
Measuring dynamic technical change: a technometric approach

Amnon Frenkel and Shlomo Maital

Samuel Neaman Institute for Advanced Studies in Science and Technology, Technion – Israel Institute of Technology, Technion City, Haifa 32000, Israel. E-mail: info@neaman.org.il

Hariolf Grupp

Fraunhofer Institute for Systems and Innovation Research, Karlsruhe, Germany

Abstract: The propose of this paper is to extend the microeconomic benchmarking approach known as 'technometrics'. We offer a novel approach to measuring technical change at the product level, based on intertemporal comparison of product characteristics, using objective performance measures. The goal of the study is to provide a straightforward tool for benchmarking technological sophistication that can be portrayed graphically and shows how technological capabilities have changed between two points in time. This paper extends the static analysis of a previous paper [1], as it again deals with sensors, and implements the dynamic technometric approach on the updated sensor data.

Keywords: Technical change; technomoetrics; dynamic; intertemporal; sensors.

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Biographical notes: Amnon Frenkel is a Senior Researcher at the Samuel Neaman Institute for Advanced Studies in Science and Technology at the Technion and Senior Lecturer in Urban and Regional Planning at Technion – Israel Institute of Technology, in Haifa, Israel. For the last ten years he has been involved in research in spatial economic, including three projects funded by the German-Israel Foundation (GIF) which were undertaken at the S. Neaman Institute in collaboration with a German research group from the Fraunhofer Institute for System and Innovation in Karlsruhe, Germany. He has written many scientific papers and research reports on industrial policy.

Shlomo Maital is Academic Director of TIM-Technion Institute of Management, and Sondheimer Professor of International Economics & Finance, at Technion – Israel Institute of Technology, in Haifa, Israel. He is the author of 70 scientific papers and has written, co-authored or co-edited eight books, including *Executive Economics* (The Free Press, 1994) and (with Hariolf Grupp) *Managing New Product Development & Innovation: A Microeconomic Toolbox* (Edward Elgar, in press).

Hariolf Grupp is Deputy Director of the Fraunhofer Institute for Systems and Innovation Research (ISI), Karlsruhe, Germany. He is a Reader (Privatdozent) of Economics in the Faculty of Economics and Management, Technical University of Berlin, as well as Adjunct Professor in the Faculty of Economics,

Karlsruhe University. He received the Fraunhofer Prize (1988) for new tools to measure innovation and also the Best Scientific Paper award (together with Shlomo Maital) at the International Conference on Management of Technology in Gothenburg, 1997. Author of six books and more than a hundred journal publications.

1 Introduction

One of the most complex problems facing managers is how to benchmark their firms' technological capability relative to competitors, in order to identify points of strength and weakness, as part of strategic planning. It is no accident that the best-selling Harvard Business Review article of all time is C.K. Prahalad and Gary Hamel's [2] famous piece on the core competencies of the firm. Today managers understand how vital it is to identify core competencies – but face major difficulties when seeking to quantify and benchmark capabilities in technology.

This paper presents an empirical analysis of technical change in industrial sensors based on the technometric approach developed by Grupp [5]. The model used was originally developed for measuring technological capabilities based on the leading-edge products at the macro level of a national economy. In this paper we apply the technometric approach at the micro-micro level of the firm (individual products) in a dynamic perspective. To measure technical change at the individual product level, a technometric feature-by-feature comparison was undertaken twice, once in 1991 and again in 1997. By comparing benchmarking scores for each product feature between 1991 and 1998, the quality improvement for each firm's sensors was measured. To our knowledge, this is one of the first attempts to measure technical change for individual products in a direct manner, by focusing on improvements in key product features (another such example is on solar cells; compare Grupp [3]).

Data on product features were initially collected from pamphlets distributed at the industry's key trade fair for measurement instruments, held every two years in Nuremberg, Germany, in 1991. Using the technometric approach, we compared the quality of industrial sensors for the US, Japan, Germany, Israel and other countries at that point in time [1].

In 1998, we again collected data on firms exhibiting their sensors at the Nuremberg Trade Fair held in 1997. This time, rather than focus on comparing product quality at the country level, we chose to examine product quality at the firm level, and individual product level. To this end, we chose several firms included in the 1991 survey, that also took part in the 1997 Trade Fair. We selected from these firms' catalogues products shown both in 1991 and 1997. By benchmarking each of several product features, and comparing their improvements over time, we developed a measure of dynamic technical change at the micro-micro level. This enabled us to measure in concrete terms the technology strategy chosen by each firm in seeking to strengthen its sales and market share.

The remainder of the paper is organized as follows. Section 2 presents the methodology, outlining the static and dynamic versions of our technometric model. The third section presents our database. The fourth section analyzes the data and presents our results. The last section draws together the main points of the discussion and presents our main conclusions.

2 Methodology

2.1 The technometric approach

The technometric approach enables direct measurement of technical features of products for the evaluation of technological innovation changes. The direct measures are of great importance in economic analyses, especially in measuring the quality of products and the quality differences among products in the marketplace.

