APPLYING TECHNOLOGY FORECASTING TO NEW PRODUCT DEVELOPMENT TARGET SETTING OF LCD PANELS

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ABSTRACT

This chapter illustrates the Technology Forecasting using Data Envelopment Analysis (TFDEA) process on Liquid Crystal Display (LCD) performance characteristics from 1997 to 2012. The objective of this study is to forecast future state-of-the-arts (SOAs) specifications as well as to diagnose past technological advancement of the LCD industry. Appropriate characteristics were determined from a group of LCD technologists. Data was gathered from public databases and outlying data points were cross-referenced as a validity check. The TFDEA process is defined and its application to the dataset is described in detail. The results not only provide information on how LCD industry has evolved but also provide an insight on future NPD targets.

INTRODUCTION

Since the 1970s, Liquid Crystal Display (LCD) technology moved from small displays such as watches to large scale televisions/public displays. As performance demands increased, demands on manufacturing managers to plan and deliver competitive products have also increased (Craig, 2004). As demand for mobile computing and high-definition video standards took hold, worldwide sales of LCD and plasma displays increased dramatically along with decreases in unit cost. At the same time, businesses began replacing Cathode Ray Tube technology-based computer monitors with LCD displays (Take, 2003). The range of display technology is vast and the technologies are ever changing (see Fig.1) (Takiguchi, 1999).

The increasing demands pressed flat panel manufacturers to invest in larger sizes, greater resolution, and color/contrast improvements. LCD manufacturers have planning teams to forecast future LCD performance characteristics to remain competitive. Marketing companies track LCD technology trends using internal analysis. Often, advancements are constrained by external issues (i.e., broadcast standard adoption rates) that inhibit throughput or manufacturing limitations. An example of this is how LCDs are cut from ''mother glass'' with well-defined size constraints and do not improve in size in a continuous fashion, but increase in a step-wise mode. Weight or power usage can be improved continuously (HP, 2008).
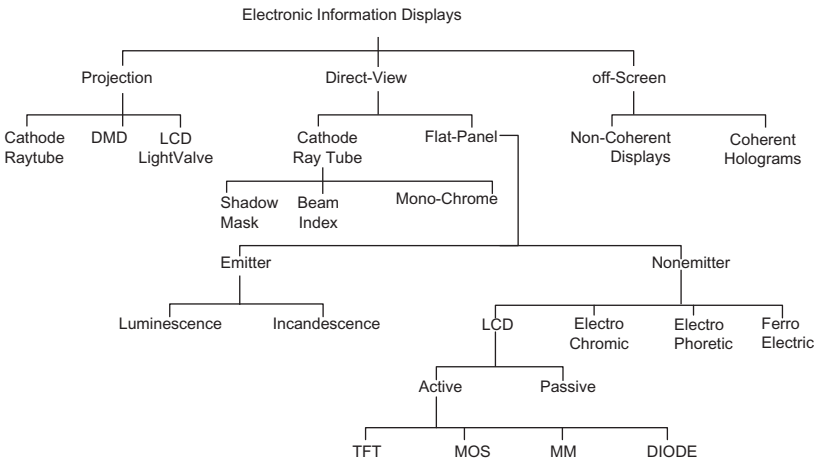

Fig. 1.   Electronic Information Display Taxonomy.

RESEARCH GOALS AND DESIGN CONSTRAINTS

Overall Research Aims

The objective of this research is to determine changing patterns in the LCD image quality and physical device characteristics to forecast future values of similar products.

Projection Horizon Goals

A "panel" of industry experts at a major flat panel manufacturer was interviewed to determine benchmark characteristics used for performance measurements. Modeling data to produce projections from 2012 to 2017 was determined by the best match to actual industry planning timeframes.

Historical Data Boundary

The history of LCD technologies goes back to the 1960s, however, 1997 was used as the starting point for this study because of the critical mass of larger ($>15''$) LCD products were available in the market. This represented a point where LCD products moved beyond mobile computing and was of the most interest to our panel of experts.

Type of Displays Considered

As shown in Fig. 1, there is a range of technology options for electronic information displays. This chapter focuses on Direct-View, Flat Panel, Non-emitter, Active, and Thin-Film technologies which represent the bulk of high-definition televisions and computer monitors.

