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**Article** *in* International Journal of Innovation and Technology Management · October 2015

DOI: 10.1142/S0219877016500061

International Journal of Innovation and Technology Management
Vol. 13, No. 1 (2016) 1650006 (27 pages)

DOI: 10.1142/S0219877016500061



# Competitive Pricing Using Data Envelopment Analysis — Pricing for Oscilloscopes

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Received 24 December 2013
Revised 25 January 2015
Accepted 8 March 2015
Published 1 October 2015

The research in this paper proposes a new technique for pricing products in competitive markets taking into account the features and prices of competing product offerings. This technique is based on a methodology known as data envelopment analysis (DEA) and is referred to as competitive pricing using data envelopment analysis (CPDEA). With the development of technology accelerating and new products coming to the market at an ever faster pace, prices of current products are often adjusted based on the state-of-the-art (SOA) technology in the market in order to remain competitive. CPDEA measures the product features that are most important to customers and calculates the performance efficiency values using the DEA method. CPDEA regards price as a performance feature, using this approach the manufacturer can adjust the price in order for a product to reach the SOA frontier and maintain competitive pricing. This research demonstrates the proposed method applied to a popular product category in the test and measurement industry: oscilloscopes. The authors investigated the features of oscilloscopes that are most important to users, then a feature dataset from different oscilloscope models was collected, and the performance efficiency values of the different models were calculated. The product prices are then adjusted in order for efficiency to be as close to 1 as possible which means that the products are considered SOA in the market. In this way, we obtain a more competitive price for the older products, while also setting the prices for the advanced products in a way that captures the value of their additional features.

*Keywords*: Pricing; market-oriented; data envelopment analysis.

## 1. Introduction

Technology continues to evolve at an ever increasing pace. This makes it more challenging than ever to balance all the elements of the market mix (product, people, price, place and promotion) and stay competitive [Grewal and Levy (2010); Kotler

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(1994); Perreault *et al.* (2008)]. One of the most difficult and important of these elements to assess is pricing.

There are a number of existing analytical tools that can be used to help with this task. However, they are largely based on customer or expert survey research which can be subjective, complicated and expensive to conduct.

In this study, we used the market for oscilloscopes to study the dynamic relationship that exists between features and pricing using data envelopment analysis (DEA). This market was chosen based on the wealth of public information on features and pricing; plus this is a mature market where buyers are sophisticated and understand the value of even small very technical features. In other words, this should be an efficient market.

DEA was chosen based on the ability to measure multiple product features along with product pricing all at the same time to establish an efficient frontier. Products that exist on this frontier are said to be state-of-the-art (SOA). With these results in hand it is then possible to adjust elements of the mix, in this case pricing, to create SOA products in spite of their more limited "feature set".

This study first reviews the marketing mix and the topic of pricing in more detail along with the tools that are currently used. Second, the methodology of the research, including the process and technique for competitive pricing using data envelopment analysis (CPDEA), is introduced. Third, the market for oscilloscopes is analyzed in detail. Then the results are gathered and DEA analysis is performed. This work is used as the foundation to find the optimal prices for current offerings. Finally, this study draws conclusions based on these results and provides direction for further research.



## 2. Literature Review

### 2.1. *Product pricing*

In product marketing, it is common to refer to the primary marketing elements around a product as the marketing mix. One simple and intuitive way to visualize the marketing mix is by using the strategic marketing model. This model has been applied in numerous customer engagements to find and resolve inconsistencies in product offerings. It consists of five elements: product, people, price, place and promotion — all built around the firms' competitive strategy and brand recognition.

One of the most difficult elements to master is product pricing. If the product price is set too high then volumes will not be sufficient to sustain the product offering of the company (in cases of a single product offering); if product price is set too low then all the value associated with the offering will not be captured (e.g. we leave money on the table) — in some cases we may not even be able to capture the cost of goods sold (COGS).

In general, there are three considerations when setting product pricing. The first is the COGS. Firms should not sell a product below the actual cost to produce it without some other type of consideration. For example, companies often sell PC printers at or below cost, knowing that they will earn much more on the continuing purchase of ink and supplies. However, this model will not work for most product sales where there is not a continuing stream of repurchases [Dobney (2012); Mohr *et al.* (2010)].

The second consideration is the value in the mind of the customer. Customers purchase with the desire to solve a problem or fulfill a need [Harmon *et al.* (2007)]. Pricing decisions should be made with an eye towards capturing as much of this value as possible. Once again, there may be cases where we give up near-term value for strategic reasons (e.g. market penetration); however, the acquisition of market share would compensate for the additional value.

The third consideration is competitive pressure in the marketplace. If a competitor is offering an equivalent solution, at a price that is less, with all other things equal, then that competitor would be expected to be more effective in the marketplace. There are elements such as a strong brand that can upset this equation (e.g. the brand transfers some additional value to otherwise like products); however, in general, equivalent solutions should be priced in a similar price range.

While this sounds pretty straightforward, in practice understanding all the different dimensions of the competitive and economic environment, product features and unique customer motivations and attitudes can be extremely challenging. To assist in this regard several different methodologies have been developed. The five most common include: conjoint analysis, Van Westendorp price sensitivity meter, Gabor–Granger, brand versus price trade-off (BPTO) and expert panel session. In 2000, an international study of 175 marketing and management professionals found that conjoint analysis was used most frequently (44%), followed by Van Westendorp (28%) and expert panel sessions (27%). Gabor–Granger and BPTO were used less frequently at 20% and 16% respectively. Of those surveyed less than 4% had a high satisfaction rate with their pricing methodology — most (56%) were moderately satisfied — the balance had a low satisfaction rating (40%). Thus, even in the marketing community there is general agreement (96%) that the tools available to assist with pricing are not sufficient [Dierick and Depril (2010)].

*Conjoint analysis*: Conjoint analysis is a technique that allows prospects to trade price against features for a number of products. The goal is to understand both trade-offs and the elasticity of demand at different price points. Products that have an inelastic price will show little change in demand when prices increase — products with elastic price will show the opposite. The technique involves showing users different combinations of features and prices and allowing them to rank them (weighted ranking with the total being 100) [Curry (1996); Green and Savitz (1994); Johnson and Olberts (1996); Sawtooth Software (1988)].

Compiling the responses allows the researcher to create a demand curve for the product and different product combinations. There can be sampling error, especially in the case of many choices; however, with a large sample size the error rate can be reduced.

*Gabor–Granger*: This is another survey technique named after the economists who invented it in the 1960's. Prospects are given a survey asking if they will purchase products at a specific price point. Once the results are collected, the prices are changed, and the process is completed again. By capturing the willingness to purchase at each price point the researcher can create both a demand curve and a forecast revenue curve. If revenue is then compared to COGS along this curve then the optimum price can be selected.

*Van Westendorp*: Prospects are asked four questions to determine what prices are too cheap, what price is a bargain, what price is expensive and what price is too expensive. This information is then plotted to see where the curves cross; for example, where the bargain and too expensive curves cross. The end result is a range of acceptable prices that can factor into the pricing strategy.

*Brand price trade-off*: In this case customers evaluate a range of products and prices are adjusted until customers stop purchasing. This type of analysis can also be done with a special case of conjoint analysis holding pricing constant and judging purchase decisions.

*Expert panel sessions*: This technique allows a marketing team to interact with a group of customers or market experts and ask specific targeted questions. Unlike a focus group that is usually targeted at a "random" group of prospects that fit the target market criteria, this technique counts on having an interactive session with key customers or thought leaders who understand the product category well.

These techniques, while all providing useful input to the pricing decision, are based largely on survey research that is dependent on the response of the prospect (or expert). There is always the potential for errors when the opinions of participants do not map directly to the prospects in the market being addressed. This risk decreases with an increase in sample size — once again, assuming the demographics of the audience are correct. However, this does not eliminate the gap that exists between buyer perception (what potential customers say they would do) and buyer behavior (what customers actually do).