The technometric model can provide an answer to one of the most important questions that firms face in considering whether or not to produce a new product, or a new version of an existing product: what is the product's quality relative to competitive products? Results from previous studies have shown that the technometric indicators could signal a decline in product quality two or three years before a reduction in quality actually occurs owing to the existence of technological gaps [4]. This 'early warning indicator' could help the firm to act to improve the quality of its product before it is too late.

In this study, we outline the technometric approach to technology benchmarking, which was introduced in the 1980s [4] in a revised terminology:

i = product, $i = 1, \dots, n$

j = feature, $j = 1, \dots, m$

K = vector of product features

k = firm, $k = 1, \dots, r$

t = time index, $t = t_0, t_1$

u = units of measurement for feature " j "

$$\begin{pmatrix} K(i, 1, k', t) \\ K(i, 2, k', t) \\ \dots \\ \dots \\ K(i, r, k', t) \end{pmatrix} * \begin{pmatrix} u(1) \\ u(2) \\ \dots \\ \dots \\ u(r) \end{pmatrix} \Rightarrow \begin{pmatrix} K^*(i, 1, k', k, t) \\ K^*(i, 2, k', k, t) \\ \dots \\ \dots \\ K^*(i, r, k', k, t) \end{pmatrix} \quad (1)$$

Equation (1) simply uses the u vector to eliminate the units of measurement (e.g., degrees, pounds, inches) in which technical product features or specifications are measured.

The mathematical definition of the Technometric index K^* is shown in equation 2:

$$K^*(i, j, k', k, t) = \frac{[(K(i, j, k', t) - K(i, j, k_{\min}, t))]}{[(K(i, j, k_{\max}, t) - K(i, j, k_{\min}, t))]} \quad (2)$$

Equation (2) converts the K values to $[0,1]$ metrics, by expressing the j^{th} attribute of brand k' in relation to a minimum value, set as zero (the value of the simplest, or least sophisticated, feature available on the market), and a maximum value, set as one (the value of the most sophisticated feature available on the market).

For some features, a higher feature score (e.g., weight) means lower product quality. Hence, equation (3) is used in such cases, where the need arises to invert feature scores:

$$K^*_{inv}(i, j, k', k, t) = \frac{[(K(i, j, k', t) - K(i, j, k_{\max}, t))]}{[(K(i, j, k_{\min}, t) - K(i, j, k_{\max}, t))]} = 1 - K^*(i, j, k', k, t) \quad (3)$$

The essence of the technometric method is the use of physical units for measuring feature sophistication and quality, while the [0,1] metric enables:

- (a) aggregation of feature scores, into an overall score for the entire product, or
- (b) comparison across features, and across products.

2.2 The dynamic model

Over time there appear technical improvements in the product features in comparison to the capabilities measured in the initial period. Measuring the technological improvement on the time axis is done relative to the metric distance from a given initial distribution at t_0 by extending the time period to t_1 . The initial position is frozen and used as a reference point for evaluating the technological improvement between the two periods as presented in the following equation:

$$K^*(i, j, k', k, t_1) = \frac{[(K(i, j, k', t_1) - K(i, j, k_{\min}, t_0))]}{[(K(i, j, k_{\max}, t_0) - K(i, j, k_{\min}, t_0))]} \quad (4)$$

Equation (4) introduces change over time. It measures the j^{th} feature score at time t_1 in relation to feature scores in period t_0 [5].