Units Measured

Working with industry experts, a list of fundamental attributes representing the core tradeoffs between products was developed. Data collected included the following:

- Release Date: (year)
- Screen Size: (inches) measured diagonally

- Bezel Size: (millimeters) derived by subtracting the beginning of the active area from the outside shell measurement
- Weight: (kilograms)
- Resolution: (pixels) horizontal times vertical resolution
- Viewing Angle (degrees)
- Contrast Ratio: (lumens) difference between 0 and 100% energized pixel(s) (Learn About LCD TV and TFT LCD Displays, 2012).

ANALYSIS

Data Gathering

Panelook.com provided two-thirds of the research data and the rest of it were collected from online scanned manuals and various other sources including review sites. Statistical outliers were verified from secondary sources and removed if unconfirmed. In order to sample the full range of data, the authors searched criteria filtered on upper, middle, or low bounds on target characteristics. Derivative products of base-models that did not add to usable differences were removed from the dataset. There were 389 models, with diagonal screen sizes ranging from 14 to 108″, in the final data set from 20 manufacturers from 1997 to 2012 (see sample data in Table 1).

Method

Modern benchmarking analyses frequently use frontier analysis (or best practice) methods. The idea is to model the frontier of the technology rather than to model the average use of the technological possibilities (Bogetoft & Otto, 2010). This approach has a strong advantage in learning from the best

Table 1. Sample Data.

Manufacturer	Product	Release Date	Screen Size	Bezel Size	Weight	Resolution	Viewing Angle	Contrast Ratio
NEC	EA192M	1997	19	43.18	3.52	1,310,720	170	1,000
AUO	T370HW01 V0	2004	37	75.44	10.00	2,073,600	178	800
Samsung	LTI700HD01-006	2012	70	80.56	45.00	2,073,600	178	2,400

rather than being influenced by the inclusion of mediocre performers. Since its founding in 1978 (Charnes, Cooper, & Rhodes, 1978), Data Envelopment Analysis (DEA), has been widely used as a frontier model for organizational benchmarking (Seiford, 1996). In 2001 it was extended to examine product-oriented performance by extending Moore's Law to a wider set of performance indicators and termed TFDEA (Technology Forecasting using DEA) (Anderson, Fare, Grosskopf, Inman, & Song, 2002). It has since been applied to a wide range of industries including battle tanks (Kim, Kim, & Kim, 2007), fighter jets (Inman, Anderson, & Harmon, 2006), disk drives (Inman, 2004), telecommunications protocols (Anderson, Daim, & Kim, 2008; Kim, Daim, & Anderson, 2010; Lim, Anderson, & Kim, 2012), and commercial airplanes (Lamb, Anderson, & Daim, 2012).

TFDEA is able to leverage DEA's natural ability to handle rich models and applications in terms of flexibly handling both multiple inputs and multiple outputs. This is particularly important in the case of technology forecasting and new product development because the tradeoffs between product characteristics can vary by manufacturer, by market segment, and over time.

Fig. 2 summarizes this model procedure. Briefly, x_{ik} represents the ith input and y_{rk} represents the rth output of technology k. The variables for the linear program underlying DEA are λ_{jk} and $\phi_k^{t_f}$ The variable $\phi_k^{t_f}$ also serves as the objective function and represents the amount of output which should be generated by technology k at time period t_f if it were state-of-the-art at that time. The variable λ_{jk} describes how much of technology j is used in setting a target of performance for technology k. Details of TFDEA procedures can be found in original research (Inman, 2004).

TFDEA can be conducted in two stages – model validation and actual extrapolation. Specifically, parameters to be used for the TFDEA model are determined in the first stage and future state-of-the-arts specifications of LCD products are estimated in the second stage.

