



Modeling diffusion of multi-generational LCD TVs while considering generation-specific price effects and consumer behaviors



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ABSTRACT

An effective diffusion model characterized by the technology-induced function diversification and cost reductions can be developed to reflect whether competition exists among multiple generations of technology and to interpret how price reductions stimulate consumption. New technology can enhance the production skill levels of LCD TV manufacturing, enabling successive generation of LCD TV to become larger-sized than the previous generation, reducing the overall cost in manufacturing process and resulting in the price reduction of LCD TVs. However, previous diffusive predictions of LCD TVs using conventional multi-generational models ignore the price effect on market potentials and generational substitutions, so a novel generation-specific multi-generational model for the first time incorporating heterogeneous price elasticity and consumer behaviors across various LCD TV sizes is constructed in this work. This study applies nonlinear least square method to simulate the parameters of our modified model and further compares the accuracy between our modified model and the existing models. Analytical results indicate that price reduction strongly correlates with LCD TV sales, implying that price reductions increase the market potential of each LCD TV generation. Our modified model performs superior to the conventional multi-generational model in terms of predicting future shipment orbits of 26-, 42-, and 46-in. LCD TVs.

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1. Introduction

An effective diffusion model characterized by the technology-induced function diversification and cost reductions can be developed to reflect whether competition exists among multiple generations of technology and to interpret how price reductions stimulate consumption. New technology can improve the skill levels of manufacturing, enabling successive generation of technological product to contain more functions than the previous generation, reducing the overall cost in manufacturing process and resulting in the price reduction of the high-tech products. The development of liquid crystal display televisions (LCD TVs) brings us several advantages over conventional cathode ray tube (CRT) TVs. For instance, LCD TVs are not only slimmer, lighter, with higher resolution and larger screens, but also brighter, with better contrast, and they consume less power than conventional CRT TVs (Hung, 2006). Notably, LCD TVs are rapidly replacing conventional CRT TVs in households (Teo et al., 2003); thus, consumers now consider LCD TVs as durable products. LCD TVs have the dual properties of durable and technological commodities. Additionally, the size of LCD TVs available in the marketplace increases continuously due to technological progress. Chen et al. (2006) have

utilized analytic hierarchy process to confirm that when the market supplies different sizes of thin film transistor (TFT)-LCD technological products, the consumer behavior of product selection emerges. As each generation of LCD TV becomes larger than the previous generation, smaller sized LCD TVs are replaced by larger-sized ones. Furthermore, technology progress reduces the production costs of LCD TVs, leading to the price decline as their technology matures and production expands. Since the TFT-LCD industry is capital intensive, LCD TV manufacturers must determine whether they can recover research and development (R&D) expenses before the next generation of LCD TVs enter into the market. Therefore, forecasting the market substitutions of multi-generational LCD TVs with considering the price reduction factors is important in technology science fields.

Most studies applied conventional S-curve model to analyze diffusion orbits of technology (Nieto et al., 1998; Tseng and Hub, 2009; Christodoulos et al., 2011; Tsai and Li, 2011; Tsai, 2013). Cheng (2012) explores the relationship between technology diffusion and new material diffusion in advanced ceramic powders. Bengisu and Nekhili (2006) applied the conventional Gompertz model to forecast trends for 20 emerging technologies. Lee et al. (2006) applied the logistical S-curve to analyze growth patterns of telecommunication services. Subsequently, scholars have demonstrated that product characteristics and functions of dynamic random access memory (DRAM) and flash memory in various generations are treated as homogeneous; thus, the market for

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previous product generations diminishes rapidly. Norton and Bass (1987) constructed multi-generational models to identify the phenomenon in that DRAM can be replaced by next-generation DRAM. Regarding LCD TV technology diffusion, small LCD TVs entered the consumer market first, followed by large LCD TVs as technology matured. Large LCD TVs erode the market of small LCD TVs. However, these studies have not explored the market dynamics of specific products that are both “durable” and “high-tech commodities” under the multi-generational framework. Thus, when examining the market dynamics of multi-generational LCD TVs, this work simultaneously considers and incorporates both the market dynamics of each generation of LCD TV as well as the circumstance of various generations substituting for each other.

In addition to the occurrence of substitution between different product generations as indicated in the aforementioned studies on multi-generation diffusion, previous studies on “price elasticity” also emphasize that the price impact on sales volumes of durables (Kamakura and Balasubramanian, 1987; Jain and Rao, 1990). The dynamic price model proposed by Robinson and Lakhani (1975) implies that price plays an important role for companies in strategy management especially in a rapidly evolving business. Parker (1992) further explores how price elasticity variation over the product lifecycle affects consumers’ adoptions. Horsky (1990) confirmed that consumers’ decision on whether to adopt monopolistic product depends on the price-income ratio. These works all assumed that the studied product is sold in a monopolistic market where no substitute good exists to carve up the market share (Robinson and Lakhani, 1975; Kalish, 1983, 1985). Namely, past literature on price elasticity focus mainly on the impact of price elasticity on a single product.

Also, Fig. 1 shows shipment and price trends for LCD TVs during 2002–2010. Prices of LCD TV panels decrease over time as productivity expands, such that unit cost declines due to economies of scale. As LCD TVs prices continue to decline, the likelihood that consumers will purchase LCD TVs increases (Tsai et al., 2010). Moreover, prior to 2006, the unit prices of each generation of LCD TVs (26-, 32-, 42-, 46-in.) are different, exerting different impact on the shipment volume and the alternation of generations. Especially in the early stages of LCD TV development, few factories could manufacture 46-in. LCD TVs due to limited technology. Because 46-in. LCD TVs were not able to be mass produced, the demand for the generation of 46-in. LCD TVs overwhelmed its supply, resulting in an especially high price for the 46-in LCD TVs,

meanwhile curbing the customers’ intention of purchase. Fig. 1 shows that the 42- and 46-in. LCD TV are priced drastically differently in 2005. More consumers tend to choose 42-in. LCD TVs because the unit price of 42-in. LCD TVs are much lower than that of 46-in. LCD TVs. These 42-in. LCD TV adopters further introduce more successive consumers to purchase 42-in. LCD TVs. The price difference between 42- and 46-in. LCD TVs results in a greater word of mouth impacts for the 42-in. generation than for the 46-in. generation. Due to a larger market potential of the 42-in. LCD TVs, the gap between shipment volumes of the 42-in. and the 46-in. generations is obvious. Even if after 2006 the LCD TVs are able to be mass produced, the unit price of each generation (26-, 32-, 42-, 46-in. LCD TVs) gradually converges, the powerful impact of the word of mouth accompanying the 42-in. generation still influence its shipment volume growth to be larger than that of the 46-in. generation. Due to the different price of each generation, the word of mouth effect and the market potential of each generation also varies, resulting in the different extent of one generation’s substitution for another sized LCD TV.

Based on the above-mentioned reasons, estimations of LCD TV diffusion are likely biased with the restrictive conventional Norton and Bass (1987) multi-generational model because this model neglects specific price effects of each generational LCD TVs. Conventional multi-generational model is unable to timely responds to the shipment deviations among various multi-generational LCD TVs. In addition, previous price elasticity models considering the impact of price over sales only take into account the price of one single product, without taking into consideration the varying substitution extent of such price impact on multi-generational products. If we applied existing price elasticity models to explore the diffusions of multi-generational LCD TVs, the drawbacks of these existing models are their negligence of each LCD TV generation’s varying impact of word of mouth and market potential induced by the price change of each LCD TV generation. Thus, in order to properly predict the sales of each LCD TV generation, this work considers the extent of impact on the substitutions of multi-generational LCD TVs due to the price changes. Our novel model combines the characteristics of multi-generational substitutions and price elasticity.