Figure 1 Schematic diagram of the technometric change over time in product k

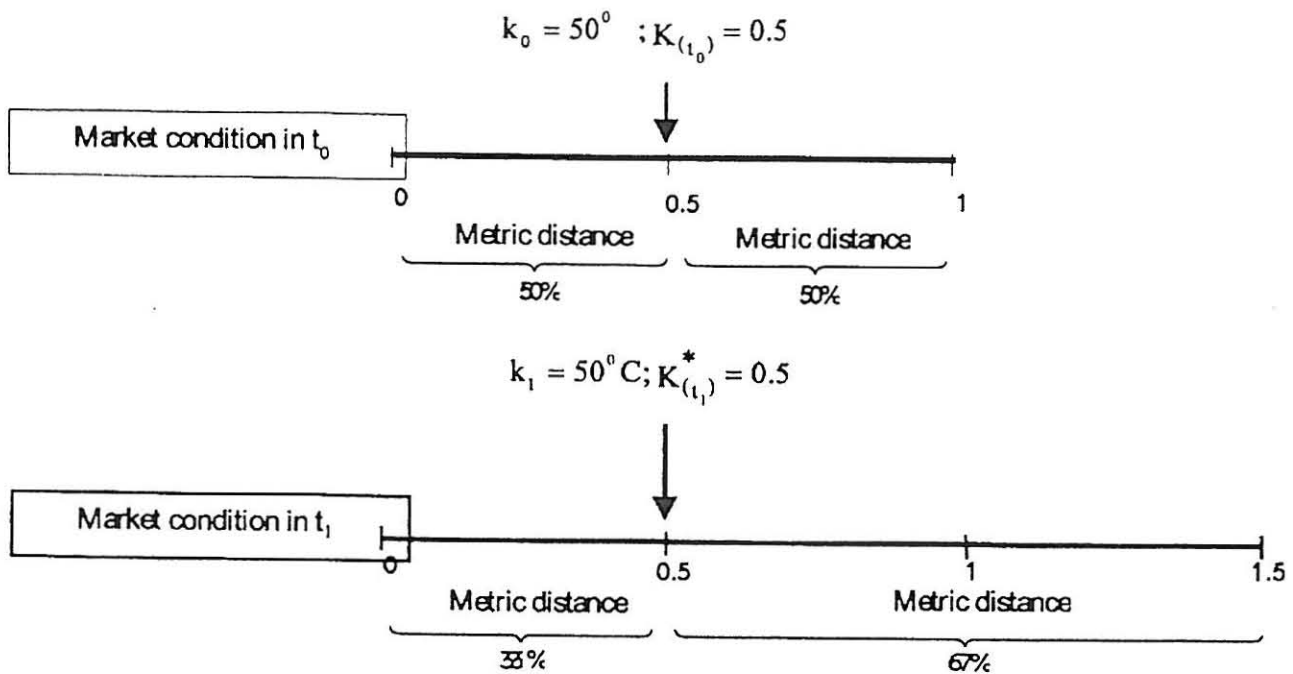


Figure 1 provides an example, in which a temperature sensor can measure up to a maximum temperature of 50°C, at time t_0 ; while the least sophisticated sensor on the market measures up to 20°C and the most sophisticated, up to 80°C. This product's technometric feature score is therefore 0.5: $(80-50)/(80-20)$. This sensor is 'half way' from the least to the best.

If this feature remains constant during time t_1 , while the most sophisticated sensor improves its maximum temperature to 110°C, then the benchmark score remains at 0.5 on a 'progress scale' that is extended to 1.5; the sensor is now one third of the way to the progress frontier. In this simple manner, managers can benchmark their products and track how they measure up relative to competitors', over time.

3 Framework of the study

3.1 Database

In Koschatzky *et al.* [1], we use the technometric benchmarking approach to compare industrial sensors for a given point in time (1991). This study was based on a mail survey of some 268 firms producing sensors that measured pressure, temperature, acceleration, force and humidity. We chose this sample, after visiting the large sensor trade fair in Nuremberg, at which over 400 firms had exhibits. Of those 268 firms who made sensors appropriate for our study and to whom we wrote, 150 firms responded. A detailed database was constructed, benchmarking individual product features for specific brand names. We later used this database to identify those product features that generate inferred customer value, by examining (through regression analysis) those features that appeared most closely related to product price [6].

In 1998, we repeated our 1991 survey, with a view to measuring, for individual products, the technological improvements that had occurred since our earlier study. To this end, we identified the 663 participating firms at the Nuremberg Trade Fair held in 1997 and wrote to each one. Of these, some 100 firms responded and sent us detailed data on their product features. We then identified firms whose sensors had appeared in the earlier 1991 study, as well as in the 1998 one. We tried to choose companies from different countries, to provide as broad as possible a spectrum of technologies.

3.2 Choice of products and attributes

For this study of dynamic technical change, we chose to focus on pressure sensors. Pressure sensors serve a variety of industrial uses, and can be based on several different physical principles, of which the most common are: piezo-resistance; strain-gauge; and induction (see also [1]).

For our study, we chose to focus on piezo-resistance pressure sensors. In our database, we identified seven firms making such sensors (Jumo, Eurosensor, Kulite, Pewatron, Philips, Keller, Bourdon). Of these, five were included in the 1991 study (Jumo, Eurosensor, Kulite, Pewatron, Philips); three of those five also supplied data for the 1998 study (Jumo, Eurosensor, Kulite), permitting a comparison between 1991 and 1998. Two companies in the 1991 data did not respond to our 1998 survey; in contrast, two firms provided data in 1998 who were not represented in the 1991 study (Keller and Bourdon).

We selected six key physical sensor attributes, as dimensions on which technical change would be measured and compared:

- Measuring range: maximum range of pressures the sensor could measure, in bars.
- Maximal operating temperature: the highest temperature at which the pressure sensor could operate efficiently (degrees).
- Minimal operating temperature: the lowest temperature at which the pressure sensor could operate efficiently (degrees).
- Sensor weight: weight of the sensor (grams); measures miniaturization; many sensors are used in products where size and weight are important.
- Non-linearity: maximal measuring error, measured as the deviation from a linear response line (%).
- Hysteresis: maximal measuring error, caused by fluctuations in measuring various pressures, measured as deviation from the initial measured pressure (%), and reflecting the tendency of a system to remain in its initial state even when subject to change.