Model Validation

Fig. 3 illustrates the model validation process to determine an appropriate model for the LCD industry. Since TFDEA measures technological superiority using an efficiency framework, suitable characteristics of LCD products need to be determined as input(s) and output(s) values. As in other recent forecasting techniques' applications, "Backtesting," was used to validate the effectiveness of forecasting model by running the current model up to a
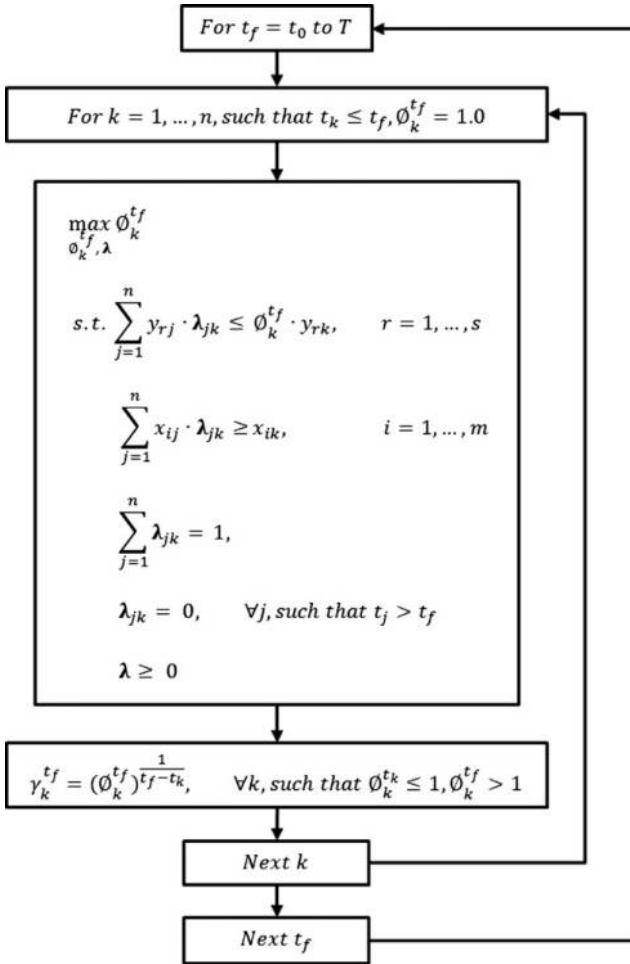
$$\text{For } t_f = t_0 \text{ to } T$$

$$\text{For } k = 1, \dots, n, \text{ such that } t_k \leq t_f, \emptyset_k^{t_f} = 1.0$$

$$\max_{\emptyset_k^{t_f}, \lambda} \emptyset_k^{t_f}$$

$$s.t. \sum_{j=1}^{n} y_{rj} \cdot \lambda_{jk} \leq \emptyset_k^{t_f} \cdot y_{rk}, \qquad r = 1, \dots, s$$

$$\sum_{j=1}^{n} x_{ij} \cdot \lambda_{jk} \geq x_{ik}, \qquad i = 1, \dots, m$$

$$\sum_{j=1}^{n} \lambda_{jk} = 1,$$

$$\lambda_{jk} = 0, \qquad \forall j, \text{ such that } t_j > t_f$$

$$\lambda \geq 0$$

$$\gamma_k^{t_f} = (\emptyset_k^{t_f})^{\frac{1}{t_f - t_k}}, \qquad \forall k, \text{ such that } \emptyset_k^{t_k} \leq 1, \emptyset_k^{t_f} > 1$$

$$\text{Next } k$$

$$\text{Next } t_f$$

Fig. 2. TFDEA Process.

certain point in time and calculating how it would have performed had it actually been applied in the past. It was adopted to compare the accuracy of different models (Rösch, 2005). This backtesting procedure is analogous to using a holdout sample to validate a more traditional statistical model. Therefore, it is necessary to determine a proper point of time to divide the dataset. Finally, TFDEA parameters including orientation (input/output), returns to scale (RTS) (constant returns to scale/variable return to scale/

nonincreasing return to scale/nondecreasing return to scale), and frontier (static/dynamic) are selected using this process.