Since the model concerning the impact of price reduction on word of mouth and market potential in multiple generational products is not well established in academia, this is the first study proposing to change the existing conventional multi-generational model and to construct a novel multi-generational model by incorporating generation-specific price and consumer features to address the diffusion of durable high-tech products. Three critical differences between the existing model and our modified multi-generational model and which combines the characteristics of multi-generational substitution and price elasticity are expressed as follows. First, this work relaxes the restrictive assumption of identical purchasing behavior in the conventional multi-generational model (Norton and Bass, 1987) and constructs a novel multi-generational model that incorporates the different consumers’ behaviors and different price elasticity across various generations of LCD TVs to express LCD TV market dynamics, because the characteristics of differently sized LCD TVs differ. This study applies a market segmentation framework to interpret heterogeneous price elasticity and consumer behaviors associated with different LCD TV generations. According to the market segmentation of Kotler (2009), the characteristics of consumers groups vary for different LCD TV sizes. Consumers of large LCD TVs are generally people who like to enjoy themselves. They have the tendency to buy products impulsively due to appealing commercials, and typically do not care about other consumers’ praises or opinions. That is, consumers of large LCD TVs do not make decisions based on word of mouth from other consumers. Thus,

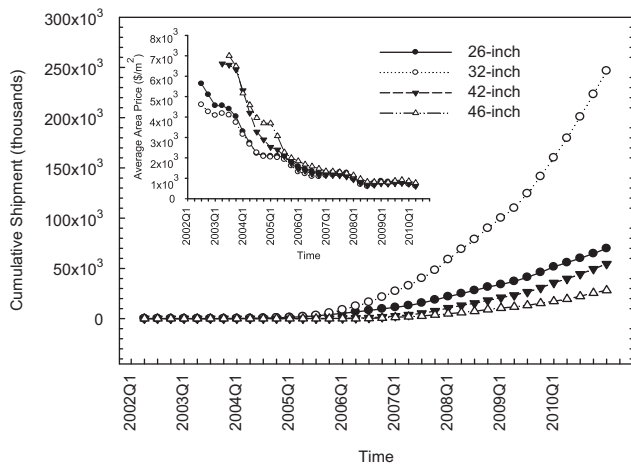


Fig. 1. Average area price per square meter ($\$/m^2$) and shipped units versus time in the first quarter of 2002 (2002Q1) to the fourth quarter in 2010 (2010Q4) for 26-, 32-, 42-, and 46-in. LCD TV panels (Data source: DisplaySearch databases).

in terms of consumer behaviors, the imitation effect decreases as the innovation effect increases in proportion to the size of LCD TVs. Innovation effect represents the intrinsic tendency of an individual consumer to purchase an LCD TV during a promotion or in response to advertising. Conversely, imitation effect represents consumer intention to purchase LCD TVs after coming into contact with LCD TV adopters. Additionally, as prices decline, consumers who can only afford small LCD TVs tend to switch to large LCD TVs. The extent to which price reductions induce sale growth is larger for large LCD TVs than for small LCD TVs, such that price reductions tend to expand market potential more for large LCD TVs than for small LCD TVs. According to the features of aforementioned different price elasticity and consumer behaviors across various LCD TV generations, this work characterizes the diffusion of multi-generational LCD TVs as a function of specific price elasticity, and innovative and imitative behaviors across various LCD TV sizes in the proposed generation-specific multi-generational model with the price effect.

Second, our proposed model follows [Tversky and Kahneman's \(1974\)](#) heuristic theory of anchoring and adjustment and assumes that consumers regard the initial price of a new LCD TV when first launched as the “reference point.” Consumers compare the new prices with the reference points and make purchasing decisions according to their price comparison results. As the price drops further, the number of people who purchase LCD TVs increases, thereby increasing market potential. In our model, market potential of each LCD TV size is thus specified as time-variant and related to individual price reductions under the market segmentation framework. When applying our modified model in computing the shipment of LCD TVs in 2005, the substantial price difference between 42- and 46-in. LCD TVs leads to a greater imitation effect and greater market potential for the 42-in. LCD TV generation than for the 46-in. one, broadening the gap between shipment volumes of the 42-in. and the 46-in. LCD TVs. Thus, our model is able to reflect the varying price impact on word of mouth, market potential, and shipment variations more rapidly than existing [Norton and Bass \(1987\)](#) model.

Third, our model forms a nonlinear ordinary differential equation that is solved numerically using the simultaneous nonlinear least square method ([Coleman and Li, 1994, 1996](#)). [Fig. 2](#) shows the computational procedure for the simulation-based optimization method used in this work. Model parameters are thus optimized using our collected data from DisplaySearch databases for optimal accuracy. Once a computed solution is obtained, it is calibrated with real data to yield an accurate simulation. If simulation result tolerance exceeds the error, optimal parameters and results are outputted. Otherwise, a least square optimization technique is used to update and modify parameters for the next simulation. The simultaneous non-linear least square method in the numerical simulations uses a sequential search technique to obtain parameter estimates. Consequently, numerical simulation can produce good estimates of parameters in the model with a relatively small dataset.

This study changes the existing multi-generational model, applies our modified model to LCD TVs, and compares the power between our modified model and existing models by providing numerical illustrations. Two modified price effect models are simulated. One model is the multi-generational model that assumes an identical imitation, innovation and price effect. Such model is defined here as the “generation-identical multi-generational models with the price effect”. The other model is the multi-generational model, which assumes a specific imitation, innovation and price effect, and is defined here as the “generation-specific multi-generational models with the price effect”. Effects of price elasticity, consumers' imitative behaviors and market potential are analyzed systematically. Furthermore, this work forecasts future orbits of global LCD TV shipments and compares the

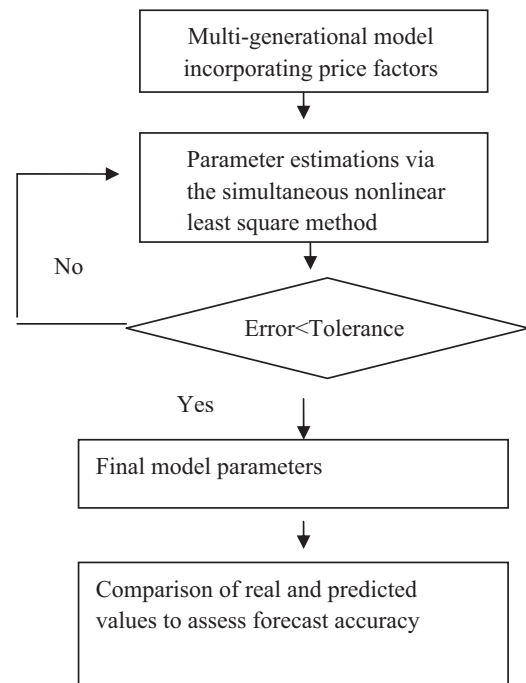


Fig. 2. Flowchart of the computational procedure and investigation steps.

accuracy of the conventional multi-generation model with the two alternative models—the generation-identical multi-generational model with the price effect and the generation-specific multi-generational model with the price effect. This work determines whether the multi-generational models with the price effect, which incorporate price reductions, perform better than the conventional multi-generational model. Analysis results indicate that cumulative sales increase exponentially over time for multiple LCD TV generations. Those owning LCD TVs persuade potential consumers to purchase LCD TVs. Simulation results also indicate that 32-in. LCD TVs have the largest market share, while the market potential of smaller LCD TVs is close to their upper limits. In accordance with market segmentation hypothesis, consumers of LCD TVs prefer different LCD TV sizes for different locations, such as public spaces, living rooms, and bedrooms. Thus, large LCD TVs are not as common as small LCD TVs (i.e., 32-in. LCD TVs); thus, previous generations of small LCD TVs cannot be fully replaced by large LCD TVs in successive generations. Particularly, the two modified multi-generational models illustrate how LCD TV price reductions stimulate imitative behaviors of LCD TV consumers. Due to the impact of price on LCD TV purchase behaviors, the models, the generation-specific or generation-identical models that incorporate the price effect, have better prediction accuracy than the conventional model.