Table 1 shows the value of these six attributes for piezo-resistant pressure sensors, for the seven companies in our sample: Jumo, Keller and Bourdon (Germany); Kulite (USA); Eurosensor (UK), Philips (Netherlands), and Pewatron (Switzerland). Since each firm makes a wide range of pressure sensors, we recorded the maximum and minimum values for each attribute, intra-firm. This then enabled us to conduct cross-firm comparisons, searching for the maximum and minimum values for the entire seven-firm sample, on the way to calculating our technometric benchmark scores according to equations (2) to (4). It will be recalled that the highest feature value gets the score of (1) in 1991 and the lowest, the score of (0). Table 1 shows technometric scores for each of the seven firms, and for each of the six features, for 1991 and 1997. *Since our study aims to examine the technology envelope, we picked the best-performing sensor for each firm, in order to measure the extremes of technology, but considered the most sophisticated, and least sophisticated, attributes on the market.*

Table 1 Value of physical characteristics for piezo-resistant pressure sensors for seven firms: 1991 and 1997: and technometric scores for each firm

Name of Firm	Parameter	Specifications 1991						Specifications 1997					
		Measuring Range (bar)	Temperature operating		Sensor Weight (gr.)	Linearity	Hysteresis %	Measuring Range (bar)	Temperature operating		Sensor Weight (gr.)	Linearity (%)	Hysteresis (%)
			Max. °C	Min. °C					Max. °C	Min. °C			
Jumo (Germany)	Maximum	400	120	-30	14	0.3	0.1	1000	200	-50	14	0.3	0.1
	Minimum	1	50	0	310	0.6	0.1	0.25	90	-30	320	0.35	0.2
	K*	0.29	0.33	0.67	0.96	0.55	0.98	0.73	0.71	0.93	0.96	0.55	0.98
Eurosensor (UK)	Maximum	345	125	-40	0.3	0.05	0.01	34.5	125	-40	3	0.02	0.01
	Minimum	0.14	80	-20	3	0.5	0.15	0.07	125	-40	27	0.1	0.1
	K*	0.25	0.36	0.80	1.0	1.0	1.0	0.03	0.36	0.80	0.99	1.06	1.0
Kulite (USA)	Maximum	1379	260	-55	13	0.2	0.1	2100	273	-195.5	3	0.1	0.1
	Minimum	69	120	-20	150	0.2	0.3	0.35	37.5	-30	270	0.1	1
	K*	1.0	1.0	1.0	0.96	0.73	0.98	1.52	1.06	2.87	0.99	0.91	0.99
Pewatron (Switzerland)	Maximum	100	100	-30	1	0.3	0.2						
	Minimum	1	80	-20	170	0.5	6						
	K*	0.07	0.24	0.67	0.99	0.55	0.97						
Philips (Netherlands)	Maximum	400	180	-30	2.8	0.5	0.1						
	Minimum	0.4	80	20	200	0.5	0.1						
	K*	0.29	0.62	0.67	0.99	0.18	0.98						
Keller (Germany)	Maximum							1000	150	-45	8	0.2	0.1
	Minimum							0.1	40	10	440	0.5	0.5
	K*							0.73	0.48	0.87	0.98	0.73	0.99
Bourdon (Germany)	Maximum							5000	150	-55	15	0.2	0.2
	Minimum							0.25	40	-25	1200	0.8	0.8
	K*							3.63	0.48	1.00	0.95	0.73	0.97

4 Empirical results

4.1 Comparison analysis

Figures 2 and 3 show the technometric profile of piezo-resistance sensors for 1991 and for 1997, respectively. These profiles are a graphic way of visualizing product quality, feature by feature, within a corporate brand name. They also permit a clear, visual view of how relative product quality changed between 1991 and 1997, feature by feature. In comparison, one may derive the extent of technical change in these six years.

From Figure 2 we learn that four firms except Kulite offer about the same quality in terms of measuring range, maximum and minimum operational temperature. In these features, Kulite is the world leader. In terms of weight all five brands are about equal as it is the case for hysteresis. In linearity (accuracy) the product of Eurosensor performs best, i.e., is the most accurate product among the five products compared.

In the three features concerning weight, linearity and hysteresis, little has changed over the six years from 1991 to 1997. Some more detailed observations may be found on the next pages. Obviously, the sensor of Bourdon leads the measuring range now with an outstanding attribute, but the Kulite sensor has also improved in this respect. The same is true for minimum temperature of operation, which may be much lower for the newer products of Kulite.