Fig. 4 shows characteristics identified from the model validation process. As bezel size and weight tend to be proportional to screen size, normalized specifications, namely per-inch data, are used as inputs. For the output variables, screen size, pixel number, and contrast ratio were used to define the fundamental characteristics of display performance in terms of forecasting purpose.
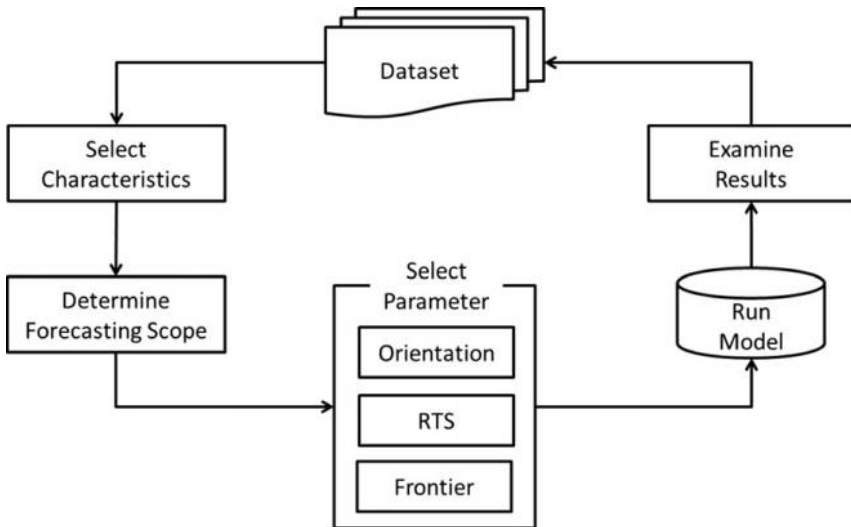

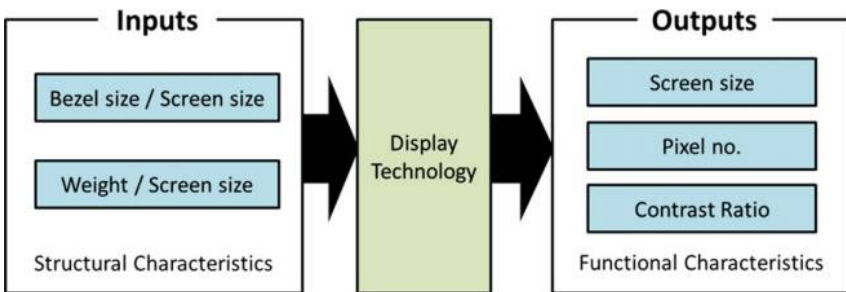*Fig. 3.* Model Validation Process.

Fig. 4. DEA Model Structure.

Ideally, manufacturing cost should be included as an input but this is typically very difficult to include for many reasons:

- Each company has different ways of calculating cost and cost allocation methods.
- Cost is typically a rapidly decreasing value based on yield and learning, so a particular value in time would be needed.
- Different factories may be used for the same product with different cost functions.
- International currency fluctuations make it difficult to compare.
- Actual costs are confidential and therefore not available in industry publications.

In place of costs, a product price such as list price, manufacturer suggested retail price, or average selling price is sometimes used as a proxy for cost. Unfortunately, neither cost nor price was consistently available for the range of products.

Table 2 summarizes details of the analyzed model and results. A range of options was tested and the model was selected on the basis of characteristics of the application and accuracy in the validation stage.

TFDEA allows either static frontier or dynamic frontier to be used. The frontier year is a measure of the products that are being used to be compared against. For example, assume a 2005 LCD panel is being compared against panels from 2007 and earlier. The best comparisons for this product might be a combination of panels from 2006 and 2007. The static frontier year would use a fixed date of 2007 while a dynamic frontier year uses a combination of the dates of the products (2006 and 2007) such as 2006.5. In this application, a static frontier was used.

Table 2. Model Results.

Frontier Type	Orientation	2nd Goal	Return to Scale	Avg. RoC	Frontier Year	MAD
Static	OO	N/A	VRS	1.169682	2007	1.891382
Input(s)	Output(s)	SOA products at release	SOA products on frontier	RoC contributors	Release before forecast	Release after forecast
2	3	88	7	30	9	76

Orientation can be either input-oriented or output-oriented and can be best thought of as whether the primary goal is "input-reducing" or "output-augmenting." While both screen performance and reducing bulkiness are important, in this time period, the LCD industry is better characterized as being driven by improving screen performance taking priority over making designs lighter and more compact. Therefore, an output orientation was selected for this application but a future study might find an input orientation a better fit if improving screen performance takes a back seat to bulkiness reduction. Hence, the model evaluates technologies based on how much advancement of outputs was produced using the same level of inputs.

DEA allows for various returns to scale assumptions. The most common are variable returns to scale (VRS) and constant returns to scale (CRS). Using CRS implies that for an actual product, a doubling of each of the inputs should result in a feasible product with double each of the outputs. In our application, doubling the inputs of the LCD panel does not correspond to a realistic design with double the outputs. Therefore, a VRS model was selected.