We summarize the contributions of our modified multi-generational model in three folds. First, especially when the price of different LCD TV changes drastically, our model is able to immediately reflect the varying impact on word of mouth, market potential, and advertisement affected by the price change, as well as precisely responds to the shipment deviations among various multi-generational LCD TVs with different unit prices, making different shipment projections for different sized LCD TVs. As the extension of substitution theory ([Fisher and Pry, 1971](#)), heterogeneous consumer behaviors and price elasticity are first specified in our modified model to illustrate how the different price of each generation affect the imitation effect and the market potential of each generation, leading to the different extent of one generation's erosion of another generation. The settings of multiple generations

correspond to actual substitutions of these high-tech products, so this paper can properly interpret the consumer behaviors of various LCD TV sizes under the market segmentation framework.

Second, this investigation is the first study to confirm that the consumers' behaviors of purchasing multi-generational high-tech products is in accordance with the heuristic theory of anchoring and adjustment. Based on a psychological perspective, the proposed model considers consumer comparisons of current price with initial price at product launch, such that imitation effect, innovative effect or market potential is specified as a function of this price comparison in our extended multi-generational model to forecast global consumption of multi-generational LCD TVs; this is in contrast to the assumption of constant market potential in previous studies (Sundqvista et al., 2005). By doing so, our proposed model performs superior to the existing models in predicting the shipments of LCD TVs, which implies the roles of the heuristic theory in technology forecasting.

Third, our findings provide the insights concerning the proper factory expansion decisions for the TV industry. After 2004, the price decline of LCD TV is the crucial reason for the growth of LCD TV shipment and to accelerate the substitution of the CRT TV as the household TV. Market potential for different sizes of LCD TVs increases as prices decline. Moreover, the quarterly shipment volume of LCD TVs has even become greater than that of CRT TVs since 2008. The TV industry adopting our model can precisely predict the substitution of LCD TVs for CRT TVs, and foresee the market potential extensions of LCD TVs. For example, if one of the world's top three suppliers of CRT TV picture tubes, Chunghwa Picture Tubes, can utilize our model and decide to develop LCD TV assembly lines in time and reduce picture tubes production, the loss on picture tubes may be reduced while profiting more on LCD TVs.

The remainder of this paper is organized as follows. Section 2 summarizes the conventional multi-generational models and modified multi-generational models with the price effects in our research. Section 3 provides the numerical solutions of our multi-generational models. Section 4 gives the empirical results of coefficient estimations, market potential evaluations, and forecast accuracy. Finally, conclusions are given in Section 5.

2. Multi-generation models

2.1. Conventional multi-generation model

In the Norton and Bass (1987) multi-generational model, sales of successive generations of a product take the following form:

$$\begin{aligned} S_1(t) &= F(t)m_1[1-F(t-\tau_2)], \\ S_2(t) &= F(t-\tau_2)[m_2 + F(t)m_1][1-F(t-\tau_3)], \\ S_3(t) &= F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]][1-F(t-\tau_4)], \\ S_4(t) &= F(t-\tau_4)[m_4 + F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]]], \end{aligned} \quad (1)$$

where $S_i(t)$ is cumulative sales of the i th generation. Generations of LCD TVs are classified by size. The 26-, 32-, 42-, and 46-in. LCD TVs represent the first, second, third, and fourth generation, respectively. Notably, τ_i is the time of introduction of successive product generations. We assume $\tau_i = 0$ for the first generation.

In the original single generation model (Norton and Bass, 1987), the differential equation representing adoption can be solved when the initial condition of $F(t_0 = 0) = 0$ is assumed, such that the cumulative percentage of adoptions can be written as follows:

$$F(t) = \frac{(1 - e^{-(p+q)t})}{(1 + q/p)e^{-(p+q)t}}, \quad t \geq 0 \quad (2)$$

Here, $F(t-\tau_i)$ is the cumulative distribution function from the Bass (1969) model, or the cumulative percentage of potential adopters of generation i . As in the Norton and Bass (1987) model, constants p and q are interpreted as coefficients of innovation and imitation, respectively. The coefficient of innovation, p , represents the intrinsic tendency of an individual consumer to purchase an LCD TV during a promotion or in response to advertising. Conversely, the imitation coefficient represents consumer intention to purchase LCD TVs after contact with LCD TV adopters. Namely, interpersonal communications or interactions among members of a social system stimulate successive consumers to follow experienced buyers in purchasing LCD TVs. This imitative behavior explains diffusion process acceleration as a logistical process.

Norton and Bass (1987) assume that coefficients p and q remain constant in the cumulative distribution function (CDF), regardless of which generation is being modeled. Parameter m_i is the incremental market potential at any period t for generation i over the potential of the $(i-1)^{st}$ generation. Thus, m_1 , m_2 , m_3 , and m_4 are maximum market potential at a specific time without considering market competition with previous and subsequent generations for the first, second, third, and fourth generations, respectively. For market dynamics of the first generation, only a proportion $F(t)$ of the market potential would actually make a purchase; thus, $F(t)m_1$ represents cumulative potential sales of first-generation LCD TVs. However, actual sales, $S_1(t)$, have been reduced by a proportion of buyers who decide to buy second-generation products instead; thus, actual sales reduce to $F(t)m_1[1-F(t-\tau_2)]$ after second-generation LCD TVs enter the market. Notably, $S_2(t)$, $S_3(t)$, and $S_4(t)$ are modeled in a manner similar to $S_1(t)$. Implicit in the Norton and Bass (1987) model is the assumption that technological substitution proceeds one generation at a time; that is, buyers do not immediately skip the second generation to the third generation.

2.2. Generation-identical multi-generation model with the price effect

As mentioned, the Norton and Bass (1987) multi-generational model assumes the sales volumes is unrelated to price reductions. However, unit prices of various LCD TV types in 2005 decreased to half that in 2003 (Fig. 1). As LCD TV prices drop, the number of consumers that can afford LCD TVs increases. This market potential is likely sensitive to price reductions. Further, Kamakura and Balasubramanian (1987), Bhargava et al. (1991) and Tsai (2013) emphasized the impact of price on market potential dynamics of products or consumers' imitation behaviors. The assumption of a constant market potential violates real situations, such that the applicability of the conventional multi-generational model is limited.