## 2.2. *Oscilloscope market*

The basic functionalities of an oscilloscope are electrical signal acquisition, conditioning, attenuation and amplification. Electrical signals are presented visually as waveforms in a display with functional attributes like vertical channels, horizontal channels, time basis, system triggers and display units [Pereira (2006); Tektronix (2011b)]. Conceptually the user can imagine the $x$-axis of the display as time and the $y$-axis as voltage displayed as a waveform. This analysis provides a set of measurements and analysis of electrical signals, which can be stored or retrieved.

Oscilloscopes are used in electronics and electrical engineering to analyze and capture electric signals in the time domain. Complex circuits have now found their way into everything from home appliances to automobiles, and even product packaging. Given our dependence on electronic devices, oscilloscopes have become an important tool for testing, debugging and troubleshooting in many industries. The evolution of the oscilloscope has historically been linked to technology breakthroughs in communications technology, and over time, are increasingly defined through technological features and specific domain applications [Hannes (2009); Pereira (2006)].

Oscilloscopes went from an early technological stage measuring waveforms through spinning rotors using the degree of rotation recorded on paper, to a second stage in which advances in photographic technology introduced photographic oscilloscopes [Swift (2009)].

The next big revolution in oscilloscopes technology came with analog cathode ray tubes (CRT), which continued to grow with triggered-sweep oscilloscope technology. The digital oscilloscope became prevalent in the early 80's, its adoption quickly accelerated with technology evolution and ubiquitous transition to digital platforms in industrial and consumer products [Hannes (2009); Bommakanti (2011)].

## 3. Research Objective and Methodology

### 3.1. *Research objective*

The research in this paper proposes a new technique for pricing products in competitive markets taking into account the features and prices of competing product offerings. This technique is based on a methodology known as DEA and is referred to as CPDEA.

The speed of innovation and new product development in competitive markets continues to accelerate at a rapid pace. In this environment, when new products are introduced they do not necessarily disappear, they often remain in the market at a price that decreases over time to reflect the market's perception of reduced value — the latest and greatest products often command a price premium. Providers of products and services need to be able to price their products competitively: if they price too high then volume can drop to zero; price too low and money is left on the table.

This paper uses DEA to set prices of the product currently on the market so that these products are brought to the SOA surface. In another word, products can be priced using CPDEA in order to become competitive on the market.

### 3.2. *Overview of DEA*

DEA can be used to measure the SOA and technology trade-off surfaces. A DEA efficiency frontier is constructed by considering the key attributes of the individual products in the market, which is a representation of the current technological SOA. Gordon and Munson [1981] developed a procedure for determining the SOA, and Andersen and Petersen [1993] used DEA to rank efficient decision-making units (DMUs) relative to a reference technology spanned by all other units.

In the realm of new product development, DEA is usually used to evaluate the efficiency of products which are currently on the market. The products on the SOA surface which are efficient have an efficiency of 1. The inefficient products have an efficiency number greater than 1 when the "output" orientation is used; or a number smaller than 1 when the "input" orientation is used.

R is used as a tool to do DEA analysis in this paper. R is a free software environment for data analysis and visualization. R provides a scripting language that offers a level of control that a menu-based system cannot readily provide. The methods used in this paper are available in the "Benchmarking" package [Bogetoft and Otto (2010)]. The DEA method contained in the "Benchmarking" package provides a fast and effective way to calculate efficiencies.

### 3.3. *The technological performance evaluation of products*

When a technology product is evaluated according to technological performance, the hierarchical decision model is frequently used. The criteria and subcriteria are decided by customers with regard to the utility that the product provides. At the lowest level, a product model is composed of a series of technological features, which are listed, and then compared to each other, because these features embody the utility of each product model to customers [Inman *et al.* (2006)].

After the technological features are identified, a model for technology performance evaluation is set up, as shown in Fig. 1. In this model, we used $n$ technological features.

Some features are numerical and the other features are descriptive. For the numerical features the utility might be a function of the numeric value, for example, the higher the maximum bandwidth, the better the performance — the utility of the feature increases as the maximum bandwidth rises. However, it does not increase in proportion to the maximum bandwidth value; it increases as a function of natural log function. So we can transform the natural log of the maximum bandwidth into the utility function of bandwidth.

For the descriptive features, such as "ease of use", it is not as simple to get the utility directly from customers. It can only be obtained by doing direct survey research. So, for this reason, this study avoided using descriptive features to evaluate the models.

The data values should reflect the utility value since this project used an output-oriented DEA model. In the case of a feature such as weight, where the utility increases with a decrease in value, the reciprocal can be used to transform the variable. Lower values for weight are valuable for portable applications; while this feature is less important than space for bench models. However, since space can be positively correlated with weight (e.g. thinner units weigh less) then we can use this transformation regardless of segment.

To calculate the efficiency of each model in technological performance, the formulation to calculate the technological efficiency (TE) can be shown as Eq. (1).

Objective function:

$$\mathrm{TE}_o = \min(\alpha_o), \tag{1}$$

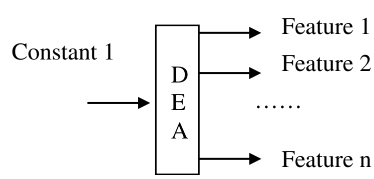


Fig. 1. Common model for technology performance evaluation.

such that

$$\sum_{j=1}^{J} y_{i,j} \cdot \lambda_j \leq \alpha_o \cdot y_{i,o}, \quad \forall i,$$

$$\sum_{j=1}^{J} \lambda_j = 1,$$

$$\lambda_j \geq 0, \quad \forall j,$$

where $o$ is the sequence number of the DMUs which is targeted to calculate its efficiency, $\mathrm{TE}_o$ is the technological performance efficiency of the targeted DMU, $i$ is the sequence number of output features, $j$ is the sequence number of the DMUs, $j = 1, 2, 3, \ldots, J$ and $y_{ij}$ is the feature value of the $i$th-output of the $j$th-DMU.

Since the input is a constant 1, we choose to use variable return to scale (VRS) and output orientation (OO). The DMUs with TE value equal to 1 are efficient in terms of technological performance. The DMUs with TE value greater than 1 are inefficient in terms of technological performance [Lim and Anderson (2012); Bogetoft and Otto (2010)].

To perform DEA calculation, the "Benchmarking" package in R is used. The newest version of R was downloaded from www.r-project.org. Manuals and other materials are also available on the same website. The "Benchmarking" package was then installed and the command "> library(Benchmarking)" is used to access the package. Research data was then imported from a text file with comma separated values (.csv file — using Microsoft Excel choose "Save as" and select csv from the pull-down). In this case, the input $x$ is a matrix with a single column and a row for each DMU — the value for each DMU in this column is set to a constant of 1. The output $y$ is a matrix with the feature values with each row corresponding to a DMU and each column representing a technological feature.

The following is an example of the R code used.

```
>x<-constant1
>y<-6technology.features
>e<-dea(x,y,RTS="vrs",ORIENTATION="out")
>e
```

### 3.4. *CPDEA model: Price as a feature in the evaluation of market performance*

The key to CPDEA is to include price as an evaluation feature so that it can be adjusted in order for a product model to reach the SOA surface. The level of technological advancement can be evaluated by examining specific technological performance features. However, for customers, the amount of money spent to purchase the overall utility provided by a specific bundle of features is a significant concern. A useful way to conceptualize this is to consider the price as an input to a DEA model and to consider the technological performance features as the outputs, as shown in Fig. 2.

