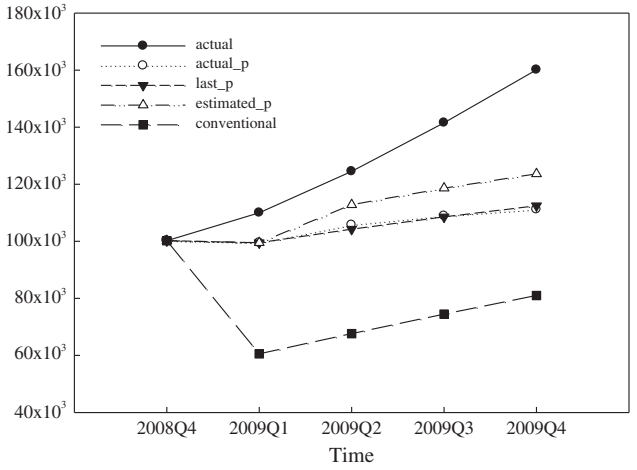
Fig. 9. Comparison of actual shipments of 20-inch LCD TVs with simulated values, by the conventional and extended models at 95% penetration rate level. "Actual," "conventional," "actual_p," "last_p" and "estimated_p" in the figure represent the three price indicators used to predict shipments in test periods: actual price in test prices, the last prices in the training period, and estimated price calculated by price prediction model (Eq. (9)).

different initial values each time and ultimately yielding 1,000 sets of parameters. This work selects parameter values located within one standard deviation among these 1,000 sets of parameters and, then, calculates their means, *t*-statistics and prediction accuracy (Table 12). According to *t*-statistics results, the coefficient of price is significantly positive, indicating that price can increase sales. This observation confirms that price affects shipment volumes, which is the same if predicted with our extended Gompertz model. Additionally, Table 12 lists the outcome of the extended multi-generational Gompertz models. This table reveals that the shipments of 40-inch, 42-inch and 46-inch LCD TVs are overestimated, particularly for the large-sized LCD TVs. Additionally, accuracy analysis of a multi-generational model indicates that the multi-generational model is less accurate than our extended Gompertz model. This difference is largely attributed to the fact that different sizes of LCD TVs are considered as homogeneous products in a multi-generational model; in general, consumers tend to select the optimum size for their living space. According to the market segmentation theory, different sizes of LCD TVs do not tend to substitute one another, explaining why a forecast done with a multi-generational model should not generate as accurate an outcome as our extended Gompertz model.

5.2. Gompertz Models which Adopts Market Potential as the Incremental Parameter

This work also constructs alternative Gompertz models which takes market potential *L* as the incremental parameter instead of estimating market potential by the market penetration rate. As for the extended Gompertz model which takes market potential

a) Extended Gompertz models with the absolute price change value



b) Extended Gompertz models with the change ratios of prices

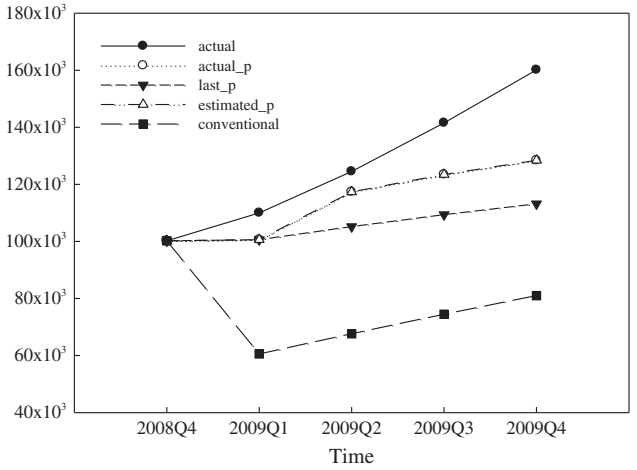
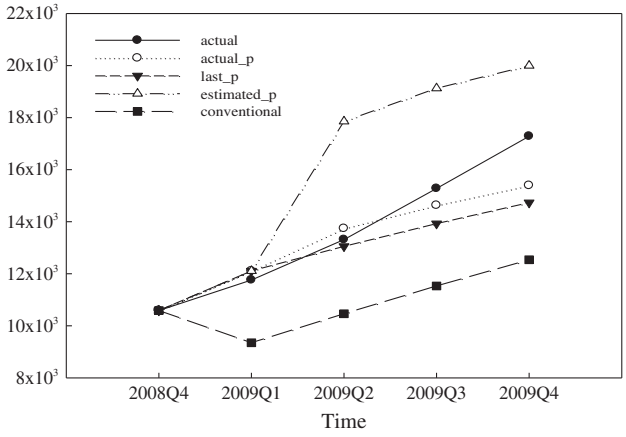