Decreasing LCD TV prices can encourage consumers to act on the praise of previous consumers and favorable valuations by LCD TV owners and purchase LCD TVs (Fig. 1). The unit price of LCD TVs declines rapidly after LCD TVs are first marketed ($t=0$). As price reduction is the key factor strengthening the purchasing behaviors of potential LCD TV consumers, this work relaxes the restrictive assumption of constant market potential. The price function of multi-generational LCD TVs in this work is now expressed as Eq. (3):

$$G_i(P_i) = (P_{i,0} - P_{i,t}), \quad (3)$$

where $P_{i,t}$ is price at time t (average US dollar per square meter) for the i th generation. This work uses time 0 as the time point when a new LCD TV is launched in the market; thus, $P_{i,0}$ is the initial price for the i th generation. In Eq. (3), $G_i(P_i)$ represents the price gap in the interval $[0, t]$, from the time when a new LCD TV is first marketed ($t=0$) to time t for generation i . Since the price drops dramatically (Fig. 1), LCD TV consumers are profoundly impressed

by such substantial price drop. According to the heuristic theory of anchoring and adjustment developed by [Tversky and Kahneman \(1974\)](#), consumers start with an implicitly suggested reference point, the “anchor,” and adjust that number based on additional information. Hence, LCD TV consumers tend to regard initial price, P_0 , the price when a new LCD TV is first put on sale ($t=0$), as the reference point. As the price divergence, $(P_0 - P_t)$, increases, the number of people who identify a substantial price drop in LCD TVs increases. Thus, adopters who are originally unwilling to purchase LCD TVs at high prices are increasingly willing to purchase LCD TVs, thereby expanding the market potential for LCD TVs. When price divergences enlarge, the impacts of price reductions on market size increase. Based on the heuristic theory of anchoring and adjustment, this work specifies price reduction as the price gap $(P_0 - P_t)$ in the interval $[0, t]$, from the time when a new LCD TV is first put on sale ($t=0$) to time t . The time-variant market potential size for LCD TVs varies with prices over time and is modeled as a function of price reduction, as in Eq. (4).

$$\begin{aligned}
 TM_1(t) &= m_1 G_1(P_1)^\gamma, \\
 TM_2(t) &= [m_2 + F(t)m_1]G_2(P_2)^\gamma, \\
 TM_3(t) &= [m_3 + F(t-\tau_2)[m_2 + F(t)m_1]]G_3(P_3)^\gamma, \\
 TM_4(t) &= [m_4 + F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]]]G_4(P_4)^\gamma. \quad (4)
 \end{aligned}$$

where $G_i(P_i)$ is the price gap in the interval $[0, t]$, from the time point when a new LCD TV is first put on sale ($t=0$) to time t for generation i ; $TM_i(t)$ is the market potential while considering only market competition with previous generation(s) in the i th generation at a specific time point when subsequent generations of LCD TVs have not yet been developed and marketed; and parameter γ of price elasticity is the marginal effect of a price reduction on the market extension of LCD TVs. Without considering the price effect before subsequent generations of LCD TVs enter the market, market potential for the first generation will be the sales potential of the first generation, m_1 . A proportion of buyers of first-generation LCD TVs buy second-generation products, such that the market potential of the second generation will be the proportion of sales potential of the first generation, $F(t)m_1$, plus some increment m_2 due to new uses of products made possible by technological advances embodied within a product. The market potential of second-generation LCD TVs before the third generation of LCD TVs enters the market is $[m_2 + m_1F(t)]$. Market potentials of subsequent generations are modeled in a similar way as the second generation. The market potential of the third and fourth generations are $[m_3 + [m_2 + m_1F(t)]F(t-\tau_2)]$ and $[m_4 + F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]]]$ when ignoring the effect of price reductions and substitutions on subsequent generations. When considering the price effect, price reductions enhance the market potentials of multi-generational LCD TVs; thus, coefficient γ is the extents to which prices expand market potential size. Next, price effect, Eq. (3), is input into Eq. (1) and the price impact on sales of multi-generational LCD TVs is expressed in Eq. (5).

$$\begin{aligned}
 S_1(t) &= F(t)m_1[1-F(t-\tau_2)]G_1(P_1)^\gamma, \\
 S_2(t) &= F(t-\tau_2)[m_2 + F(t)m_1][1-F(t-\tau_3)]G_2(P_2)^\gamma, \\
 S_3(t) &= F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]][1-F(t-\tau_4)]G_3(P_3)^\gamma, \\
 S_4(t) &= F(t-\tau_4)[m_4 + F(t-\tau_3)[m_3 + F(t-\tau_2)[m_2 + F(t)m_1]]]G_4(P_4)^\gamma. \quad (5)
 \end{aligned}$$

In Eq. (5), the market potential depends on price reductions and is not constant over time. Market potential dynamics in this work is a function of the price gap in the interval $[0, t]$, from the time when a new LCD TV is first marketed ($t=0$) to time t . As the value of price elasticity coefficient γ increases, the impact of price reductions on market potential increases. Whether price elasticity coefficient γ increases as LCD TV diffusion increases is determined. This work uses coefficient γ to determine how price influences LCD

TV growth. In Eq. (5), we specify identical price elasticity γ , innovative behavior p , and imitative behavior q across various sizes of LCD TVs to explain the market dynamics of multi-generational LCD TVs.

2.3. The generation-specific multi-generational model with the price effect

A key assumption in building the conventional multi-generational model (Eq. (1)) and generation-identical multi-generational model with the price effect (Eq. (5)) is that coefficients p and q do not change when successive generations are introduced. That is, they remain constant in the cumulative distribution function, regardless of which generation is being modeled. However, the characteristics of different generations of LCD TVs are heterogeneous. Thus, this section relaxes the restrictive assumptions of identical price elasticity, innovative behavior, and imitative behavior among multi-generational LCD TVs and revises the cumulative percentage of adoptions as Eq. (6):

$$\begin{aligned}
 S_1(t) &= F_1(t)m_1[1-F_2(t-\tau_2)]G_1(P_1)^{\gamma_1}, \\
 S_2(t) &= F_2(t-\tau_2)[m_2 + F_1(t)m_1][1-F_3(t-\tau_3)]G_2(P_2)^{\gamma_2}, \\
 S_3(t) &= F_3(t-\tau_3)[m_3 + F_2(t-\tau_2)[m_2 + F_1(t)m_1]][1-F_4(t-\tau_4)]G_3(P_3)^{\gamma_3}, \\
 S_4(t) &= F_4(t-\tau_4)[m_4 + F_3(t-\tau_3)[m_3 + F_2(t-\tau_2)[m_2 + F_1(t)m_1]]]G_4(P_4)^{\gamma_4}. \quad (6)
 \end{aligned}$$

In Eq. (6), the cumulative sales volume of LCD TVs is a function of different prices across difference generations. In contrast to the assumption of an identical price elasticity coefficient in Eq. (5), the price elasticity coefficients vary for generations due to varying demand elasticity for different LCD TV sizes. Price elasticity of the first, second, third, and fourth generation, γ_1 , γ_2 , γ_3 , and γ_4 , represents the individual price elasticity of the 26-, 32-, 42-, and 46-in. LCD TVs. In Eq. (6), the cumulative percentage of adoption without considering the price reduction effect is expressed as Eq. (7):

$$F_i(t) = \frac{(1 - e^{-(p_i + q_i)t})}{(1 + q/p e^{-(p_i + q_i)t})} \quad (7)$$