Average Rate of Change (Avg RoC) was found to be 1.169682, which means the overall performance of LCD products has improved by an average of 17% a year. Fig. 5 displays the annualized pattern of RoC over time. Gamma values indicate the progress in a product's performance in the current year as compared to the previous year. The rate fluctuates from year to year, and in each year we can see which products had the largest advance. From 1997 to 2012, LCD products from Samsung and LG dominated the rate-of-change list (2004 and 2005 technologies were annualized by other
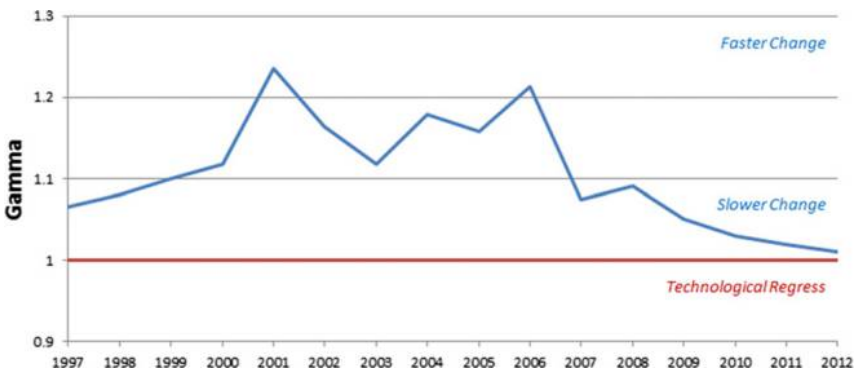

Fig. 5. Annualized Rate of Change (RoC).

Table 3. Top 5 Rate-of-Change Products.

Rank	Release Year	Model	Producer	Rate of Change
1	2006	LM240WU2-SLB2	LG	1.555610
2	2006	LTM270M1-L01	Samsung	1.322629
3	2005	LTM240M1-L01	Samsung	1.303089
4	2004	LM300W01-A3	LG	1.245964
5	2001	SyncMaster 180T	Samsung	1.236020

mediocre technologies). The years of 2001 and 2006 had the fastest rates of change. This can be explained by breakthrough technologies introduced during those times (see Table 3).

The frontier year was defined as 2007 which means the dataset was divided into two groups. The first had LCD panels included from 1997 up to and including 2007. The second set was used for backtesting to see how well the results from 1997–2007 forecasted the 2008–2012 data for validation purposes. This was a challenge due to the slowing rate of change shown in Fig. 5.

The mean absolute deviation, MAD, was 1.89 years. Hence, it is expected that there could be a 22-month error when this forecasting model is applied to LCD industry from 2007.

Lower row of Table 2 shows the number of display technologies captured from the model; 2 inputs and 3 outputs characteristics were chosen for the model.

This model found that 88 out of 389 products were state-of-the-art when they were introduced. The non-state-of-the-art products are ones that were surpassed by a product or a combination of products.

Seven products were identified as state-of-the-art in 2007. Thirty products (out of 88 state-of-the-arts) were taken into account when the model calculated the average rate of change because they used to be state-of-the-art when they were released in the market but have been superseded by products released afterwards. In other words, TFDEA tries to capture this obsolescence process to measure the technology advancement.