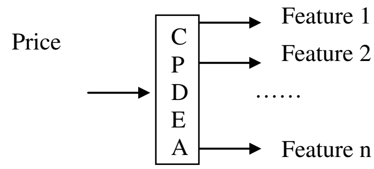


Fig. 2. CPDEA model.

The more a customer pays to buy the product model, assuming an efficient market, the higher technological performance they will expect the model to have. Assuming that there are several models with the same technological performance, the model with the lowest price is on the SOA frontier, and the other models are driven below the SOA frontier due to the higher prices.

The inclusion of price as an input to the performance evaluation criterion differentiates the market performance from the technological performance.

To compare the efficiency of each model in market performance, the formulation to calculate the marketing efficiency (ME) can be shown as Eq. (2). It uses the price as the only input and the utilities of the technology features as outputs. It is an input-oriented model.

Objective function:

$$\mathrm{ME}_o = \min(\theta_o), \tag{2}$$

such that

$$\sum_{j=1}^{J} p_j \cdot \lambda_j \le \theta_o \cdot p_o,$$

$$\sum_{j=1}^{J} f_{i,j} \cdot \lambda_j \ge f_{i,o}, \quad \forall i,$$

$$\sum_{j=1}^{J} \lambda_j = 1,$$

$$\lambda_j \ge 0, \quad \forall j,$$

where $o$ is the sequence number of the DMUs which is targeted to calculate its efficiency, $\mathrm{ME}_o$ is the market performance efficiency of the targeted DMU, $i$ is the sequence number of output features, $j$ is the sequence number of the DMUs, $j = 1, 2, 3, \ldots, J$, $p_j$ is the feature value of the price of the $j$th-DMU and $f_{i,j}$ is the feature value of the $i$th-output of the $j$th-DMU.

The following is an example of the R code used.

```
> p<-price
>f<-technology.features
>e<-dea(p,f,RTS="vrs",ORIENTATION="in")
>e
```

### 3.5. *CPDEA research process*

The basic principal of CPDEA is to measure the ME of product models (DMUs) and adjust the price to make the specific DMUs efficient (e.g. make sure they are on the frontier). There are eight steps in the CPDEA process.

(i) Determine market and product models to evaluate.
(ii) Determine key attributes that define "technological performance".
(iii) Determine the correct way to represent the utilities of the attributes.
(iv) Collect data on all relevant products.
(v) Formulate the CPDEA model.
(vi) Run the CPDEA model to generate efficiency values.
(vii) Adjust prices to bring efficiency values to 1.
(viii) Analyze the results.

In this subsection, the entire CPDEA process will be demonstrated using the pricing of oscilloscopes currently available at the time of this study.

#### 3.5.1. *Determine market and the product models to evaluate*

This research used the current market for oscilloscopes to demonstrate the feasibility of CPDEA. The data gathering process is captured in Fig. 3 as below.

The search for specific models to evaluate started with gathering documents on the public website of Tektronix. This research uncovered product benchmarks where Tektronix's products were compared against other manufacturers with similar specifications. Going one step further, the products found in the Tektronix benchmarks were then identified by model types and manufacturers. The website for each of these manufacturers was then researched for product specifications. The manufacturer brands researched in this study included: Agilent, GW Instek, LeCroy, Rigol, Tektronix and Yokogawa. These models were all available in the market in December, 2012.

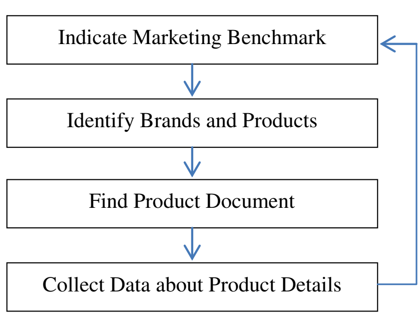


Fig. 3. The data collection procedure.

3.5.2. *Determine key attributes that define "technological performance"*

The advances in oscilloscope functionality continue to result in more complex products with advanced capabilities, performance and technical characteristics which can be observed in the technical specifications and data sheets. Since the use of oscilloscopes is deeply rooted in technical fields, selected technical specifications are looked upon as important trends [Nelson (2010)].

One of the most critical features in an oscilloscope is bandwidth. Bandwidth is recognized as an important specification that defines the maximum frequency ranges of signals that can be displayed while also displaying the accurate amplitude of signals, having wide ranges of bandwidth can accurately measure rise time of signals in forms of frequency and shapes of the frequency waves [Lashlee (2008)]. In information theory, bandwidth is mathematically defined using the Nyquist–Shannon sampling theorem [Pereira (2006)]. Even with the trend towards higher bandwidth continuing, Frost and Sullivan conclude in 2012, that lower bandwidth models will remain viable in the market [Nelson (2010)].

Bandwidth is not the only important specification in oscilloscopes; specifications involve multiple aspects that are worth considering. A presentation published by Rohde and Schwarz, a significant manufacturer in the oscilloscope market, argues that sampling rates and memory depth are also critical to solid oscilloscope technical specifications [Rohde and Schwarz (2012)]. Sampling rate is important when converting signals of waveforms to digital value. Faster sampling rate in oscilloscope provide greater resolution and accuracy of results. Looking into digital oscillators, memory depth is closely related to sampling rate and becomes an import factor as well. Memory holds data sampling rate overtime and records transient events in details [Tektronix (2011b)].

In oscilloscopes, triggers outline the point in time where series of repeating windows of waveforms stabilize; this provides data that can be analyzed in more detail. The trigger function is used to synchronize horizontal sweeps to the proper point of a signal and provides flexibility in controlling the stabilization of repetitive waveforms while also capturing single shots within the waveform [Rohde and Schwarz (2012)]. There are different types of trigger functions such as edge triggering, a basic common function that works with analog and digital oscilloscopes. Unlike analog oscilloscopes, digital oscilloscopes provide an advantage with numerous variations of trigger settings and advance triggering control [Tektronix (2011a)].

Agilent Technologies makes the case that bandwidth, sampling rate and memory are all critical features; however, users should focus more on the needs of their specific application and not on general capabilities. In addition, Agilent argues for architectural technology that increases functionality such as: portability, better forms of display, a focus on verification rather than debugging, multiple measurements of mixed signals and serial architecture [Lashlee (2008)].

Finally, an important component that provides visual output of waveform and signal is the screen. Larger display sizes have gradually become important providing more space for visual outputs and viewing multiple channels. In addition to larger screen sizes, higher resolution display technologies have also been implemented transitioning from the classic CGA, to VGA and XGA. Digital oscilloscope displays can also have a conceptual $z$-axis that allows displaying (highlighting) a third dimension of waveform as well as the standard bidimensional $x$- and $y$-axis [Agilent (2003)]. A typical display size for an oscilloscope can range from 5 inches to 8 inches. Several models from a number of different providers offer display sizes larger than 8 inches.

The research here uses oscilloscopes as a case to demonstrate the procedure. The process begins by considering the most important aspect of oscilloscope performance, which is determined based on a scan of literature, the Tektronix website, and with input from a local oscilloscope expert. Six key features were identified which are important to the technological performance of oscilloscopes.

To validate these selections, a survey was created and submitted to technical professionals in industry and academia that use this equipment. The survey included the original four criteria with a rating scale of 1 to 5 for importance (5 being the most important). We also included a section where survey participants could add other factors that they considered important and rate their importance as well.

We received responses from eight technical professionals with combined industry experience of 146 years. The amount of experience of survey participants ranged from one year to 40 years, with the group average being slightly more than 18 years.

After normalizing the responses, we observed that bandwidth, maximum sample rate, maximum channels and trigger modes, in this order, were the most important product features to consider. There were three other factors that were identified as important by multiple survey respondents: USB interface, display (color/size) and trigger bandwidth.