In Eq. (7), the innovation coefficients of the first, second, third, and fourth generation, p_1 , p_2 , p_3 , and p_4 represent the innovative behaviors of 26-, 32-, 42-, and 46-in. LCD TVs. The imitation coefficients of the first, second, third, and fourth generation, q_1 , q_2 , q_3 , and q_4 , represent imitative behaviors of 26-, 32-, 42-, and 46-in. LCD TVs. In contrast to assumptions of identical innovation and imitation coefficients in the generation-identical multi-generational model (Eq. (5)), innovation and imitation coefficients are heterogeneous in the generation-specific multi-generational model (Eq. (6)). Because the time-variant market potential size of LCD TVs varies with generation-specific prices over time, market potential size is restated as a function of generation-specific price reduction, as in Eq. (8).

$$\begin{aligned}
 TM_1(t) &= m_1 G_1(P_1)^{\gamma_1}, \\
 TM_2(t) &= [m_2 + F_1(t)m_1]G_2(P_2)^{\gamma_2}, \\
 TM_3(t) &= [m_3 + F_2(t-\tau_2)[m_2 + F_1(t)m_1]]G_3(P_3)^{\gamma_3}, \\
 TM_4(t) &= [m_4 + F_3(t-\tau_3)[m_3 + F_2(t-\tau_2)[m_2 + F_1(t)m_1]]]G_4(P_4)^{\gamma_4}. \quad (8)
 \end{aligned}$$

3. Numerical solution

3.1. Simultaneous non-linear least square method

This work applies [Burden and Faires's \(2005\)](#) numerical optimization approach in the computer simulation process and computational procedure (Fig. 2). The multi-generational model assumes that some proportion of buyers of the previous generation of LCD TVs

buy next-generation LCD TVs. To meet the substitutive characteristics of multiple generations, the multi-generational models simultaneously extracts parameters of multi-generational LCD TVs; otherwise, dynamics of substitutions and competition among multiple generations will be biased. Thus, the simultaneous non-linear least square method is applied to extract parameters of multi-generational models (Marquardt, 1963; Dennis, 1977). Once the computed solution is acquired, it is calibrated with real data to yield an accurate simulation. If tolerance exceeds error, optimal parameters and computational results are outputted. Otherwise, a least square optimization technique is used to update and modify parameters for the next simulation.

3.2. Forecasting ability

Sampled data are divided into two periods: one period is the training sample period and the other period is the testing sample period. All prediction models are developed using the training sample, which ranges from initial periods for various sizes of LCD TVs in the sample to the fourth quarter of 2009. Next, this work applies estimated parameters calculated from the training sample to evaluate shipment orbits in the test sample. Forecast accuracy of the test sample from the first quarter of 2010 to the fourth quarter of 2010 is then compared among the three models.

To verify whether the extended model performs better than the conventional multi-generational model, accuracy of the forecasted orbit in test sample is compared between conventional multi-generational model and our proposed extended multi-generational models, which incorporate price factors. After the accuracy of the conventional and extended multi-generational models as well as collected data is compared and validated with the test sample, this work verifies whether the extended model, which accounts for price effects, performs better than the conventional model.

Regarding the criteria of model accuracy, Kaasa (2009) employed the root mean square error (RMSE) approximation to confirm the accuracy of their investigation models, so this paper follows Kaasa (2009) to utilize RMSE to examine the prediction performance of the three models—the conventional multi-generational model, the generation-identical multi-generational model with price effects, and the generation-specific multi-generational model with price effects. Besides, mean absolute percentage errors (MAPEs) and mean absolute deviations (MADs) of the cumulative quarterly shipments in the test sample are also used to compare the forecasting accuracies of the three models. Calculated errors will indicate which method is most accurate. The MAPEs are computed as $MAPE = 1/n \sum_{t=1}^n |Y_t - \hat{Y}_t| / Y_t$; the MADs are computed as $MAD = 1/n \sum_{t=1}^n |Y_t - \hat{Y}_t|$; and RMSEs are computed as $RMSE = \sqrt{\frac{\sum_{t=1}^n (Y_t - \hat{Y}_t)^2}{n}}$, in which is Y_t the actual sales volumes, \hat{Y}_t is the predicted sales volumes calculated by our proposed multi-generational model.

4. Results and discussion

The number of LCD TV units shipped globally each quarter and global prices of LCD TVs are obtained from DisplaySearch databases. The study period, which contains 32 quarters, is from the first quarter of 2003 to the fourth quarter of 2010. Because various sizes (26-, 32-, 42-, and 46-in.) of LCD TVs are introduced into the market in different periods, the real number of units shipped is from the first quarter of 2003, the first quarter of 2003, the fourth quarter of 2003, and the first quarter of 2004 for the 26-, 32-, 42-, and 46-in. LCD TVs, respectively. Therefore, 32, 32, 29, and 28

observations are obtained for the 26-, 32-, 42-, and 46-in. LCD TVs, respectively.

4.1. Parameter estimation results

Actual market and price data for the 26-, 32-, 42-, and 46-in. LCD TV panels are used to fit multi-generational models and to compute model parameters for each LCD TV size. Parameters estimated are the innovation coefficient, imitation coefficient, and price elasticity coefficient as well as the market potential. To obtain a baseline for comparison, actual data are fitted within the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect to estimate parameters. Table 1 shows simulated results of parameter estimations. For both the conventional multi-generational model and the generation-identical multi-generational model, regardless of LCD TV size, parameter estimation results show that the imitation coefficient, q , is markedly greater than the innovation coefficient, p , suggesting that imitative behaviors dominate LCD TV diffusion. For the generation-specific multi-generational model, the ratios of the imitation coefficient to the innovation coefficient (q/p) are 176.20, 123.70, 105.67, and 101.90 for the 26-, 32-, 42-, and 46-in. LCD TVs, respectively. These ratios decrease as the size of LCD TVs increases. Likewise, as the size of LCD TVs increases, the magnitude of the imitation inclination decreases. Because consumers of large LCD TVs generally pay much attention to their own enjoyment, they typically buy products impulsively due to appealing commercials, not caring about other consumers' praises or opinions. Thus, the imitation effect decreases as the size of LCD TVs increases, while the magnitude of the innovation effect increases as LCD TV size increases.

For the modified multi-generational model that incorporates the price effect, including the generation-identical and generation-specific multi-generational models, the price elasticity coefficient, γ_i is positive. Price reductions to LCD TVs strengthen demand and the positive reception of other consumers who originally did not buy LCD TVs, thereby expanding the market potential for LCD TVs. For the generation-specific model with the price effect, the price

Table 1

Parameter estimations of innovation coefficient, imitation coefficient, price elasticity and market potential for the conventional multi-generational model, the generation-identical multi-generational model with the price effect, and the generation-specific multi-generational model with the price effect.

Conventional		Generation-identical		Generation-specific	
M_1	172,863	M_1	17,707	M_1	10,806
M_2	762,920	M_2	86,957	M_2	35,731
M_3	118,536	M_3	6,074	M_3	3,780
M_4	102,299	M_4	5,938	M_4	1,152
p	0.0005	p	0.0013	p_1	0.0005
				p_2	0.0010
				p_3	0.0006
				p_4	0.0010
q	0.1644	q	0.0774	q_1	0.0881
				q_2	0.1237
				q_3	0.0634
				q_4	0.1019
		γ	1.1199	γ_1	2.6364
				γ_2	2.2878
				γ_3	2.5990
				γ_4	2.6100

Notes: The 26-, 32-, 42-, and 46-in. LCD TVs represent the first, second, third, and fourth generations, respectively. Coefficients p_1 , p_2 , p_3 , and p_4 are innovation coefficients of the first, second, third, and fourth generations, respectively. Coefficients q_1 , q_2 , q_3 , and q_4 are the imitation coefficients of the first, second, third, and fourth generations, respectively. Coefficients γ_1 , γ_2 , γ_3 , and γ_4 are the price elasticity of the first, second, third, and fourth generations, respectively.