Figure 2 Technometric profile of piezo-resistive sensors – comparison among five firms in 1991

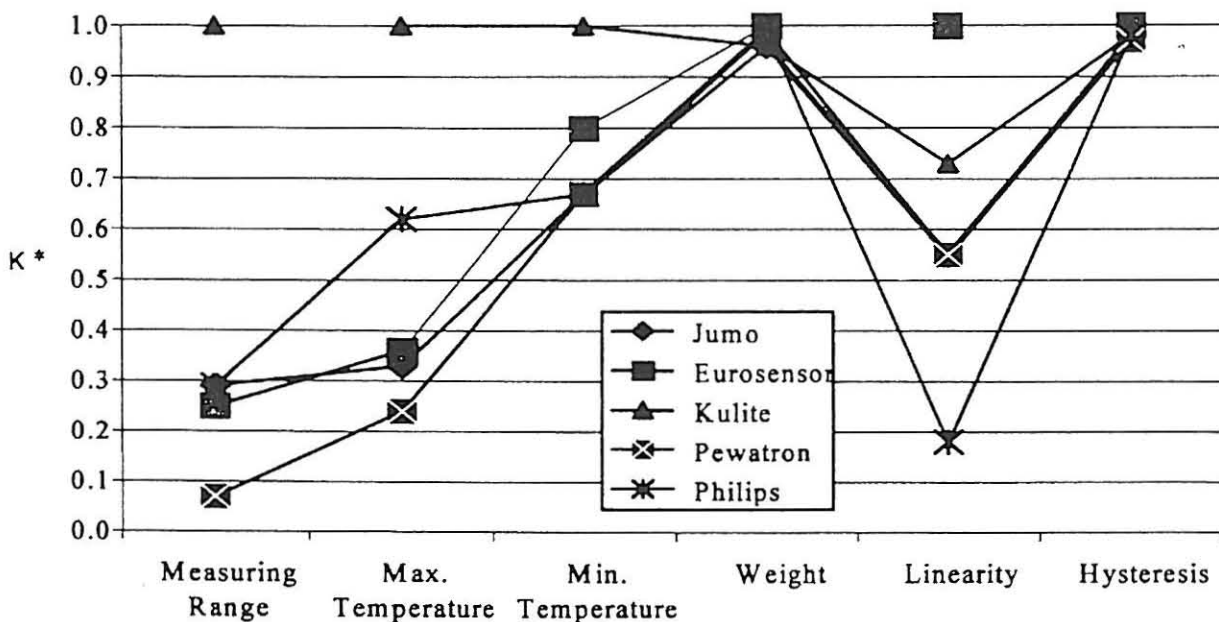
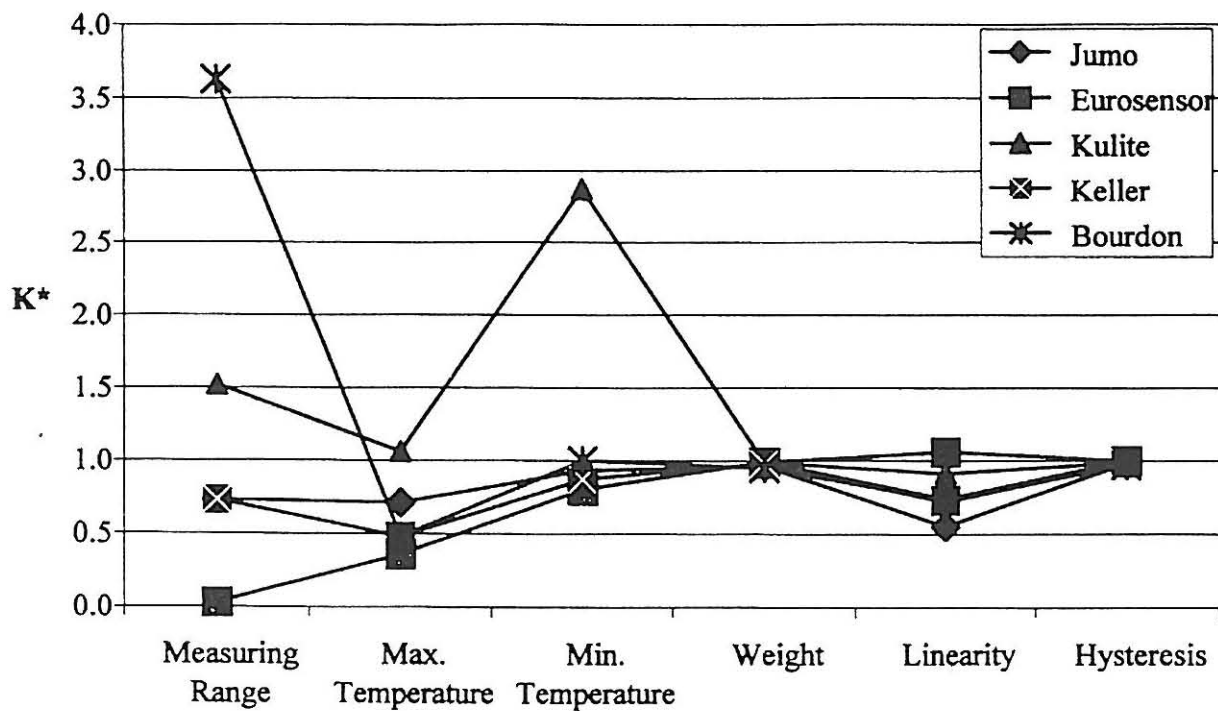


Figure 3 Technometric profile of piezo-resistive sensors – comparison among five firms in 1997 .