There were an additional 14 written responses that were identified by a single respondent. These elements included: different trace color, autoset MES, Ethernet port, digital sampling, ease of use, resolution bits, sample clock jitter, easy upgrade, cascading triggers, trigger external digital sources, exception interrupt, negative trigger history, GPIB and standard software.

Given the experience of the participants and the frequency and rank for the top four elements it was certain these should be considered in any analysis.

A follow-up phone call was also conducted with the Electrical Engineering Lab at Portland State University to discuss the results. That discussion led to the addition of several new elements: internal memory, display size, display resolution and interface ease of use. Trigger modes, especially from an external digital source, were determined to be valuable; however, trigger modes are a standard feature included on every model. We also discussed the importance of compatible probes.

Price was not in the survey; however, this will be included in our analysis because with all other factors being equal, price drives purchase/upgrade decisions.

The outcome of the survey indicates that bandwidth, maximum sample rate, weight, maximum number of scope channels, vertical resolution bits and number of I/O modes are the most concerned technological attributes.

### 3.5.3. *Determine the correct way to represent utilities of the attributes*

Once the key attributes are identified, the forms to represent the utilities of these attributes must be determined. The utility, or usefulness, is the perceived ability of something to satisfy needs or wants. The more desired an attribute is, the higher utility it has. For some attributes, the higher the values are, the more desired the models are, hence these attributes have higher utilities when the attributes' values are higher, such as bandwidth, maximum sample rate and maximum number of scope channels, vertical resolution bits and number of I/O modes. For some other attributes, the lower the values are, the more desired the models are, hence these attributes have higher utility value when they have lower attributes' values, such as weights (the lower the weights are, the higher the utilities are). So the utilities could be regarded as a function of the attributes' values. Not all utility functions are linear. According to experiences, in the case of oscilloscope models, the utility function of bandwidth, maximum sample rate and total weight could be indicated as Eqs. (3)–(5) [LeCroy (2008)]:

$$U(\text{Bandwidth}) = \text{Ln}(\text{Bandwidth}), \tag{3}$$

$$U(\text{Max sample rate}) = \text{Ln}(\text{Max sample rate}), \tag{4}$$

$$U(\text{Total weight}) = \frac{1}{\text{Total weight}}. \tag{5}$$

After the utility features are identified, the technology performance model is set up, as shown in Fig. 4.

### 3.5.4. *Collect data on all relevant products*

The research in the manufacturers' and distributers' websites performed earlier led to extensive product documentation including data sheets, product specifications, benchmarking documents, revision and software update documentation and product end-of-life documents. From the benchmarking documents, other models and manufacturers that were previously under the radar were identified and researched.

The product parameters researched were based on the information retrieved from the expert survey results. Most parameters were relatively easy to locate in the data sheets and product specifications. The data about the oscilloscope models are shown in Appendix A.

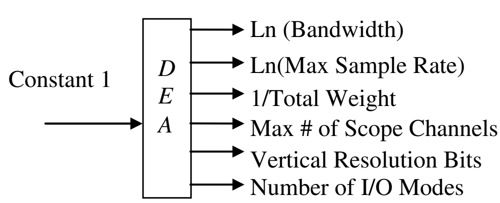


Fig. 4. The technological performance evaluation model of oscilloscopes.

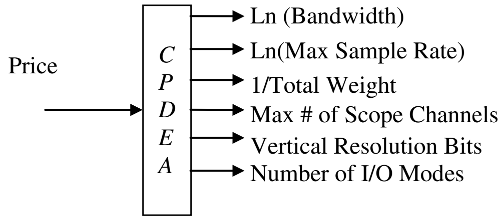


Fig. 5. The CPDEA model of oscilloscopes.

### 3.5.5. *The formulation of the CPDEA model*

The CPDEA model uses price as an input and the remaining $n$ technological feature values as outputs. After the technological performance model is identified, the input should be replaced by price and the CPDEA model is set up, as shown in Fig. 5.

To calculate the efficiency of each product model, the formulation can be shown as Eq. (2).

An explanation to Eq. (2) is shown in Fig. 6. The product models (points) under the surface can become SOA models by decreasing prices.

The CPDEA model uses VRS and input orientation (IO).

### 3.5.6. *Run the CPDEA model to generate efficiency values*

Usually, pricing adjustments are needed when a new more advanced model is released, which offers new features at a comparable price to older models. In this instance, the older model needs a decrease in price to maintain its position as a SOA product in market performance.

The other pricing requirement happens with newer models, if this model is more advanced in technological performance compared to existing models in the market, it needs appropriate pricing to capitalize on the higher utility it can provide. The high-end model usually enters the market with a high price. This high pricing is profitable provided the demand elasticity of the product is low. Marketing professionals want to find the lower limit to keep the high-end models as profitable in market performance as possible. The pricing of high-end models should avoid the situation of pricing less than the lower limit.

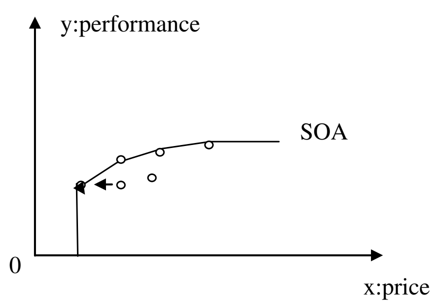


Fig. 6. Explanation of Eq. (2).

CPDEA only requires the calculation of efficiency value, define the input and outputs and calculate the efficiency values using Eq. (2).

In this case, the input $\boldsymbol{p}$ is a matrix with one column comprising the prices of the DMUs. The output $\boldsymbol{f}$ is a matrix of feature values with each row corresponding to a DMU and each column representing a technological feature. The following is an example of R code.

```
>p<-price
>f<-6technology.features
>e<-dea(p,f,RTS="vrs",ORIENTATION="in")
>e
```

Since the CPDEA model is an input-oriented model, the efficient DMUs have ME values equal to 1 and inefficient DMUs have ME values less than 1 [Lim and Anderson (2012); Bogetoft and Otto (2010)].

The next step is to make price adjustments to assure that the designated models get a competitive advantage as an SOA models (e.g. get an efficiency value which is 1).

Products may have different models for different market niches; this does not matter to the selection of the model. The DEA methodology can handle all the models in the market simultaneously. In the examination of oscilloscope pricing that follows, DEA is used to look at all segments simultaneously including stationary oscilloscopes and portable oscilloscopes.

#### 3.5.7. *Adjust prices to bring efficiency to* 1

Once the efficiency values of the models have been generated, the models with efficiency values which are not equal to 1 will be adjusted to 1 by reducing the prices. When doing the adjustment to price we used Eq. (2) as a standard form of CPDEA.

When new advanced product models are released and the old models are driven away from the SOA surface, the prices of the old models should be adjusted according to the new model's price and technological features using the following steps:

(i) Calculate the ME of the selected models using CPDEA model.

(ii) If the model's efficiency calculated by the standard form $\mathrm{ME}_o < 1$ then decrease the price, the adjusted price is calculated by Eq. (6) as follows:

$$p'_o = \mathrm{ME}_o \cdot p_o, \tag{6}$$

where $o$ is the sequence number of the DMU which is targeted to calculate its efficiency, $\mathrm{ME}_o$ is the marketing performance efficiency of the targeted DMU calculated by Eq. (2), $p'_o$ is the adjusted price of the targeted DMU, $p_o$ is the original price of the targeted DMU.

(iii) Run the CPDEA model again to get updated efficiency values to validate that $\mathrm{ME}_o = 1$.

When the efficiency value is less than 1, the model is outperformed by other model(s). In this case, the manufacturer would be advised to decrease the price to remain competitive. The price should be decreased to the point where the efficiency value is 1.

When a new advanced model is going to be put into the market, pricing is a key step in marketing research. CPDEA provides marketing professionals with a powerful tool to look at the competitive offerings available and price the new product properly to avoid overpricing or underpricing.