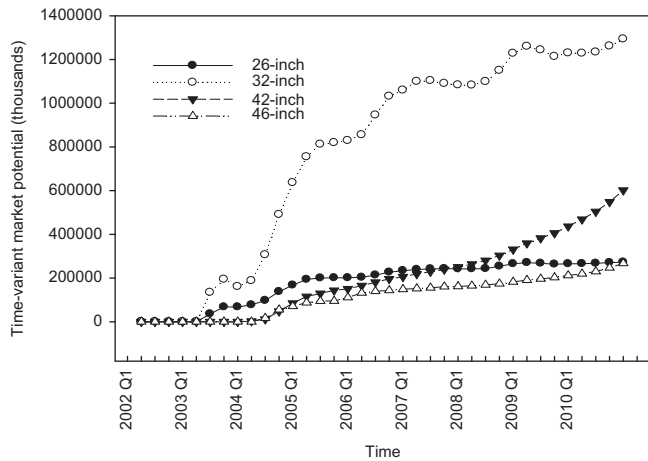


Fig. 3. Time-variant market potentials by the generation-identical multi-generational models.

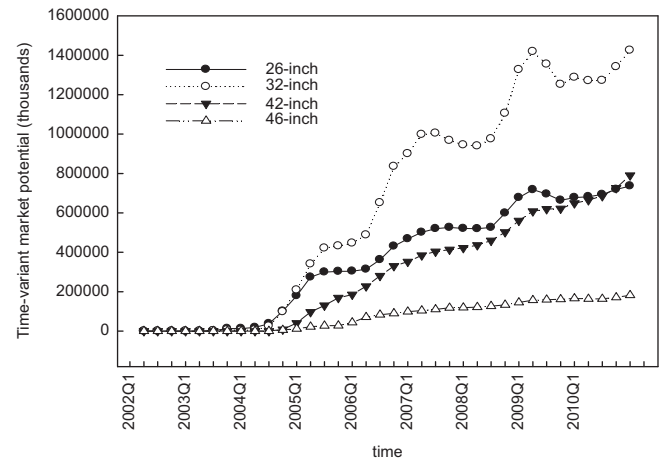


Fig. 4. Time-variant market potentials by the generation-specific multi-generational models.

elasticity coefficient of 32-in. LCD TVs, γ_2 , is smallest among the various LCD TV sizes (Table 1). Notably, 32-in. LCD TVs are versatile and can be placed in both bedrooms and living rooms. Thus, the demand for 32-in. LCD TVs results in the smallest price elasticity coefficient, γ_2 , among the various LCD TV sizes (Table 1). Conversely, price elasticity of large LCD TVs is greater than that of 32-in. LCD TVs because most consumers cannot afford large LCD TVs. Once price decreases for large LCD TVs, consumers who originally purchased smaller LCD TVs tend to purchase large LCD TVs, increasing the price elasticity of large LCD TVs.

Estimated market potential size for each LCD TV generation using the conventional multi-generational model, which assumes constant market potentials, indicates that the 32-in. LCD TVs have the greatest market potential. For example, LCD TV consumers who place LCD TVs in public places, living rooms or bedrooms, have different needs and wants for LCD TV sizes. Large LCD TVs may be used in exhibition halls or living rooms, while small LCD TVs suit small public rooms or bedrooms. Product attributes or functions of LCD TVs vary with size, such that different spaces require different sizes of LCD TVs. Because the 32-in. LCD TVs is versatile, it is functional in a wide range of locations and spaces. Therefore, 32-in. LCD TVs remain the dominant LCD TV size purchased. Conversely, the market potential of each other LCD TV size is less than 25% of the market potential of 32-in. LCD TVs. Notably, 32-in. LCD TVs have not been replaced by large LCD TVs, a finding that is consistent with implications of the “market segmentation” hypothesis (Kotler, 2009; Smith, 1956).

A comparison of the market potentials by the three models (i.e., the conventional multi-generational model, the generation-identical multi-generational model with the price effect, and the generation-specific multi-generational model with the price effect), indicates that coefficients M_1, M_2, M_3, M_4 of the conventional model are largest. The conventional multi-generational model assumes constant market potentials, such that M_1, M_2, M_3, M_4 , which are market potentials for the 26-, 32-, 42-, and 46-in. LCD TVs, remain constant over time. However, coefficients M_1, M_2, M_3 , and M_4 of the modified multi-generational model with the price effect only represent market potentials at product launch with no effect of price reductions on market extensions. The difference in definitions for coefficients M_1, M_2, M_3 , and M_4 enlarge estimated values by the conventional multi-generational model more than those by the modified multi-generational models with the price effect. This is the primary reason for the discrepancy in estimated parameter values of market potential – M_1, M_2, M_3 , and M_4 – between the conventional multi-generational model and the modified multi-generational model with the price effect (Table 1).

Table 2

MAPEs, MADs and RMSEs of the conventional multi-generational models, the generation-identical multi-generational model with the price effect and the generation-specific multi-generational model with the price effect for the 26-in., 32-in., 42-in., and 46-in. LDC TVs during the test period.

	26-in.	32-in.	42-in.	46-in.
Conventional				
MAPE	0.1144	0.0277	0.4322	0.4955
MAD	9,819.57	8,550.66	27,969.62	16,539.32
RMSE	9,201.93	9,600.99	26,020.35	15,937.51
Generation-identical				
MAPE	0.0923	0.0184	0.2286	0.1156
MAD	7,982.45	5,215.94	14,957.50	3,885.31
RMSE	7,700.56	5,182.12	14,439.03	3,877.41
Generation-specific				
	26-in.	32-in.	42-in.	46-in.
MAPE	0.0853	0.0350	0.0431	0.0378
MAD	7,114.55	9,507.94	2,789.86	1,255.86
RMSE	6,178.27	8,870.65	3,036.37	1,363.72

This work further calculates the time-variant market potential size, $TM_i(t)$, over time using Eq. (8) for generation-specific multi-generational LCD TVs. Figs. 3 and 4 show the patterns of time-variant market potential, $TM_i(t)$, calculated by the generation-identical and generation-specific multi-generational models with price effects, respectively. Analytical results indicate that market potential size increases gradually as the prices of multi-generational LCD TVs decrease. The intervals of market potential estimated by the generational-identical and generation-specific multi-generational models with the price effect (Figs. 3 and 4) are the time-variant market potential size for the 26-, 32-, 42-, and 46-in. LCD TVs, which include constant market potential values computed by the conventional multi-generational model (Table 1). Comparing constant market potential in the conventional multi-generational model (Table 1) with time-variant market potentials in the generation-identical or generation-specific multi-generational models (Figs. 3 and 4) for each generation of LCD TVs indicates that each constant market potential estimated by the conventional multi-generational model is located within the interval of each time-variant market potential by either the generation-identical or the generation-specific models with the price effect.

Combining price trends (Fig. 1) and fluctuations of market potential size (Fig. 4) suggests that prices of LCD TVs increased for multiple LCD TV generations around 2004, indicating that market potential size expanded slowly before 2004. After 2004,

market potential and adoption of LCD TVs grew aggressively due to continuous price reductions. Decreases in price increased the size of the market potential and promoted LCD TV sales.