Fig. 10. Comparison of actual shipments of 32-inch LCD TVs with simulated values, by the conventional and extended models at 70% penetration rate level. "Actual," "conventional," "actual_p," "last_p" and "estimated_p" in the figure represent the three price indicators used to predict shipments in test periods: actual price in test prices, the last prices in the training period, and estimated price calculated by price prediction model (Eq. (9)).

L as an incremental parameter, the NLS statistical method generally has difficulty in optimizing the parameters of extended Gompertz equations. Statistical NLS optimization methods fail to estimate the model parameters of the extended Gompertz model, except for the 46-inch LCD TV data. Although the parameter optimization can converge for 46-inch LCD TV data, the estimated parameter value is unacceptable. The estimated market potential parameter of the 46-inch LCD TV is 591,401 thousand units. The market penetration rate is only 1.01% in the last quarter of 2008, when this work uses this estimated market potential of 591,401 thousand units to calculate the market penetration rate. These estimated results contradict the actual circumstances in the LCD TV panel industry where the market is nearly saturated and supply has exceeded demand in recent years. As for the conventional Gompertz model, only the 40-inch LCD TV data can statistically optimize the parameters of the extended Gompertz model. Although the parameter optimization can converge to estimate parameters for 40-inch LCD TV data, the estimated parameter value is unreasonable as well. The estimated market potential of the 42-inch LCD TV is 827,926 thousand units. The market penetration rate in the last quarter of 2008 is only 0.58% when this work uses this estimated market potential 827,926 thousand units to calculate the penetration rate. These estimated results also fail to reflect actual circumstances in recent years, in which the supply for LCD TVs has exceeded demand. This phenomenon implies that taking market potential *L* as an incremental parameter in the Gompertz model to optimize the parameter would be infeasible.

a) Extended Gompertz models with the absolute price change value



(b) Extended Gompertz models with the change ratios of prices

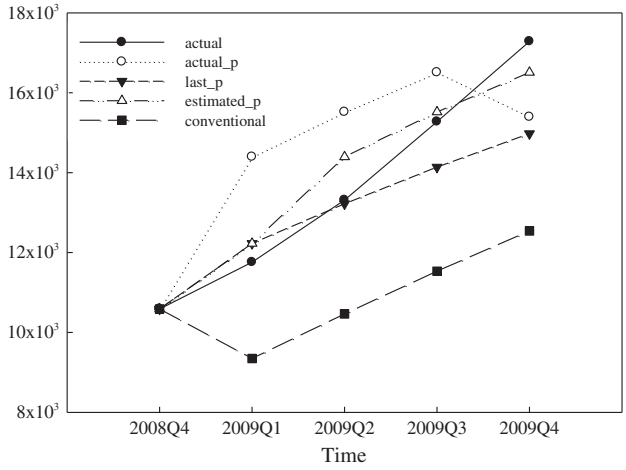


Fig. 11. Comparison of actual shipments of 46-inch LCD TVs with simulated values, by the conventional and extended models at 50% penetration rate level. "Actual," "conventional," "actual_p," "last_p" and "estimated_p" in the figure represent the three price indicators used to predict shipments in test periods: actual price in test prices, the last prices in the training period, and estimated price calculated by price prediction model (Eq. (9)).