The forecast result of backtesting shows that 9 products were released before the forecast, and 76 products were released after the forecast. This is consistent with the industry perception that the technology advancement has been slowing down (Tsai, 2012). Fig. 6 shows detailed results of this forecasting. Since the dataset was divided into two parts for backtesting, the model forecasted post-2007 products based on the RoC identified from
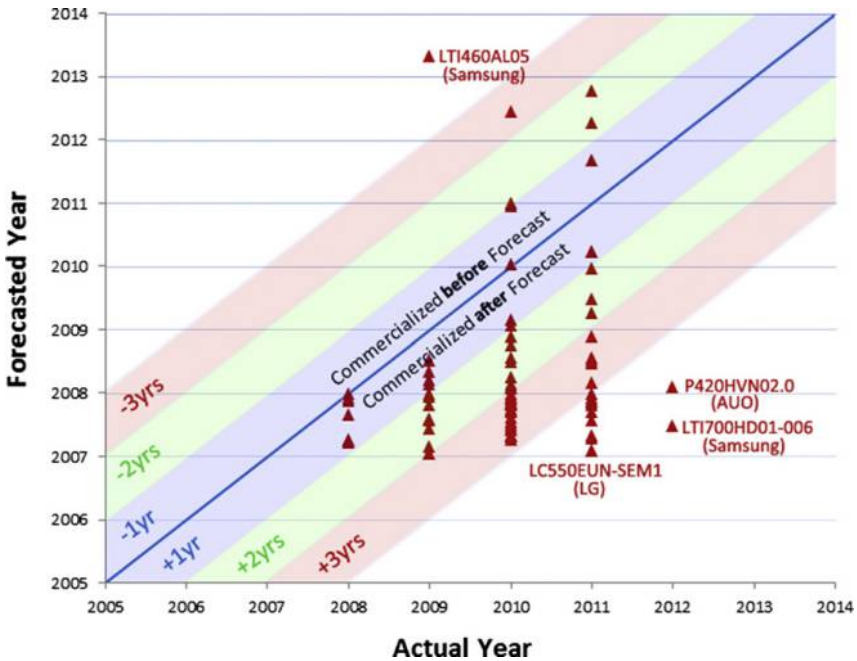
Fig. 6. Forecasting Results.

up-through-2007 technologies. As seen in the figure, some technologies are on the diagonal line which denotes perfect forecasting. Furthermore, most of forecasts are within ± 3 years range (note that mean absolute deviation is 1.891382, namely, 22 months).

Fig. 6 has four products with large forecast deviations from actual release dates; Table 4 provides more information on these products. The first model, "LTI460AL05," came out much earlier than expected and warranted attention. It had a 7.65 mm Bezel, which was much thinner than peers in 2009 (50.90 mm). The model forecasted that this level of technology (particularly a bezel this thin while maintaining the performance) would take more than 6 years from 2007 considering the average rate of change. However, it actually took only 2 years to introduce this product in the market.

On the other hand, three models came out later than were expected given their specifications. All three, "LC550EUN-SEM1," "P420HVN02.0," and "LTI700HD01-006," had relatively low contrast ratios (1400) and heavy screens (0.64 and 0.23). Therefore, they were introduced later than forecasted

Table 4. Examining Outliers.

Model (Producer)	Super Efficiency	Release Year	Forecasted Year	Error	Distinctive Feature
LTI460AL05 (Samsung)	0.370872	2009	2013.33	−4.33	Ultra-thin Bezel
LC550EUN-SEM1 (LG)	0.984897	2011	2007.10	+3.90	Low contrast ratio
P420HVN02.0 (AUO)	0.842535	2012	2008.09	+3.91	Heavy screen
LTI700HD01-006 (Samsung)	0.927418	2012	2007.48	+4.52	Heavy screen

by the model. However, this doesn't necessarily indicate that those were inferior products. Rather, manufacturers might have put more emphasis on other features that the forecasting model did not capture. For example, LTI700HD01-006 was a Digital Information Displays (DID) system which was aimed at outdoor digital signage and e-board applications requiring high reliability and robustness. In hindsight, it is not surprising that this product appears "obsolete" at time of release relative to the mainstream, indoor-oriented products. This product could be deleted from the analysis with no impact other than improving MAD (Table 4).

NPD Target Setting

With the model selected from validation process, future state-of-the-art products can be readily extrapolated. Since the model is using output oriented measurement, the simplest way is to multiply current output characteristics by average rate of change (1.169682) assuming constant input characteristics. Table 5 presents projected future state-of-the-arts from 2013 (+1 yr) to 2017 (+5 yrs) with bezel size/screen size of 1.06 and weight/screen size of 0.28. Conversely, if one wants to know when a specific level of technology can be realized as a state-of-the-art, expected time can be calculated by measuring gap between current level of technology and target specifications.

In order to facilitate planning such as focusing R&D resources on certain output performance, further application that can consider trade-offs among the output characteristics is also possible. This uses the inverse-DEA process to place a virtual product on the frontier line with given efficient, namely, state-of-the-art products.

Table 5. Projected SOAs Considering Concurrent Improvement.