4.2. Forecasting results

In this section, this work assesses the ability of the three models to predict LCD TV shipments. Parameters of all three models are estimated by using quarterly LCD TV shipments in the training sample, ranging from the beginning period to the fourth quarter of 2009. Using the conventional multi-generational model, the generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect, forecasted cumulative LCD TV shipments from the first quarter of 2010 to the fourth quarter of 2010 are then compared with actual cumulative shipments. Forecasting errors by each model are then measured using MAPE, MAD, and RMSE for the conventional multi-generational model, the generation-identical multi-generational model with the price effect, and the generation-specific multi-generational model with the price effect (Table 2).

For all LCD TV sizes, MAPEs, MADs and RMSEs of the conventional multi-generational models are greater than those of the other models incorporating price effects. The MAPEs, MADs, and RMSEs are smallest for the generation-specific multi-generational models with the price effect in predicting cumulative shipments of 26-, 42-, and 46-in. LCD TVs. The MAPE, MAD, and RMSE are smallest for the generation-identical multi-generational model with the price effect in predicting cumulative shipments of 32-in. LCD TVs. This again demonstrates that the modified multi-generational models with the price effects perform better than conventional multi-generational models in predicting future LCD TV sales volumes.

In addition, regardless of LCD TV size, the MAPEs of cumulative shipments by the generation-specific multi-generational models with the price effect are $< 10\%$. However, MAPEs of cumulative shipments by the conventional multi-generational model are $> 10\%$ for the 26-, 42-, and 46-in. LCD TVs. We infer that models with the price effect (both generation-specific and generation-identical) are more accurate in forecasting than the conventional multi-generational model. The multi-generational models with the price effect perform better than the conventional model, as price elements incrementally validate predicted LCD TV shipments.

Figs. 5–8 compare simulated and real shipments of 26-, 32-, 42-, and 46-in. LCD TVs, respectively. Computed shipments are plotted against time for calculation with the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect. Clearly, simulated shipments via the conventional multi-generational model without considering price factors differ from real shipments. Simulated shipments by the generation-specific multi-generational models with the price effect are closer to actual shipments than shipments simulated by the conventional model for 26-, 42-, and 46-in. LCD TVs.

Although the MAPE of the generation-specific multi-generational model with the price effect (0.0350) is slightly larger than that of the conventional multi-generational model (0.0277) for 32-in. LCD TVs, simulated error difference is relatively minor. Martin and Witt (1989) asserted that the forecasting capacity of a model is “excellent” when the MAPE is $< 10\%$; forecasting capacity is “good” when MAPE is located in the interval $[10\%, 20\%]$ ($10\% < \text{MAPE} < 20\%$); and forecasting capacity is “reasonable” when MAPE is in the interval $[20\%, 50\%]$ ($20\% < \text{MAPE} < 50\%$). The generation-specific multi-generational model with the price effect did not perform better than the other two models, but, according to the criteria developed by Martin and Witt (1989), the forecasting ability of all three models was “excellent” in predicting cumulative shipments of 32-in. LCD TVs. The MAPE

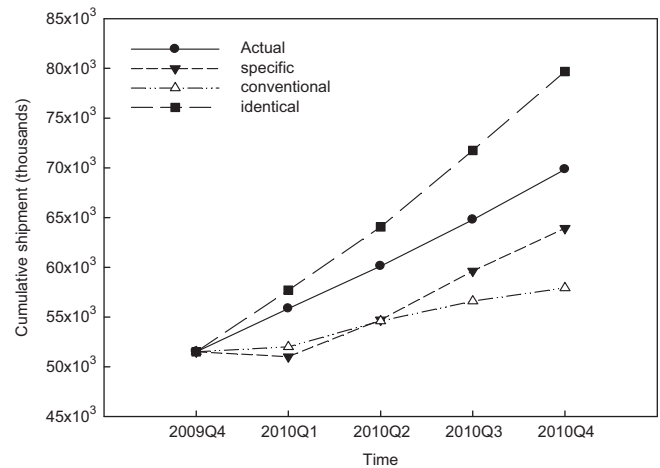


Fig. 5. Actual shipments of 26-in. LCD TVs compared with simulations by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect. “Actual,” “conventional,” “identical,” and “specific” in the figure represent actual shipments and predicted shipments computed by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect.

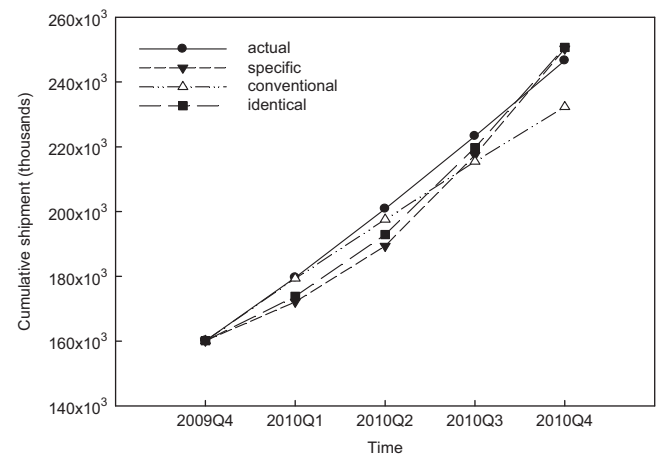


Fig. 6. Actual shipments of 32-in. LCD TVs compared with simulations by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect. “Actual,” “conventional,” “identical,” and “specific” in the figure represent actual shipments and predicted shipments computed by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect.

difference was minor between the conventional and multi-generational models with the price effect.

When using the conventional multi-generational model, simulated errors for the 42- and 46-in. LCD TVs are large. The MAPE of the conventional multi-generational model is $> 40\%$ for the cumulative shipment of 42- and 46-in. LCD TVs. The forecasting ability of the conventional multi-generational model is only “reasonable” and markedly inferior to that of the proposed model, which incorporates the price effect. Conversely, the proposed multi-generational models, the generation-specific and generation-identical multi-generational models with the price effect, are markedly superior to the conventional model in predicting 42- and 46-in. LCD TV shipments. A possible interpretation is that price reduction was not significant after 26- and 32-in. LCD TVs first entered the market. Because 26- and 32-in. LCD TVs were

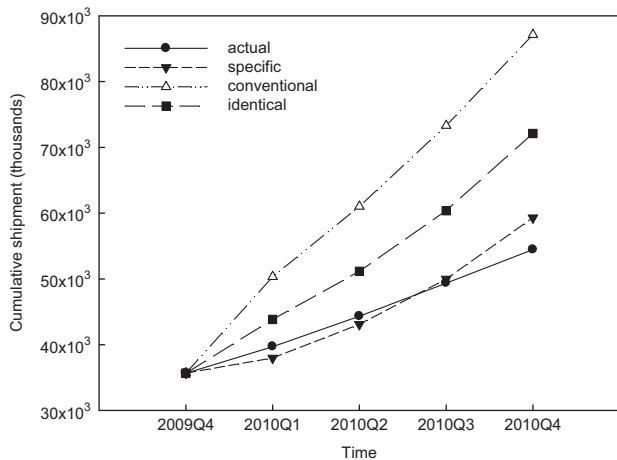


Fig. 7. Actual shipments of 42-in. LCD TVs compared with simulations by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect. “Actual,” “conventional,” “identical,” and “specific” in the figure represent actual shipments and predicted shipments computed by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect.