6. Conclusions

This work presents a novel model to overcome the limitations of the conventionally adopted Gompertz growth model by incorporating price factors and estimating product demand. To our knowledge, this work explores for the first time the diffusive evolutions for various size levels of LCD TV panels by applying a Gompertz growth model that considers how price declines increase shipments. Feasibility of the proposed model is also demonstrated by comparing the goodness of fit and predictive ability of the extended Gompertz models which incorporate price factors with those of the conventional Gompertz model.

Analytical results indicate that the Gompertz curve reliably features the life cycle of LCD TVs. When LCD TVs first go on the shelves, consumers flock to purchase them. Demand quantity for LCD TVs surges, explaining why the marginal growth rate of LCD TV shipments is positive in the early stage of product life cycle. However, as popularity of the LCD TV diminishes, LCD TVs appeal less to consumers, explaining why the demand quantity decreases over time. Thus, the marginal growth rate of shipments becomes negative, and the cumulative shipments curve tends to level out, whose pattern is the same as the long and smooth tail of the Gompertz curve.

Especially for all LCD TV sizes in this work, consumer purchasing tends to increase with the price reductions in the extended Gompertz model. Comparing the initial price with the later reduced prices reveals that the price reductions induce consumers to purchase a LCD TV. Analytical results again support the anchoring and adjustment heuristic theory of Tversky and Kahneman [13]. Hi-tech products generally depend more on consumers to accept reduced prices than durable products do. This difference is owing to that few individuals are familiar with the functions of hi-tech products upon market entry. Time-varying price declines

Table 5
Forecast accuracy of extended Gompertz models with the absolute price change value, in which the price in the fourth quarter of 2008 is used to predict cumulative shipments in the test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE			0.0492	0.0222
15	MAD	X	X	610	275
	RMSE			615	276
20	MAPE	0.1164	0.0682	0.0200	0.0064
	MAD	3689	2160	632	205
	RMSE	3737	2174	639	249
26	MAPE		0.2003	0.1978	0.1978
	MAD	X	9196	9155	9195
	RMSE		10142	10363	10546
32	MAPE	0.1973	0.2202	0.2351	0.2342
	MAD	27858	31071	33230	33239
	RMSE	31150	34662	37244	37673
37	MAPE	0.0982	0.125127	0.1517	0.1653
	MAD	3468	4380.323	5280	5742
	RMSE	4345	5295.814	6237	6724
40	MAPE	0.1220	0.1536	0.1874	0.2061
	MAD	4075	5067	6112	6688
	RMSE	5218	6219	7242	7799
Penetration rate		10%	20%	30%	50%
Size	MAPE			0.0637	0.0471
37	MAD	X	X	2008	1678
	RMSE			2109	2275
40	MAPE	0.2579	0.1158	0.0470	0.0825
	MAD	7848	3398	1355	2740
	RMSE	7930	3434	1505	3500
	MAPE	0.3934	0.2258		
42	MAD	11325	6298	X	X
	RMSE	11397	6343		
	MAPE			0.0898	0.0714
46	MAD	X	X	1216	1129
	RMSE			1277	1461