Pricing using CPDEA should be performed as follows:

(i) Give a price to the new product model; calculate the efficiency of this new model using CPDEA model.
(ii) If the efficiency $\mathrm{ME}_o < 1$, decrease the price using Eq. (2).
(iii) If the efficiency $\mathrm{ME}_o = 1$, examine the efficiencies of other DMUs, if there is any other $\theta_{mk}$ turned from 1 to less than 1, $k \in \{1, 2, \ldots, K\}$ and $k \neq o$, increase the price.
(iv) Repeat the steps (ii) and (iii) to make the efficiency value $\mathrm{ME}_o \in (0.99, 1]$.
(v) Run the CPDEA model again to get updated efficiency values $\mathrm{ME}_k$, $k \in \{1, 2, \ldots, K\}$.

In this case, when the efficiency value becomes equal to 1, the model lies on the frontier of the SOA surface, which might move the SOA surface and make other models lose the position ($\mathrm{ME}_k$ turns from 1 to less than 1, $k \in \{1, 2, \ldots, K\}$ and $k \neq o$). That means the influenced model will become inferior. Some aggressive vendors might price in this way so that the model can become the SOA if the affected model is not produced by them. However, this choice will lower the profit of the new model.

When this vendor also produces the influenced SOA model, they might want the influenced model and the target model both on the SOA surface ($\mathrm{ME} = 1$). The vendor might choose to make efficiency as close to 1 as possible rather than permit it to move from the SOA surface.

There is an extreme situation; a particular model could be the SOA model in the market with respect to technological performance. From a competitive standpoint, this model cannot be priced too high since the price does not influence the position of the model on the SOA surface. The price can be extremely high; however, because of the advanced technological features of it, the model will remain on the surface of SOA. In this case, the price's lower limit is the second technologically competitive model's price which is the highest price of similar model; the upper limit is the customer's value which the model provides. Usually, the vendor has to consider the demand of the product according to demand-price elasticity. The other pricing methods discussed in the literature review have to be used to address a price for the novel advanced model.

An explanation to the lower and upper limits of a new advanced model is shown as Fig. 7.

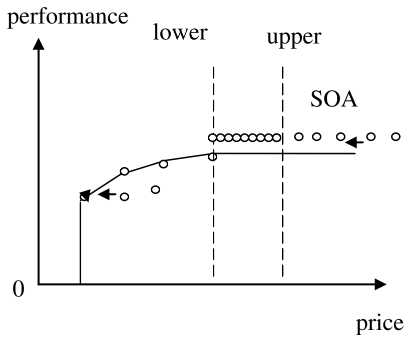


Fig. 7. An explanation to lower and upper limits of a new advanced model.

### 3.5.8. *Analyze the results*

Once price has been adjusted the models should have competitive prices. However, because of feature limitations they still may not be able to deliver the utility required by customers. Thus, the difference needs to be explored a second time.

There are several possibilities for the difference between the expected prices and market prices.

(i) The price is obsolete, which needs adjustment to make the product stay in the SOA in the market.
(ii) Some models are being promoted with price discounts. The discounted prices are not listed.
(iii) Some models are about to exit the market.
(iv) Some models have outstanding descriptive features which are not included in the CPDEA models.
(v) Some models have shortcomings which are not included in the CPDEA model.
(vi) Some products with high demand-price elasticity, the manufacturer would like to lower the price to promote an advanced model in order to obtain maximum profit.

## 4. Oscilloscopes' Technological Performance Evaluation

In order to evaluate the performance of the models we use "bandwidth (Mhz)", "max sample rate (analog) (MS/s)", "max number of scope channels", "vertical resolution bits", "number of I/O modes" and "total weight (kg)" as output. We observed that the difference in "bandwidth (Mhz)" and "max sample rate (analog) (MS/s)" are large. However, the utility associated with them is not increasing linearly in proportion to the numbers, so this analysis used the natural log as an indicator of the utility of "bandwidth (Mhz)" and "max sample rate (analog) (MS/s)". When weight is considered as an output, lighter is generally considered better in this product category; therefore, the reciprocal of "total weight" was used as an output. In this way, the CPDEA model was set up as shown in Fig. 4.

In Appendix B, the values of "technological performance efficiency" demonstrate the technological level of the models.

This analysis shows that the values are close to 1, which means that the models have close performance according to the six outputs used. DMUs 2, 8, 15, 21 and 26 have a larger value, greater than 1.05, which means that these five models are far below the SOA frontier in the market at the time when the research was conducted, December of 2012 — these models are outperformed.

Technological performance evaluation provides a market map of the different models. The advanced models deserve higher prices and the outperformed models can only obtain competitiveness by lowering prices.

## 5. Oscilloscopes' Competitive Pricing

### 5.1. *The CPDEA model for oscilloscopes*

After we evaluate the technological performance of the models for oscilloscopes, we will use CPDEA to adjust prices. In the market, the price is set according to the perceived value (performance) of the models. The higher the price of the model is, the better technological performance the model should offer. Thus, price is added as an input to the CPDEA model as shown in Fig. 5.

The result shows some changes in performance — the values of "market performance efficiency" are underlined which are less than 1, as shown in Appendix B. These models with a market performance efficiency which are less than 1 (DMUs 1, 2, 4, 6, 13, 14, 15, 19, 20, 21 and 26) should decrease in price.

To reach that, new price values are calculated to make the "market performance efficiency" equal to 1, as shown in Appendix B. The prices of DMUs 1, 2, 4, 6, 13, 14, 15, 19, 20, 21 and 26 need to be decreased in order for them to become the SOA in the market. The "adjusted prices" are the products of the "original prices" and the "market performance efficiency (with original prices)".

### 5.2. *The discussion about the price adjustment*

To clarify the reasons for the difference between expected price and market price, further research concerning the technological performance of the 26 models is conducted.

We found that the prices calculated using CPDEA of some units are much lower than the market prices. DMU 2 has the lowest ME, which means that it has to decrease the price almost 50% in order to reach the SOA surface. We called the vendor and found that the model has been discontinued. Thus, the result produced using the CPDEA method was further validated.

Technology features which were not included in earlier research are investigated. It was discovered that some models have some outstanding features which were not included in the analysis and warrant a higher price. It can be observed that some DMUs are differentiated by the fact that they can perform signal analysis on analog channels in addition to the digital channels that the other models provide. In fact, they represent products in a more advanced category of oscilloscopes known as mixed signal oscilloscopes (MSOs). MSOs allow users to visualize multiple time-aligned analog and digital waveforms on the same display. This opens the door to a vast range of new applications and, perhaps most importantly from the vendor's point of view, to a much wider range of customers and a higher pricing category [Adrio Communications (2011)].

The primary measurement applications of MSOs involve debugging and verifying microcontroller unit (MCU) digital signal processing (DSP)-based mixed signal designs that have embedded address and data buses [Adrio Communications (2011)]. This application domain also includes debugging and verification of serial buses, which nowadays are present in most electronic platforms; this includes I2C, SPI, RS-232, CAN, LIN, USB, Firewire buses and others. Additionally they allow for designing and debugging of digital signals in hardware with limited or no physical access to its internal circuits, e.g. ball-grid array (BGA)-based chips and densely populated printed-circuit boards (PCBs). Because of the digital channels features, MSOs are increasingly more competitive in other product categories solely dedicated to digital signal analysis like logic analyzers and other software-based debugging tools (e.g. JTAG boundary scan products).

In summary, the MSOs would generally be priced higher when including advanced features that provide more value to customers. So we separated the MSOs from the other oscilloscopes and ran the CPDEA model. The Appendices C and D are the results. According to the results in Appendix C, in the MSOs, DMUs 15 and 20 are the only ones which should decrease prices to reach the SOA frontier. According to the results in Appendix D, in the oscilloscopes other than the MSOs, DMUs 4, 6, 13, 14 and 21 should also decrease prices accordingly in order to remain competitive in SOA frontier.