Year	Screen Size (Inches)	Resolution (Megapixel)	Contrast Ratio (Luminance Ratio)
2012 (current)	41.25	2.679	2,133
2013 (+1 yr)	48.25	3.134	2,495
2014 (+2 yrs)	56.44	3.666	2,919
2015 (+3 yrs)	66.01	4.288	3,414
2016 (+4 yrs)	77.21	5.016	3,993
2017 (+5 yrs)	90.32	5.867	4,671

Table 6. Alternate 2017 SOAs Projections.

Screen size (Inches)	Resolution (Megapixel)	Contrast Ratio (Luminance Ratio)
56.93	2.189	11,385
	4.379	11,320
	6.568	10,509
	8.758	8,539
	10.947	6,678
87.58	2.189	9,196
	4.378	9,130
	6.568	8,758
	8.758	8,101
	10.947	6,658
109.47	2.189	6,787
	4,379	6,678
	6.568	6,131
	8.758	5,693
	10.947	5,036
131.37	1.095	3,941
	2.189	3,613
	4.379	3,722
	6.568	3,284

Table 6 presents diverse ranges of future state-of-the-arts specifications in 2017 (+5 yrs) from this process. Since each column combination can represent a state-of-the-art specification, a new product a developer may be able to get benefit from this virtual design concept when he/she tries to propose new product design.

The trend toward larger screen sizes has been very visible throughout the consumer television industry over the last decade. Table 6 allows us to examine what is expected to be state-of-the-art in 2017 for these different screen sizes. The screen sizes are similar to what might be expected for high-end home theater or certain commercial applications. The resolution values can be considered to be similar to certain video standards. For example, 1080p is currently the most common native resolution for HD televisions and is $1,920 \times 1,080$ or 2.07 megapixels. WQXGA is a higher resolution format currently used in computer monitors and is $2,560 \times 1,600$ or 4.1 megapixels. A less common format is referred to as 4K and is $4,096 \times 3,072$ or 12.6 megapixels.

Table 6 indicates that for a 57″ class HD television with resolution similar to WQXGA, the expected contrast ratio should be 11,320. Product designers could then evaluate their designs based on these specifications. If their contrast ratio is much greater, they are likely to have a product that outperforms competitors. If their contrast ratio is much lower, they should make clear why this product is different from the mass market – similar to the outdoor LCD panel discussed earlier.

LIMITATIONS AND FUTURE RESEARCH

Selection of inputs and outputs for any model is always a challenge. It is important to work with industry experts in selecting a model that balances the needs of the users, the fundamental tradeoffs in the product, data accuracy, and data availability. This model emphasized functional characteristics but could be further refined in future work with the addition of some form or proxy of manufacturing cost. Similarly, longevity (particularly for the backlights), connectivity, and power consumption are important to many buyers and could also be added in future work. It was expressed to the authors by the expert panel that contrast ratio published numbers can be "unreliable" as marketing departments take undue liberties despite attempts to create a standardized measure.

As the LCD market matures, the technologies across the specifications measured in the study are slowing down. As a result, LCD manufacturers are looking at other areas for differentiation such as display translucency, display tiling, adding computing/storage capability, or physically flexing the electronics. Adding these or other features might demonstrate greater growth or frequency of change.

Another analysis to consider would be a report on the slowing rate of change in performance characteristics and a declining sales of LCD and whether there is a relationship.

Because the average living room is limited in size and most likely will not increase significantly in the next 5 years, it seems unlikely that LCD panel sizes can continue to differentiate based on size. Innovations in other areas seem likely to increase in number and magnitude. An analysis of the market looking for this phenomenon and how the manufacturers respond might be of interest.

Further analytical refinements could be applied in future work to allow for varying rates of change. In fact, the analysis used the rate of change value (gamma) from the backtesting analysis period (1997–2007) when the industry was undergoing rapid change. Including rates of change as the industry slowed down would result in less aggressive targets for Table 6. Lastly, while TFDEA is an extreme point technique that is insensitive to poor performing products, excluding special purpose products such as outdoor displays that appear obsolete by the standards of the mainstream market would improve the diagnostics such as MAD.

CONCLUSIONS

The modeling technique generated results consistent what has been observed in the LCD market in general as components become more commoditized. The innovations in the targeted attributes are slowing down and a few of these are reaching market acceptability limits (screen size) and usefulness limit (beyond the eyes ability to distinguish resolutions). Therefore, emerging features such as refresh rate, built-in interactivity, wireless connectivity, or cloud display system, will have to be adopted as a new dimension of competition.

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