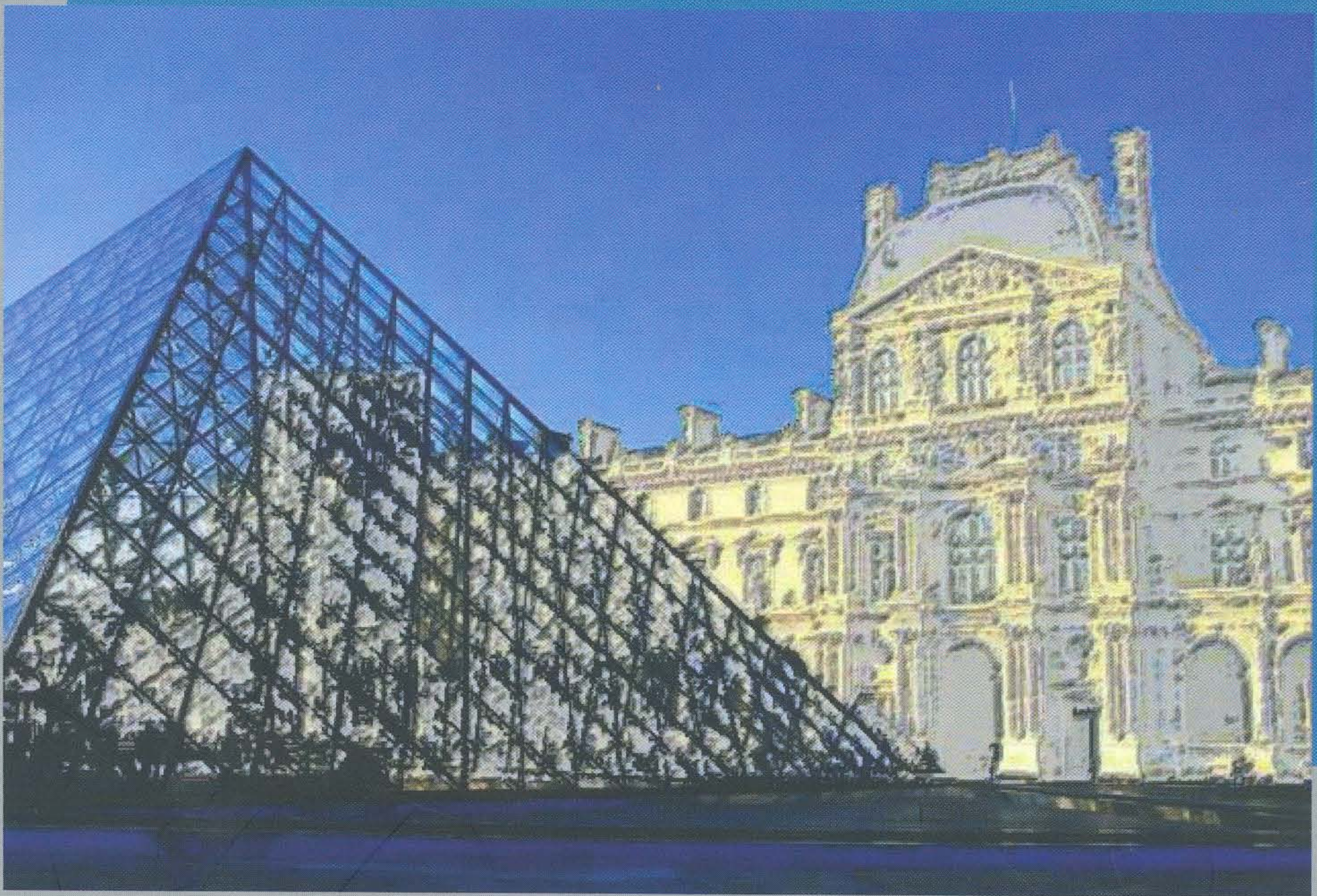
Managing New Product Development and Innovation

A Microeconomic Toolbox



Hariolf Grupp and Shlomo Maital

Samuel Neaman Institute
FOR ADVANCED STUDIES IN SCIENCE AND TECHNOLOGY

Hariolf Grupp and Shlomo Maital

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with contributions from
Amnon Frenkel and Knut Koschatzky

as well as
Asaf Ben Arieh, Galit Dopelt, Irit Gillath
Mel Horwitch, Guy Levy, Thomas Reiss,
Avi Shoham, Galit Sobel, Han Smit and Alexander Vaninsky

Samueal Neaman Institute for Advanced Studies in Science & Technology – Technion-Israel Institute of Technology