## 6. Conclusion

The research in this paper proposes a new methodology for pricing products present in the market based on the DEA method, CPDEA.

The speed of innovation and new product development in competitive markets continues to accelerate at a rapid pace. In this environment, when new products are introduced they do not necessarily disappear, they often remain in the market at a price that decreases over time to reflect the market's perception of reduced value — the latest and greatest products often command a price premium. Providers of products and services need to be able to price their products competitively: if they price too high then volume can drop to zero; if they price too low then money is left on the table.

There are a number of analytical marketing techniques that are used to determine optimal pricing. These include: conjoint analysis, Van Westendorp price sensitivity meter, Gabor–Granger, brand versus price trade-off and expert panel session. However, these techniques rely largely on direct customer survey research which is complicated and time consuming to set up; as well as subject to bias based on individual opinions.

This study uses DEA methodology to examine the actual prices and features currently available in the oscilloscope market and find those offerings that are SOA.

Product prices are adjusted in order for the efficiency to be 1 which means that the products are considered SOA. In this way, we obtain a more competitive price for the older products.

CPDEA provides an analytical tool that is not biased by subjective customer opinions to assist with competitive pricing, especially for those offerings with complex feature sets. CPDEA does not replace existing pricing research tools; however, it does represent a powerful source of market-based input that can help us make more informed decisions that are not based strictly on subjective survey techniques or stand-alone price comparisons.

## 7. Further Research

One limitation is that this methodology does not capture the additional value associated with a company or product brand. While there are certainly brands associated with lower price products and services (e.g. Southwest Airlines), there are also brands developed over time that often command a premium price even without market leading technical features. For example, notice the price differential between Lexus and Toyota — both brands belong to the same company, use the same chassis and power train, yet Lexus commands a price premium in the market. With CPDEA, we would expect offerings with the same technical features to occupy a similar space with respect to price. Future research could explore ways that brand equity could be integrated into this model.

As discussed earlier, there are some features such as "ease of use" that were not captured in this study because they required subjective assessment. However, especially with consumer products, attributes such as "ease of use" definitely influence price. A product that is too hard to use may never gain momentum regardless of price, where, as a product that is intuitive and user friendly may sell rapidly in spite of a price premium. There could be additional insights gained by exploring the right way to incorporate subjective product attributes into this model.

There is also a role that supply and demand may play in pricing. If a product is very popular, yet is in short supply, it may command a price premium in the market even if the technical features are similar to other models. The CPDEA model does consider scarcity with respect to an entire market, because all products are competing for the same wallet. When the products for an entire market are scarce then all products should experience price elevation. However, it does not consider the scarcity of a particular model especially when that model is very popular. It would be useful to experiment with methods to add an index that can capture the elements of supply and demand.

## Acknowledgments

This paper is based on a team research project conducted with the help of Ignacio Castillejos Lopez, Shengte Tsai, Christophe Perrenoud and Phaneendra Rampalli.

## References

Adrio Communications (2011). Developments in oscilloscope technology — An interview with Tektronix. Available at http://www.radio-electronics.com/articles/test-measurement/developments-in-oscilloscope-technology-an-36 [accessed on 02 DEC 2012].

Agilent (2003). Oscilloscope display quality impacts ability to view subtle signal. Agilent Technologies. Available at http://cp.literature.agilent.com/litweb/pdf/5989-2003EN.pdf [accessed on December 2012].

Andersen, P. and Petersen, N. C. (1993). A procedure for ranking efficient units in data envelopment analysis. *Management Science*, **39**, 10: 1261–1264.

Anonymous (2009). The oscilloscope. Available at http://www.owlnet.rice.edu/~phys112/Lab/Oscilloscope.pdf [accessed on 2 December 2012].

Bogetoft, P. and Otto, L. (2010). Benchmarking methods. *Benchmarking with DEA, SFA, and R*. Springer-Verlag, New York.

Bommakanti, P. (2011). Oscilloscope market set for growth in 2011. Test and Measurement World. Available at http://tmworld.com/design/manufacturing/4388849/Oscilloscope-market-set-for-growth-in-2011 [accessed on 22 November 2012].

Curry, J. (1996). Understanding conjoint analysis in 15 minutes. Sawtooth Technologies. Available at http://www.sawtoothsoftware.com/download/techpap/undca15.pdf [accessed on 2 December 2012].

Dierick, K. and Depril, D. (2010). Assessing the value of five pricing research methods. White paper, suAzio Consulting in participation with the European Pricing Platform.

Dobney (2012). Pricing research in pricing technique overview. Available at http://www.dobney.com/research/pricing_research.htm [accessed on 2 December 2012].

Gordon, T. J. and Munson, T. R. (1981). A proposed convention for measuring the state-of-the-art of products or processes. *Technological Forecasting and Social Change*, **20**, 1: 1–26.

Green, P. E. and Savitz, J. (1994). Applying conjoint analysis to product assortment and pricing in retailing research. *Pricing Strategy and Practice*, **2**, 3: 4–19.

Grewal, D. and Levy, M. (2010). *Marketing*, 2nd edn. McGraw-Hill, BurrRidger, IL, Irwin.

Hannes, J. (2009). The evolution of oscilloscopes: Analysis to synthesis. *Evaluation Engineering*, **48**, 1: 33.

Harmon, R. R., Unni, R. and Anderson, T. R. (2007). Price sensitivity measurement and new product pricing: A cognitive response approach. In *Proceedings of the Portland International Center for Management of Engineering and Technology (PICMET) 2007*, Portland, pp. 1961–1967.

Inman, O., Anderson, T. and Harmon, R. (2006). Predicting US jet fighter aircraft introductions from 1944 to 1982: A dogfight between regression and TFDEA. *Technological Forecasting and Social Changer*, **73**, 6: 1178–1187.

Johnson, R. M. and Olberts, K. A. (1996). Using conjoint analysis in pricing studies: Is one price variable enough? Sawtooth Software. Available at www.sawtoothsoftware.com [accessed on 3 December 2012].

Kotler, P. (1994). *Marketing Management*, 8th edn. Prentice-Hall, New Jersey.

Lashlee, R. (2008). Five trends in oscilloscope. Electrical Engineering Times, Taiwan. Available at http://www.eettaiwan.com/STATIC/PDF/200809/EETOL_2008IIC_Agilent_AN_37.pdf?%20SOURCES=DOWNLOAD [accessed on 22 November 2012].

LeCroy (2008). Competition for LeCroy. Available at http://www.wikinvest.com/stock/LeCroy_%28LCRY%29/Competition [accessed on 3 December 2012].

Lim, D. J. and Anderson, T. R. (2012). An introduction to technology forecasting with a TFDEA excel add-in. In *Proceedings of Technology Management for Emerging Technologies (PICMET) 2012*, Vancouver BC, pp. 1293–1298.

Mohr, J., Sengupta, S. and Slater, S. (2010). *Marketing of High Technology Products and Innovation*, 3rd edn. Pearson Education, New Jersey.

Nelson, R. (2010). Vendors target oscilloscope sweet spot. *EDN Network* [accessed on 9 September 2010].

Pereira, J. M. D. (2006). The history and technology of oscilloscopes. *IEEE Instrumental and Measurements Magazine*, **9**, 6: 27–35.

Perreault, W., Cannon, J. P. and McCarthy, E. J. (2008). *Essentials of Marketing: A Marketing Strategy Planning Approach*, 11th edn. McGraw-Hill/Irwin, Burr Ridger, IL.