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 6
Forecast accuracy of extended Gompertz models with the absolute price change value, in which the actual prices in test periods are used to predict shipments in test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE			0.0490	0.0220
15	MAD	X	X	608	273
	RMSE			611	274
20	MAPE	0.1237	0.0757	0.0263	0.0063
	MAD	3923	2398	831	199
	RMSE	3987	2428	843	217
26	MAPE		0.1977	0.1940	0.1951
	MAD	X	9092	9004	9088
	RMSE		10082	10284	10493
32	MAPE	0.1957	0.2184	0.2332	0.2328
	MAD	27716	30905	33065	33122
	RMSE	31319	34831	37419	37849
37	MAPE	0.0759	0.1062	0.1398	0.1595
	MAD	2727	3753	4887	5550
	RMSE	3764	4770	5890	6550
40	MAPE	0.1007	0.1371	0.1780	0.2013
	MAD	3423	4563	5825	6541
	RMSE	4715	5800	6991	7668
Penetration rate		10%	20%	30%	50%
Size	MAPE			0.0855	0.0414
37	MAD	X	X	2732	1451
	RMSE			2874	1914
40	MAPE	0.2839	0.1409	0.0644	0.0646
	MAD	8650	4170	1849	2174
	RMSE	8773	4247	1979	3018
	MAPE	0.4555	0.2793		
42	MAD	13120	7840	X	X
	RMSE	13314	8030		
	MAPE			0.1291	0.0534
46	MAD	X	X	1811	829
	RMSE			1844	1037

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 7
Forecast accuracy of extended Gompertz models with the absolute price change value, in which the estimated price computed by the price prediction model (Eq. (9)) is used to predict cumulative shipments in the test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE			0.0490	0.0219
15	MAD	X	X	607	272
	RMSE			614	274
20	MAPE	0.1510	0.1013	0.0440	0.0121
	MAD	4792	3216	1396	385
	RMSE	4948	3329	1459	451
26	MAPE		0.1529	0.1577	0.1826
	MAD	X	7009	7330	8508
	RMSE		7776	8490	9856
32	MAPE	0.1448	0.1686	0.1959	0.2128
	MAD	20396	23761	27735	30270
	RMSE	22925	26719	31433	34624
37	MAPE	0.0851	0.0665	0.1196	0.1551
	MAD	2725	2311	4197	5399
	RMSE	3716	2887	5191	6386
40	MAPE	0.0588	0.0846	0.1608	0.1963
	MAD	1867	2878	5278	6382
	RMSE	2475	4102	6416	7493
Penetration rate		10%	20%	30%	50%
Size	MAPE			0.2454	0.4088
37	MAD	X	X	8303	13721
	RMSE			9019	15900
40	MAPE	0.6109	0.4390	0.3221	0.1713
	MAD	19364	13899	10181	5326
	RMSE	21167	15226	11224	6074
	MAPE	1.8997	1.2457		
42	MAD	58415	37847	X	X
	RMSE	66062	42111		
	MAPE			0.4599	0.1949
46	MAD	X	X	6895	2863
	RMSE			7575	3275

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.

3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(Y_t-\hat{Y}_t\right)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 8
Forecast accuracy of Gompertz models with the change ratios of prices, in which the price in the fourth quarter of 2008 is used to predict cumulative shipments in the test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE		0.0800	0.0384	0.0154
15	MAD	X	992	477	191
	RMSE		1016	486	193
20	MAPE	0.1060	0.0570	0.01221	0.0078
	MAD	3363	1808	386	251
	RMSE	3420	1831	392	327
32	MAPE	0.1903	0.2117	0.2268	0.2317
	MAD	26961	29979	32167	32924
	RMSE	30417	33771	36386	37429
37	MAPE	0.1170	0.1446	0.1701	0.1812
	MAD	4072	5006	5867	6247
	RMSE	4821	5794	6702	7117
40	MAPE	0.1529	0.1828	0.2106	0.2226
	MAD	4992	5926	6792	7168
	RMSE	5945	6893	7778	8175
42	MAPE	0.157	0.1910	0.2200	0.2336
	MAD	4973	6024	6894	7307
	RMSE	6178	7231	8137	8573
46	MAPE	0.1444	0.1861	0.2226	0.2381
	MAD	2257	2871	3411	3642
	RMSE	2731	3348	3898	4141
Penetration rate		10%	20%	30%	50%
Size	MAPE	0.2541	0.1233	0.0442	0.0536
37	MAD	8451	4041	1375	1925
	RMSE	8665	4069	1523	2611
40	MAPE	0.2188	0.0755	0.0399	0.0897
	MAD	6749	2185	1233	3003
	RMSE	6669	2258	1441	3883
	MAPE	0.3188	0.1649	0.0793	0.0851
42	MAD	9228	4595	2097	2743
	RMSE	9329	4640	2301	3642
	MAPE	0.3549	0.1977	0.0962	0.0637
46	MAD	5218	2843	1318	1002
	RMSE	5419	2868	1353	1309