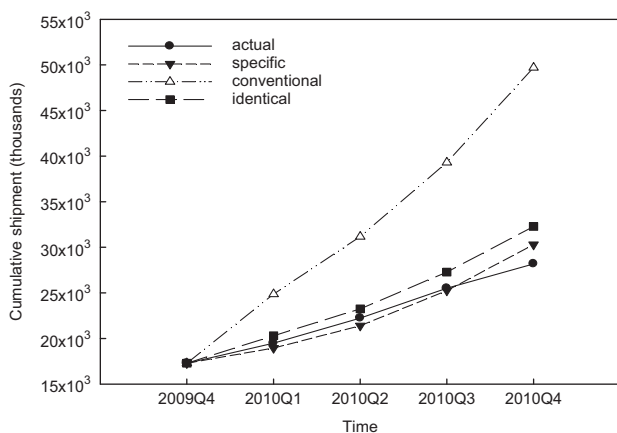


Fig. 8. Actual shipments of 46-in. LCD TVs compared with simulations by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect. “Actual,” “conventional,” “identical,” and “specific” in the figure represent actual shipments and predicted shipments computed by the three models—the conventional multi-generational model, generation-identical multi-generational model with the price effect, and generation-specific multi-generational model with the price effect.

brought to the market earlier than 42-in. and 46-in. LCD TVs, the price impact on their diffusion was limited. When the 42- and 46-in. LCD TVs entered the market, LCD TV prices declined dramatically (Fig. 2) and demand for large LCD TVs grew rapidly. As small LCD TVs dominated the market, price played an increasingly important role. Consequently, the multi-generational models with the price effect perform significantly better than the conventional multi-generational model in predicting sales volumes of large LCD TVs than of small LCD TVs.

Furthermore, the MAPEs of the generation-identical multi-generational models with the price effect are 0.2286 and 0.1156 for the 42- and 46-in. LCD TVs, respectively, while MAPEs of the generation-specific multi-generational models with the price effect are only 0.0431 and 0.0378 for the 42- and 46-in. LCD TVs. Because various consumer groups purchase different sizes of LCD TVs, the innovative and imitative behaviors of these consumers of

differently sized LCD TVs also vary. The model specification of generation-specific multi-generational model with the price effect reflects actual conditions more faithfully than the generation-identical multi-generational model with the price effect; therefore, model specification of the generation-specific multi-generational model with the price effect is more accurate than that of the generation-identical multi-generational model with the price effect. Empirical evidence confirms the suitability of the proposed generation-specific multi-generational models with the price effect in determining LCD TV shipment trajectories.

5. Conclusions

This work applied a novel alternative model to overcome limitations of the conventional multi-generational model, mainly by incorporating price effects and estimating demand for high-tech products. This is the first work to apply a multi-generational model that considers innovation, imitation, price impact, and market potential in exploring the evolution of various LCD TV sizes. To demonstrate model effectiveness, goodness-of-fit and predictive ability of the modified multi-generational models, which incorporate price effects, were compared with those of the conventional multi-generational model.

The empirical results exhibit that the next generation of LCD TVs erodes the market share of existing generation of LCD TVs, confirming that technological products in successive generations replace those in previous ones. Orbit results show that the lifecycle of multi-generational LCD TVs. When LCD TVs were first marketed, consumers flocked to purchase them. Demand for LCD TVs surged, such that the marginal growth rate of LCD TV shipments was positive early in the product's lifecycle. However, as the larger-sized LCD TVs of next generation enter the market, the smaller-sized LCD TVs of previous generations had less appeal to consumers, such that demand decreased over time. Thus, the marginal growth rate of LCD TV shipments in previous generation turns negative, and the cumulative shipments curve tends to be smooth. Additionally, the analytical results exhibit that the ratio of innovation to the imitation coefficient is higher for large LCD TVs than that for small LCD TVs, implying that consumers of large LCD TVs often value their own comfort and enjoyment more than other consumers' praises and are often easily affected by the lure of advertisements. For all LCD TVs sizes in this work, market potentials have been identified as increasing by the extended multi-generational model with price effects as price declines over time.

The principal contribution of this study to technology forecasting literature is the application of a market segmentation framework to interpret heterogeneous consumer behaviors associated with different technological generations of LCD TVs. Additionally, this study simulates substitutions of multi-generational LCD TVs using simultaneous nonlinear least square methods. Furthermore, the analytical results prove the consumers' purchase of high-tech products based on the heuristic theory of anchoring and adjustment. Our findings of time-varying market potentials induced by price reductions give strategic insights of technology management. LCD TV enterprises can expand LCD TV markets through price reductions, and thus accelerate the recovery of R&D and production costs before the LCD TVs in the next generation enter into markets.

The proposed novel multi-generational diffusion model represents a major step forward in the fields of technology forecasting and management science as summarized the following four implications to theory and practice. First, in terms of diffusion theory, the heterogeneous diffusive process, price elasticity and consumer behaviors across various generational products are

highlighted. The empirical results illustrate that the price elasticity of 32-in. LCD TVs is the smallest and the market potential of 32-in. LCD TVs is the largest among various LCD TV sizes. By relaxing the restrictive assumption of homogeneous consumer behaviors in existing model and by proposing heterogeneous features across various generations in our multi-generational diffusion model, the substitution and evolutionary process of multi-generational products can be more accurately forecasted than in previous models, especially in a rapidly changing business environment where many generations of products coexist.

Second, the implication to consumer psychology is the corroboration of consumers' price-comparison behaviors in purchasing multi-generational high-tech products in accordance with the heuristic theory of anchoring and adjustment. The substantial price difference between 42- and 46-in. LCD TVs leads to a greater market potential for the 42-in. LCD TV than for the 46-in. one, broadening the gap between sales volume of the 42-in. and the 46-in. LCD TVs. The price reduction impact on the time-variant substitution effect of one generation's erosion for another generation readily reflects how consumers compare the current price with the initial price to formulate buying decisions.

Third, our empirical results implies that in high-tech LCD TV practices the marketing and pricing strategies should be adjusted depending on the various size of the LCD TVs. This work finds that the consumers' inclinations of imitating other consumers to purchase LCD TVs decrease as the size of LCD TVs increases. Since consumers of large LCD TVs generally pay much attention to their own enjoyment, they typically buy products impulsively due to appealing commercials, not caring about other consumers' praises or opinions. Thus, the analysis results of this study can serve as a valuable reference for marketing strategy in LCD TV industries.

Lastly, with respect to technology management practices, this study provides practical considerations for factory expansion decisions in the hi-tech industry. The size of LCD TVs available in the marketplace increases continuously due to technological progress. Although larger-sized LCD TVs can replace smaller-sized LCD TVs, LCD TV manufacturers still need to determine whether research and development (R&D) expenses can be recovered before the next generation of LCD TVs enter into the market. Our novel model based on the heterogeneous price impact across various generations can forecast, more accurately than existing models, future sales volumes of multi-generational technology-based products and the possibility of recovering equipment and R&D costs.

To date, price impact in the multi-generational model illustrates how subsequent generations of LCD TVs are substituted for previous generations. Although this work yields findings that have theoretical and practical implications, it does not consider the European sovereign debt crisis, which struck suddenly in 2011 and adversely affected the LCD TV market. An important area for future research will be refinement of approaches for analyzing how financial crises affect sales volumes of high-tech products.

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