Rohde and Schwarz (2012). Fundamentals of oscilloscope primer. Rohde and Schwarz, October 2012. Available at http://www.slideshare.net/RohdeSchwarzNA/fundamentals-of-oscilloscopes-version-11 [accessed on 12 February 2012].

Smallwood, R. D. (1988). Designing a conjoint analysis study. In *Proceedings of the Sawtooth Software Conference on Perceptual Mapping, Conjoint Analysis, and Computer Interviewing*, Ketchum, ID: Sawtooth Software, pp. 289–296.

Tektronix (2011a). Triggering fundamentals. Available at http://www.tek.com/dl/55W_17291_6_0.pdf [accessed on 1 December 2012].

Tektronix (2011b). XYZs of oscilloscopes. Primer: EA/FCA-POD. Available at http://www1.tek.com/Measurement/programs/301913X312631/ [accessed on 2 December 2012].

## Appendix A. Oscilloscopes' Data Collection

| DMU | Model/Family | Oscilloscopes type | Release year | Max number of scope channels | Vertical resolution bits | Number of I/O modes | Total weight (kg) | Bandwidth (Mhz) | Max sample rate (analog) (MS/s) | Price |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | InfiniiVision MSO/DSO 3000 X-Series | InfiniiVision digital storage/ mixed signal oscilloscopes | 2001 | 4 | 8 | 4 | 3.85 | 1024 | 2560.0 | 15494 |
| 2 | Infiniium 54855A | Infiniium oscilloscope | 2004 | 4 | 12 | 4 | 13.00 | 7168 | 20480.0 | 64801 |
| 3 | DSA8300 | Digital sampling oscilloscope | 2006 | 8 | 16 | 4 | 21.00 | 61440 | 0.3 | 28700 |
| 4 | TDS1000B Series | Digital storage oscilloscopes | 2006 | 2 | 8 | 2 | 2.20 | 100 | 1024.0 | 1600 |
| 5 | TDS6000B/C Series | Digital storage oscilloscopes | 2006 | 4 | 11 | 4 | 21.00 | 12288 | 40960.0 | 39995 |
| 6 | Infiniium MSO/DSO 9000A Series | Infiniium oscilloscopes | 2007 | 4 | 12 | 3 | 11.80 | 4096 | 20480.0 | 39780 |
| 7 | Infiniium DCA-J 86100C Series | Infiniium communications analyzer | 2007 | 4 | 15 | 6 | 15.50 | 81920 | 11592.0 | 36138 |
| 8 | InfiniiVision MSO/DSO 2000 X-Series | InfiniiVision digital storage/ mixed signal oscilloscopes | 2008 | 4 | 8 | 4 | 3.85 | 200 | 1024.0 | 3383 |
| 9 | WavePro 7Zi Series | Digital storage oscilloscopes | 2008 | 4 | 11 | 5 | 18.40 | 6144 | 40960.0 | 59490 |
| 10 | DS1000B Series | Digital oscilloscopes | 2008 | 4 | 8 | 2 | 3.00 | 200 | 2048.0 | 1395 |
| 11 | DS1000D Series | Digital oscilloscopes | 2008 | 2 | 8 | 1 | 2.30 | 100 | 1024.0 | 719 |
| 12 | DS1000CA Series | Digital oscilloscopes | 2008 | 2 | 8 | 1 | 2.40 | 300 | 2048.0 | 1495 |
| 13 | DSO1000A Series | Digital storage oscilloscopes | 2009 | 4 | 8 | 1 | 3.03 | 200 | 1024.0 | 2280 |
| 14 | DSO1000B Series | Digital storage oscilloscopes | 2009 | 2 | 8 | 1 | 2.40 | 150 | 500.0 | 1590 |
| 15 | InfiniiVision MSO/DSO 7000B Series | InfiniiVision oscilloscope | 2009 | 4 | 8 | 3 | 5.90 | 1024 | 4096.0 | 19890 |
| 16 | WaveJet 300A Series | Digital storage oscilloscopes | 2009 | 4 | 8 | 4 | 3.20 | 500 | 2048.0 | 7355 |
| 17 | DPO/MSO3000 Series | Digital phosphor/mixed signal oscilloscopes | 2009 | 4 | 11 | 4 | 4.17 | 500 | 2560.0 | 13700 |
| 18 | DPO/MSO4000B Series | Digital phosphor/mixed signal oscilloscopes | 2011 | 4 | 11 | 4 | 5.00 | 1024 | 5120.0 | 13940 |
| 19 | DPO/MSO5000 Series | Digital phosphor/mixed signal oscilloscopes | 2011 | 4 | 11 | 4 | 6.70 | 2048 | 10240.0 | 28700 |
| 20 | InfiniiVision MSO/DSO 6000A Series | InfiniiVision digitizing and mixed signal oscilloscopes | 2011 | 4 | 8 | 4 | 4.90 | 1024 | 4096.0 | 20671 |

(*Continued*)

Appendix A. (*Continued*)

| DMU | Model/Family | Oscilloscopes type | Release year | Max number of scope channels | Vertical resolution bits | Number of I/O modes | Total weight (kg) | Bandwidth (Mhz) | Max sample rate (analog) (MS/s) | Price |
|---|---|---|---|---|---|---|---|---|---|---|
| 21 | GDS2000 Series | Digital storage oscilloscopes | 2011 | 4 | 8 | 2 | 4.30 | 200 | 1024.0 | 2020 |
| 22 | TDS1000C-EDU Series | Digital storage oscilloscopes | 2011 | 2 | 8 | 2 | 2.20 | 100 | 1024.0 | 1190 |
| 23 | TDS2000C Series | Digital storage oscilloscopes | 2011 | 4 | 8 | 2 | 2.20 | 200 | 2048.0 | 2280 |
| 24 | WaveAce2000 Series | Digital storage oscilloscopes | 2012 | 4 | 8 | 3 | 3.33 | 300 | 2048.0 | 2975 |
| 25 | DS2000 Series | Digital oscilloscopes | 2012 | 2 | 8 | 5 | 3.90 | 200 | 2048.0 | 1626 |
| 26 | DPO/MSO2000B Series | Digital phosphor/mixed signal oscilloscopes | 2012 | 4 | 8 | 3 | 3.60 | 200 | 1024.0 | 3570 |