An aggregate measure of technical quality can be computed by simply taking the arithmetic average of the six feature scores, for each company. These scores are shown in Table 2. In reality, some consumer preferences are required here but are not available for 1997 (see also [6]).

Table 2 Aggregate technometric score for firms producing piezo-resistant sensors, 1991 and 1997

<i>Firms' name</i>	<i>1991</i>	<i>1997</i>
Jumo (Germany)	0.63	0.81
Eurosensor (UK)	0.73	0.71
Kulite (USA)	0.95	1.39
Pewatron (Switzerland)	0.58	n.d.
Philips (Netherlands)	0.62	n.d.
Keller (Germany)	n.d.	0.80
Bourdon (Germany)	n.d.	1.29

n.d. = no data

These scores show that Kulite enjoyed technical superiority in 1991, and continues to lead in 1997, but numerically its lead has narrowed, as pressure sensors tend to become more similar in their feature performance. This pattern – which we could term ‘regression toward the mean’ – is a common one, in which processes of adoption and imitation tend to ‘homogenize’ technology-based products. For the remaining two companies included

in both the 1991 and 1997 studies, Eurosensor shows a slight decline in technical quality, while Jumo improves somewhat, relative to its (new) competitors. We conclude from Table 2 and Figures 2 and 3 that Eurosensor did not take vigorous action to remedy the weaknesses in its measuring range, and maximum and minimum temperatures.

One of the advantages of our method is that we are able to benchmark the two firms – Bourdon and Keller – in 1997 relative to 1991, even without firm-specific data for them for 1991, using market-best scores for 1991 as our base benchmark measures.

4.2 Dynamic analysis

Dynamic technometric analysis can focus on individual features, and analyse changes in each over time. Table 3 shows dynamic technometric scores for each feature, using the 1991 values as the base values. In this way, the technometric score can of course exceed 1.0, if the highest feature value in 1997 exceeds that in 1991 (which was in fact the case for Kulite's measuring range, for instance, scoring 1.52 in 1997, and scoring 2.87 for minimum temperature in 1997 compared with 1991).

Table 3 Technometric score for seven firms producing piezo-resistant sensors: dynamic comparison, 1991 versus 1997

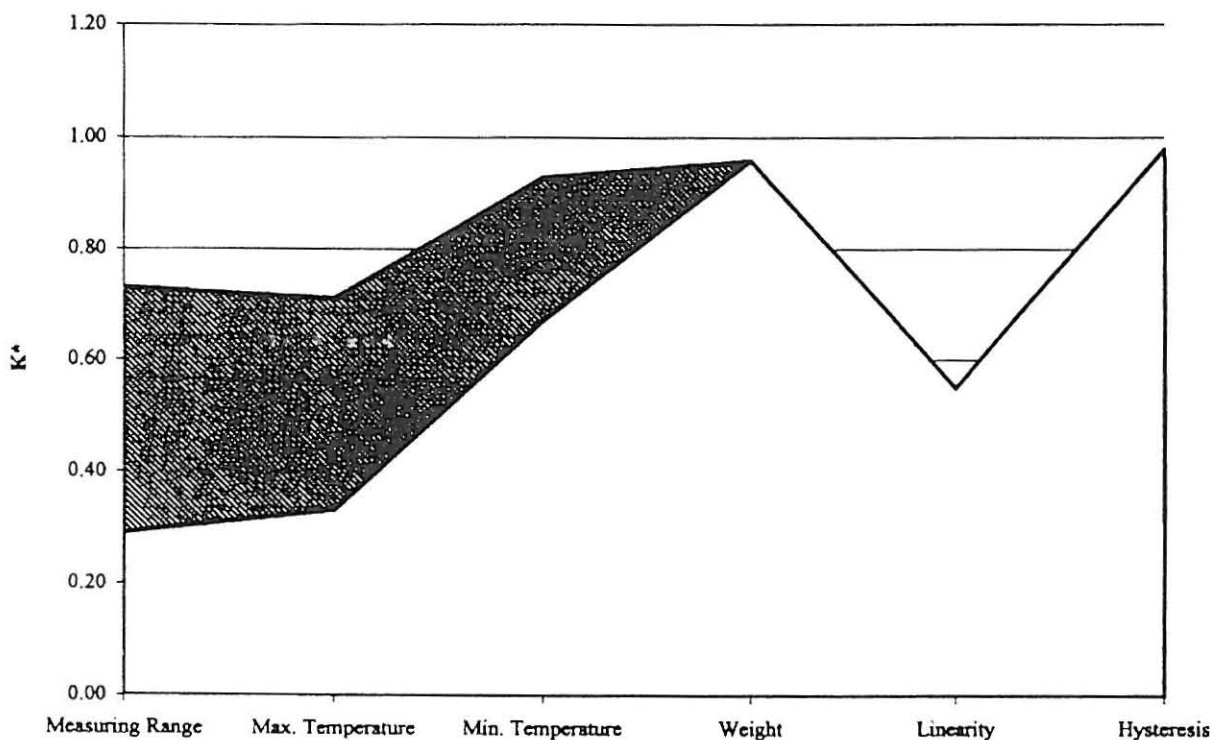
Name of Firm	Year	Specifications					
		Measuring Range (bar)	Temperature Maximum °C	Temperature Operating Minimum °C	Sensor Weight (gr.)	Linearity (% Fso)	Hysteresis (% Fso)
Jumo (Germany)	1991	0.29	0.33	0.67	0.96	0.55	0.98
	1997	0.73	0.71	0.93	0.96	0.55	0.98
Eurosensor (UK)	1991	0.25	0.36	0.80	1.00	1.00	1.00
	1997	0.03	0.36	0.78	0.99	1.05	1.00
Kulite (USA)	1991	1.00	1.00	1.00	0.96	0.73	0.98
	1997	1.52	1.06	2.87	0.99	0.91	0.98
Pewatron (Switzerland)	1991	0.07	0.24	0.67	0.99	0.55	0.97
	1997	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Philips (Netherlands)	1991	0.29	0.62	0.67	0.99	0.18	0.98
	1997	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Keller (Germany)	1991	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	1997	0.73	0.48	0.86	0.98	0.73	0.98
Bourdon (Germany)	1991	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
	1997	3.63	0.48	1.00	0.95	0.73	0.97