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 9
Forecast accuracy of Gompertz models with the change ratios of prices, in which the actual prices in test periods are used to predict shipments in test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE		0.0800	0.0383	0.0153
15	MAD	X	992	475	189
	RMSE		1014	482	191
20	MAPE	0.1122	0.0640	0.0187	0.0047
	MAD	3561	2030	593	149
	RMSE	3632	2070	612	202
32	MAPE	0.1880	0.2091	0.2245	0.2302
	MAD	26758	29749	31973	32813
	RMSE	30697	34070	36690	37717
37	MAPE	0.0913	0.1224	0.1543	0.1709
	MAD	3222	4272	5347	5907
	RMSE	4117	5155	6233	6805
40	MAPE	0.1285	0.1631	0.1973	0.2138
	MAD	4245	5323	6385	6900
	RMSE	5322	6367	7412	7932
42	MAPE	0.1493	0.1856	0.2162	0.2313
	MAD	4788	5870	6786	7241
	RMSE	6039	7110	8050	8520
46	MAPE	0.1383	0.1809	0.2189	0.2355
	MAD	2165	2793	3355	3602
	RMSE	2637	3268	3841	4101
Penetration rate		10%	20%	30%	50%
Size	MAPE	0.2680	0.1428	0.0670	0.0397
37	MAD	8915	4689	2130	1436
	RMSE	9155	4771	2315	2087
40	MAPE	0.2445	0.1023	0.0514	0.0626
	MAD	7460	3010	1530	2166
	RMSE	7584	3130	1627	3252
	MAPE	0.3301	0.1756	0.0874	0.0769
42	MAD	9557	4904	2321	2507
	RMSE	9672	4971	2553	3519
	MAPE	0.3555	0.2030	0.1030	0.0585
46	MAD	5227	2922	1422	920
	RMSE	5429	2952	1450	1214

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.
3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{n}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 10
Forecast accuracy of Gompertz models with the change ratios of prices, in which the estimated price computed by the price prediction model (Eq. (9)) is used to predict cumulative shipments in the test periods.

Penetration rate		70%	80%	90%	95%
Size	MAPE	X	0.0800	0.0383	0.0152
15	MAD		992	475	188
	RMSE		1015	486	193
20	MAPE	0.1356	0.0884	0.0378	0.0099
	MAD	4304	2805	1200	313
	RMSE	4459	2936	1291	400
32	MAPE	0.1172	0.1441	0.1848	0.2108
	MAD	16587	20445	26307	30024
	RMSE	19177	23643	30339	34486
37	MAPE	0.0601	0.0692	0.1263	0.1607
	MAD	1939	2393	4390	5557
	RMSE	2174	2944	5252	6429
40	MAPE	0.0666	0.0939	0.1690	0.2023
	MAD	2060	3111	5483	6531
	RMSE	2485	4168	6468	7531
42	MAPE	0.08089	0.1321	0.1921	0.2226
	MAD	2647	4238	6059	6978
	RMSE	3685	5461	7313	8253
46	MAPE	0.0935	0.1471	0.1989	0.2243
	MAD	1484	2283	3055	3437
	RMSE	1929	2731	3529	3931
Penetration rate		10%	20%	30%	50%
Size	MAPE	0.3751	0.2908	0.2343	0.1432
37	MAD	12662	9856	7959	4851
	RMSE	13478	10675	8771	5615
40	MAPE	0.5679	0.4246	0.3418	0.1904
	MAD	18058	13530	10884	5968
	RMSE	19908	15089	12250	6948
	MAPE	0.5475	0.3710	0.2485	0.0755
42	MAD	16394	11020	7297	2086
	RMSE	17432	11625	7682	2572
	MAPE	0.3608	0.2483	0.1619	0.04537
46	MAD	5309	3624	2331	641
	RMSE	5523	3725	2377	715

Notes: 1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.
2. "X" illustrates that the signs of the parameters in extended Gompertz model do not conform to the theoretical assumptions of product diffusion under such market penetration rate level.

3. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(Y_t-\hat{Y}_t\right)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

Table 11
Forecast accuracy of LCD TV panel shipments by using conventional Gompertz model.

Penetration rate		70%	80%	90%	95%
Size	MAPE	0.1343	0.0767	0.0233	0.0046
15	MAD	1666	952	289	57
	RMSE	1699	977	312	69
20	MAPE	0.0829	0.0292	0.0178	0.0375
	MAD	2633	928	560	1188
	RMSE	2725	1010	575	1190
26	MAPE	0.3516	0.3604	0.3622	0.3567
	MAD	15606	16031	16152	15936
	RMSE	15912	16398	16594	16433
32	MAPE	0.4176	0.4214	0.4180	0.4092
	MAD	56474	57110	56800	55726
	RMSE	57633	58458	58378	57474
37	MAPE	0.2230	0.2514	0.2720	0.2767
	MAD	7472	8424	9123	9290
	RMSE	7798	8789	9536	9738
40	MAPE	0.3032	0.3271	0.3425	0.3436
	MAD	9418	10164	10653	10704
	RMSE	9824	10608	11143	11229
42	MAPE	0.2926	0.3181	0.3359	0.3386
	MAD	8781	9545	10088	10189
	RMSE	9367	10177	10776	10921
46	MAPE	0.2548	0.2888	0.3140	0.3204
	MAD	3788	4290	4666	4767
	RMSE	4023	4548	4949	5071
Penetration rate		10%	20%	30%	50%
Size	MAPE	0.2177	0.0656	0.0270	0.1458
37	MAD	7271	2172	921	4895
	RMSE	7523	2234	1080	5136
40	MAPE	0.1402	0.0242	0.1187	0.2336
	MAD	4340	771	3700	7261
	RMSE	4496	882	3897	7584
	MAPE	0.1235	0.0230	0.1107	0.2219
42	MAD	3638	747	3365	6674
	RMSE	3762	1064	3712	7161
	MAPE	0.3333	0.1156	0.0171	0.1608
46	MAD	4907	1676	269	2404
	RMSE	5106	1706	352	2589

Table 12
Parameter estimation and forecast accuracy of multi-generational extended Gompertz models.

	Multi-generational extended Gompertz models with absolute price change value			Multi-generational extended Gompertz models with ratios of price changes		
	a_1	b_1	γ_1	a_2	b_2	γ_2
Average	10.4470	0.0422	0.0439	0.0567	0.0007	4.2295
t-statistics	181.22***	99.14***	22.05***	181.22***	99.14***	22.05***

Forecast accuracy

	MAPE			MAD			RMSE		
	Actual	Last	Estimated	Actual	Last	Estimated	Actual	Last	Estimated
Multi-generational extended Gompertz models with the absolute price change value									
37-inch	0.1200	0.1128	0.2093	5277	4964	9418	4726	4429	8769
40-inch	0.1186	0.1098	0.2280	4922	4529	9883	4489	4088	10148
42-inch	0.2514	0.2506	0.2686	9893	9864	10,655	8893	8871	9674
46-inch	0.3843	0.3815	0.3940	7686	7628	7888	7210	7155	7419
Multi-generational extended Gompertz models with ratios of price changes									
37-inch	0.0887	0.0937	0.1242	3891	4121	5461	3419	3631	4911
40-inch	0.1152	0.1186	0.1215	4743	4897	5045	4235	4394	4614
42-inch	0.2863	0.2865	0.2488	11,376	11,385	9777	10,355	10,367	8778
46-inch	0.4021	0.4008	0.3897	8054	8029	7792	7580	7556	7308

Notes: 1. *Significant at the 10% level. **Significant at the 5% level. ***Significant at the 1% level.

2. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

3. "Actual" "last" and "estimated" represent predicted shipments computed by the extended Gompertz models incorporating the three price indicators: actual price in test prices, the last prices in the training period, and estimated price calculated by price prediction model (Eq. (9)).

profoundly impact LCD TV diffusions, since LCD TV panels function dually as hi-tech and durable products. Simulation results suggest that LCD TV manufacturers can expand LCD TV sales through price reductions to accelerate the recovery of their R&D and production costs immediately. In particular, price reduction is more sensitive to the prevalence of larger-sized LCD TV panels than smaller-sized ones. In addition to the greater price reduction of larger-sized LCD TVs, the larger-sized ones also contain a larger-scale price elasticity coefficient than the smaller ones do. Price reduction has become more essential for the diffusion of larger-sized LCD TV panels than that for smaller ones. Although the diffusive magnitude of larger-sized LCD TVs is initially not as strong as that of smaller-sized ones, price declines expand the diffusion to a greater extent for larger-sized ones.

Additionally, according to estimation results of market penetration rate, the coefficients of extended Gompertz model are calculated effectively under a lower market penetration rate level for larger-sized LCD TVs, while under higher market penetration rate level for smaller-sized LCD TVs. This observation once again suggests that consumers continue to demand larger-sized LCD TVs; meanwhile, sales of smaller-sized LCD TVs have reached market saturation. Larger-sized LCD TVs entered the market later than the smaller ones, explaining why the unit price of the former is higher than that for the latter before 2006. Hence, consumers tend to purchase smaller-sized LCD TVs before 2006, increasing the market saturation of smaller-sized LCD TVs. In particular, 32-inch LCD TV panels have been determined in this work to have the largest potential market size, implying their mainstream position in the LCD TV industry. Consumers with vast living spaces typically purchase larger-sized LCD TVs in their living rooms and 32-inch LCD TVs in their bedrooms; meanwhile, those with smaller living spaces normally place 32-inch LCD TVs in their living rooms. Thus, the market potential for 32-inch LCD TVs is enormous.

Finally, the predictive errors are smaller for the extended Gompertz model with price factors than for the conventional Gompertz models, except for 15-inch, 37-inch and 42-inch LCD TVs. Although the prediction accuracy of the extended Gompertz model is not as high as that of the conventional Gompertz model for 15-inch, 37-inch or 42-inch LCD TV panels under the optimal market penetration rate level, the simulated error difference is relatively minor. Forecasting accuracy of the extended Gompertz model is "excellent", "excellent", and "good" in predicting 15-inch, 37-inch and 42-inch LCD TVs, respectively, according to the criteria of Martin and Witt [25]. Results of prediction error analysis verify the usefulness of the time-varying price declines in estimating LCD TV market growth.

Notes to Table 11:
1. The minimum errors among various level of market penetration rate are marked in grey shade for each size of LCD TVs.

2. $MAPE = \frac{1}{n}\sum_{t=1}^{n}\frac{|Y_t-\hat{Y}_t|}{Y_t}$, $MAD = \frac{1}{n}\sum_{t=1}^{n}\left|Y_t-\hat{Y}_t\right|$, $RMSE = \sqrt{\frac{\sum_{t=1}^{T}(Y_t-\hat{Y}_t)^2}{n}}$, where Y_t and $\hat{Y}_t$ represent the actual and predicted shipment at time t and n is the number of observations.

So far, this work has demonstrated the role of price impact in Gompertz growth model to illustrate the market dynamics of LCD TVs. Despite the theoretical and practical implications of the findings of this work, its design fails to consider the global financial crisis of 2008, which adversely impacted the LCD TV market. We recommend that future research analyze how financial crises obstruct sale volumes.

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