## Appendix B. The Result of the Oscilloscopes' Price Adjusting (Unsorted)

| DMU | Six technological features: Max number of scope channels | Vertical resolution (bits) | Number of I/O modes | 1/Total weight | Ln(bandwidth) | Ln(max sample rate) | Technological performance efficiency | Original prices ($) | Market performance efficiency | Adjusted prices ($) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 8 | 4 | 0.2597 | 6.9315 | 7.8478 | 1.021 | 15494 | 0.6973 | 10804 |
| 2 | 4 | 12 | 4 | 0.0769 | 8.8774 | 9.9272 | 1.007 | 64801 | 0.5293 | 34299 |
| 3 | 8 | 16 | 4 | 0.0476 | 11.0258 | −1.204 | 1.000 | 28700 | 1.0000 | 28700 |
| 4 | 2 | 8 | 2 | 0.4545 | 4.6052 | 6.9315 | 1.000 | 1600 | 0.7438 | 1190 |
| 5 | 4 | 11 | 4 | 0.0476 | 9.4164 | 10.6204 | 1.000 | 39995 | 1.0000 | 39995 |
| 6 | 4 | 12 | 3 | 0.0847 | 8.3178 | 9.9272 | 1.004 | 39780 | 0.8710 | 34649 |
| 7 | 4 | 15 | 6 | 0.0645 | 11.3135 | 9.3581 | 1.000 | 36138 | 1.0000 | 36138 |
| 8 | 4 | 8 | 4 | 0.2597 | 5.2983 | 6.9315 | 1.052 | 3383 | 1.0000 | 3383 |
| 9 | 4 | 11 | 5 | 0.0543 | 8.7232 | 10.6204 | 1.000 | 59490 | 1.0000 | 59490 |
| 10 | 4 | 8 | 2 | 0.3333 | 5.2983 | 7.6246 | 1.041 | 1395 | 1.0000 | 1395 |
| 11 | 2 | 8 | 1 | 0.4348 | 4.6052 | 6.9315 | 1.023 | 719 | 1.0000 | 719 |
| 12 | 2 | 8 | 1 | 0.4167 | 5.7038 | 7.6246 | 1.015 | 1495 | 1.0000 | 1495 |
| 13 | 4 | 8 | 1 | 0.33 | 5.2983 | 6.9315 | 1.076 | 2280 | 0.6118 | 1395 |
| 14 | 2 | 8 | 1 | 0.4167 | 5.0106 | 6.2146 | 1.046 | 1590 | 0.6323 | 1005 |
| 15 | 4 | 8 | 3 | 0.1695 | 6.9315 | 8.3178 | 1.067 | 19890 | 0.6225 | 12382 |
| 16 | 4 | 8 | 4 | 0.3125 | 6.2146 | 7.6246 | 1.000 | 7355 | 1.0000 | 7355 |
| 17 | 4 | 11 | 4 | 0.2398 | 6.2146 | 7.8478 | 1.033 | 13700 | 1.0000 | 13700 |
| 18 | 4 | 11 | 4 | 0.2 | 6.9315 | 8.5409 | 1.028 | 13940 | 1.0000 | 13940 |
| 19 | 4 | 11 | 4 | 0.1493 | 7.6246 | 9.2341 | 1.019 | 28700 | 0.7887 | 22636 |
| 20 | 4 | 8 | 4 | 0.2041 | 6.9315 | 8.3178 | 1.036 | 20671 | 0.6203 | 12822 |
| 21 | 4 | 8 | 2 | 0.2326 | 5.2983 | 6.9315 | 1.115 | 2020 | 0.6906 | 1395 |
| 22 | 2 | 8 | 2 | 0.4545 | 4.6052 | 6.9315 | 1.000 | 1190 | 1.0000 | 1190 |
| 23 | 4 | 8 | 2 | 0.4545 | 5.2983 | 7.6246 | 1.000 | 2280 | 1.0000 | 2280 |
| 24 | 4 | 8 | 3 | 0.3003 | 5.7038 | 7.6246 | 1.046 | 2975 | 1.0000 | 2975 |
| 25 | 2 | 8 | 5 | 0.2564 | 5.2983 | 7.6246 | 1.000 | 1626 | 1.0000 | 1626 |
| 26 | 4 | 8 | 3 | 0.2778 | 5.2983 | 6.9315 | 1.086 | 3570 | 0.6692 | 2389 |

## Appendix C. The Result of the Mixed Signal Oscilloscopes' Price Adjusting

| | Six technological features | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| DMU | Max number of scope channels | Vertical resolution (bits) | Number of I/O modes | 1/Total weight | Ln(bandwidth) | Ln(max sample rate) | Technological performance efficiency | Original prices ($) | Market performance efficiency (with original prices) | Adjusted prices ($) |
| 1 | 4 | 8 | 4 | 0.2597 | 6.9315 | 7.8478 | 1 | 15494 | 1.0000 | 15494 |
| 8 | 4 | 8 | 4 | 0.2597 | 5.2983 | 6.9315 | 1 | 3383 | 1.0000 | 3383 |
| 15 | 4 | 8 | 3 | 0.1695 | 6.9315 | 8.3178 | 1 | 19890 | 0.7009 | 13940 |
| 17 | 4 | 11 | 4 | 0.2398 | 6.2146 | 7.8478 | 1 | 13700 | 1.0000 | 13700 |
| 18 | 4 | 11 | 4 | 0.2000 | 6.9315 | 8.5409 | 1 | 13940 | 1.0000 | 13940 |
| 19 | 4 | 11 | 4 | 0.1493 | 7.6246 | 9.2341 | 1 | 28700 | 1.0000 | 28700 |
| 20 | 4 | 8 | 4 | 0.2041 | 6.9315 | 8.3178 | 1 | 20671 | 0.6795 | 14047 |
| 26 | 4 | 8 | 3 | 0.2778 | 5.2983 | 6.9315 | 1 | 3570 | 1.0000 | 3570 |

## Appendix D. The Result of the Other Oscilloscopes' Price Adjusting (Not Mixed Signal Oscilloscopes)

| DMU | Six technological features: Max number of scope channels | Vertical resolution on (bits) | Number of I/O modes | 1/Total weight | Ln(bandwidth) | Ln(max sample rate) | Technological performance efficiency | Original prices ($) | Market performance efficiency (with original prices) | Adjusted prices ($) |
|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 8 | 16 | 4 | 0.0476 | 11.0258 | −1.2040 | 1.000 | 28700 | 1.000 | 28700 |
| 4 | 2 | 8 | 2 | 0.4545 | 4.6052 | 6.9315 | 1.000 | 1600 | 0.744 | 1190 |
| 5 | 4 | 11 | 4 | 0.0476 | 9.4164 | 10.6204 | 1.000 | 39995 | 1.000 | 39995 |
| 6 | 4 | 12 | 3 | 0.0847 | 8.3178 | 9.9272 | 1.004 | 39780 | 0.882 | 35088 |
| 7 | 4 | 15 | 6 | 0.0645 | 11.3135 | 9.3581 | 1.000 | 36138 | 1.000 | 36138 |
| 9 | 4 | 11 | 5 | 0.0543 | 8.7232 | 10.6204 | 1.000 | 59490 | 1.000 | 59490 |
| 10 | 4 | 8 | 2 | 0.3333 | 5.2983 | 7.6246 | 1.041 | 1395 | 1.000 | 1395 |
| 11 | 2 | 8 | 1 | 0.4348 | 4.6052 | 6.9315 | 1.023 | 719 | 1.000 | 719 |
| 12 | 2 | 8 | 1 | 0.4167 | 5.7038 | 7.6246 | 1.015 | 1495 | 1.000 | 1495 |
| 13 | 4 | 8 | 1 | 0.3300 | 5.2983 | 6.9315 | 1.076 | 2280 | 0.612 | 1395 |
| 14 | 2 | 8 | 1 | 0.4167 | 5.0106 | 6.2146 | 1.046 | 1590 | 0.632 | 1005 |
| 16 | 4 | 8 | 4 | 0.3125 | 6.2146 | 7.6246 | 1.000 | 7355 | 1.000 | 7355 |
| 21 | 4 | 8 | 2 | 0.2326 | 5.2983 | 6.9315 | 1.115 | 2020 | 0.691 | 1395 |
| 22 | 2 | 8 | 2 | 0.4545 | 4.6052 | 6.9315 | 1.000 | 1190 | 1.000 | 1190 |
| 23 | 4 | 8 | 2 | 0.4545 | 5.2983 | 7.6246 | 1.000 | 2280 | 1.000 | 2280 |
| 24 | 4 | 8 | 3 | 0.3003 | 5.7038 | 7.6246 | 1.046 | 2975 | 1.000 | 2975 |
| 25 | 2 | 8 | 5 | 0.2564 | 5.2983 | 7.6246 | 1.000 | 1626 | 1.000 | 1626 |

## Biography

**Dr. Bing Wang** is an independent Research Professional located in Vancouver, BC, Canada. Dr. Wang earned her Ph.D. in Management Science from Beijing University of Posts and Telecommunications (BUPT). She has also received an M.Sc. degree in Engineering and Technology Management from Portland State University. Before leaving China in 2014 she served as an Associate Professor at BUPT. Her current research interests include market-based pricing, urban economics, decision-making, and technology management.

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