n.d. =no data

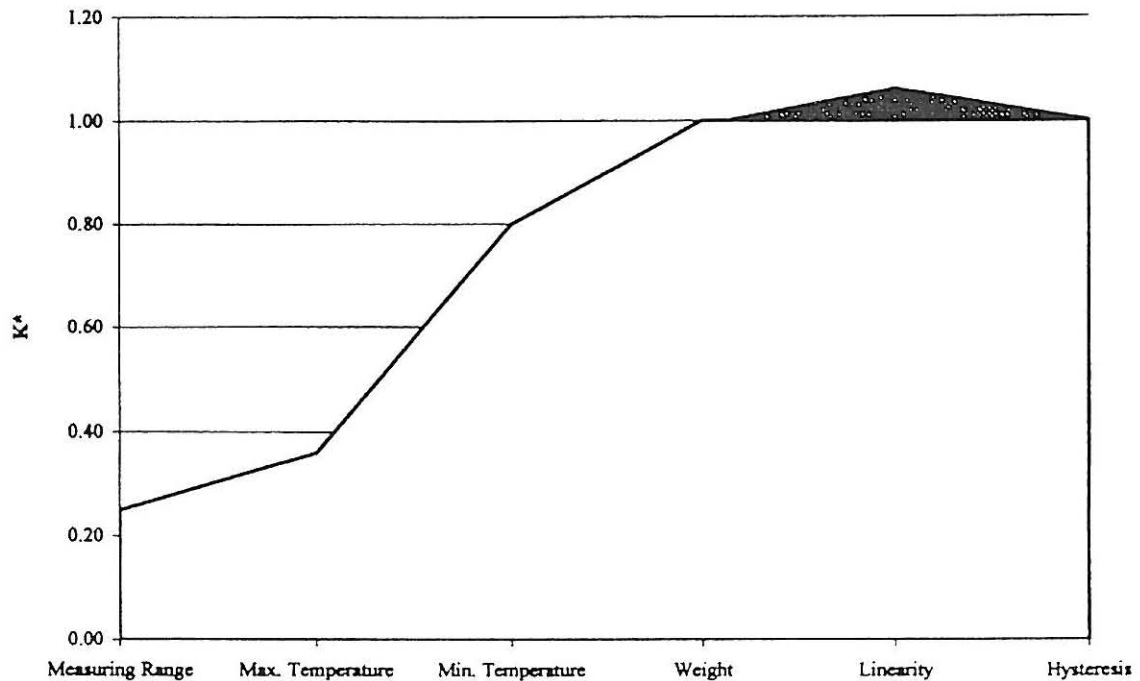
4.3 Firm analysis

For three firms, a comparison of their quality strategy is possible, since they are represented in the database in both years. Starting with Jumo (Figure 4), a clear technology management strategy seems to be the case. While the three features weight, linearity and hysteresis which were not bad in the 1991 comparison were kept as they are, Jumo improved the three specifications which were farther behind the market leader in 1991, Kulite. Jumo technology managers improved specifications nearly up to the level Kulite offered to the markets in 1991. Of course, for the 1997 comparison, this is not the leading-edge, but still Jumo is following the technological frontier.

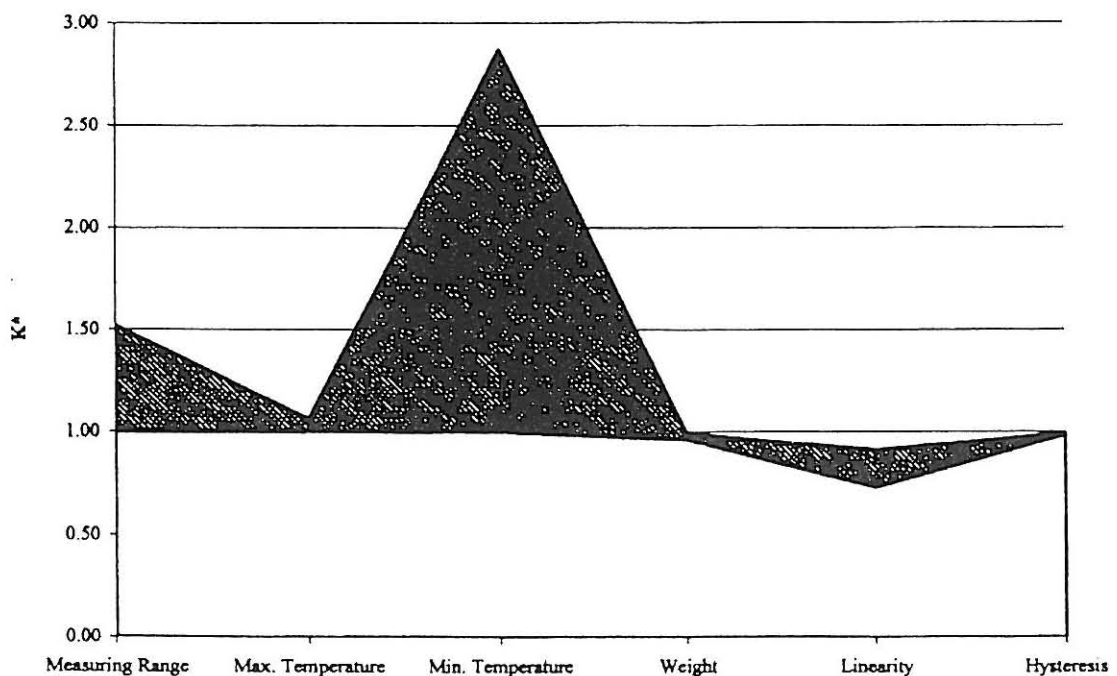
Figure 4 Dynamic comparison of Jumo piezo-resistant sensors, 1991(white) and 1997 (black), for each feature



In Figure 5 we observe that the features profile of the best brand of Eurosensor did not change much. In fact some features deteriorated (meaning that some brands with superior specifications were taken off the market, probably because of non-competitive high prices). This is true for the measuring range (not visible in Figure 5, where only improvements are marked in black). A little step forward is observed in terms of accuracy (linearity).

Figure 5 Dynamic comparison of Eurosensor piezo-resistant sensors, 1991(white) and 1997 (black), for each feature

Clearly, Kulite (Figure 6) enjoyed technological superiority in 1991, scoring highest in all but one feature, 'linearity' (accuracy). While Kulite's sensors improved relatively in linearity in 1997, they remained where they are in another accuracy measure, hysteresis, and improved somewhat their measuring range, while Bourdon sensors took top place here. The marketplace implications of this relative change depend, of course, on the relative importance the customers for sensors attach to the various features. With extreme low operating temperatures Bourdon is now far ahead of their competitors.

Figure 6 Dynamic comparison of Kulite piezo-resistant sensors, 1991 (white) and 1997 (black), for each feature.

5 Conclusion

In this study we attempt to demonstrate the usefulness of technometrics for dynamic analysis. Yet, our sensor study has several severe shortcomings. First of all, the data are limited to a few companies, and for some of them data are not present in both years 1991 and 1997. For a direct comparison of company performance we are left with only three firms. A real analysis of the dynamics in sensor technology certainly has to be founded on a more representative sample of firms.

Despite these limitations, it was possible to show that technical progress in these six years did not develop uniformly over the sensor products, as only some specifications were improved considerably. Many other features remained about the same. Thus, the theoretical notion of a 'linear trend' or else in technical progress is certainly not justified. Firms observe a technology strategy, they know of customer preferences and improve their products *selectively*. Sometimes they take advanced products off the market, probably because of high prices and low customer preparedness to pay them.

On the research agenda more such dynamic studies remain. In particular we want to include real customer preferences as was done in the hedonic study (see for example [6]). It would also be interesting to include, next to the most advanced product of major producers of sensors, a variety of their brands and compare them relative to each other. Such analysis is possible as has been shown for photovoltaic products [5, p.402]. For strategic management of technology, our novel approach to measuring technical change at the product level in intertemporal comparison of product characteristics and using objective performance measures seems to be a straightforward tool for benchmarking technological sophistication. Managers can learn how their own technological capabilities have changed between two points in time in relation to their respective competitors which may have changed significantly over time.

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