Haifa ISRAEL

Fraunhofer- ISI

Karlsruhe GERMANY

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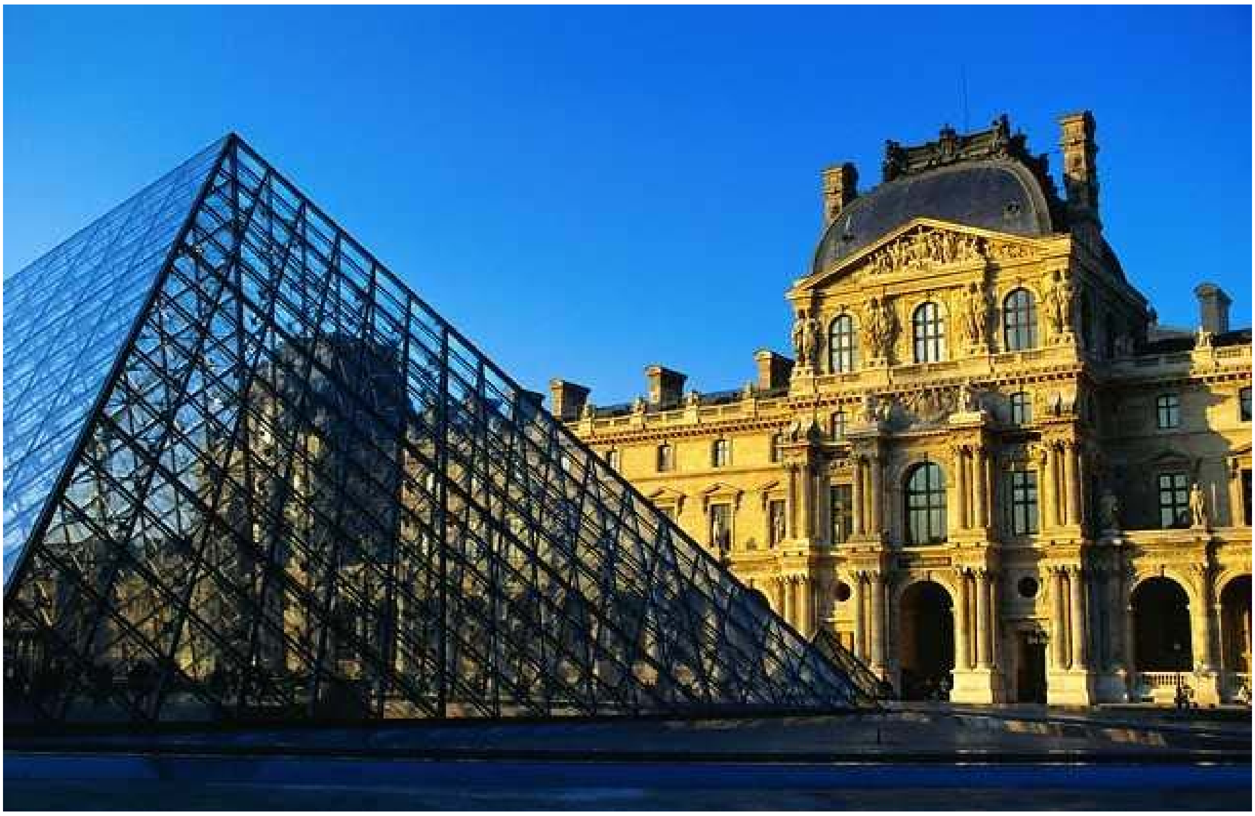

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Part I

Tools for Decisions

1 Improving Existing Products: Optimal Incremental Innovation[1]

Main Ideas in this Chapter

We start Part I by constructing in this Chapter new operational definitions of incremental innovation, standard innovation, and radical innovation, using a "technometric benchmarking" model. Based on this definition, optimal incremental innovation is formulated as a linear programming problem. The model is illustrated by an actual case: reconfiguration of a gamma camera. We show how our model can contribute to improved allocation of research and development (R&D) resources, by integrating marketing and R&D in a single decision-support model. The structure of this Chapter is as follows. The Section after the introduction outlines a typology of innovation, and proposes new definitions of the three types of innovation: incremental, standard, radical. Section 1.3 outlines our model, using cost-benefit logic and building on our typology. Section 1.4 provides an empirical illustration based on reconfiguration of a gamma camera used in magnetic imaging for medical diagnostics. We conclude with some general observations on how mathematical modelling can help integrate R&D and marketing.

1.1 Introduction

Whether, when and how to reconfigure existing products, processes or services are standing issues facing senior managers. While much research has been conducted on managing R&D to achieve dramatic, revolutionary innovations, everyday business success probably depends more on the quality of more humdrum, incremental improvements to existing products and services. Perhaps 90 per cent or more of so-called "new" products are in fact reworked versions of existing ones.

Yin (1994), for instance, argues that "... the mentality that seeks large breakthroughs instead of step-by-step cumulative efforts for incremental advances dominates technology strategy ... [as a result] cutting-edge companies have largely overlooked the significance of related economic returns (from incremental advances) in their

1 The research underlying this Chapter was supported additionally to the GIF grant by the Technion VPR Fund for the Promotion of Research, and the Y. Apter Research Fund. We thank Dr. Alexander Vaninsky for his programming assistance. A version of this Chapter was presented at a Seminar of the Tinbergen Institute, Erasmus University, where one of the authors, S. M., was Visiting Professor in Sept-Oct. 1997. An earlier version of this Chapter was published in *Research Evaluation* 7 (2), pp. 123-131, 1998, as a co-production with Asaf Ben Arieh.

planning process ..." (p. 266). Utterback (1994, p. 189, citing Gomory and Schmitt, 1988) observes, "most products sold today were here in slightly inferior form last year, and most competition is between variants." "Since standard, or dominant designs, exist in most industries, one can argue that incremental innovation is a far more prevalent and common management problem - though perhaps a more tractable one - than radical innovation", Christensen, Suarez & Utterback (1996) note.

Decision-makers facing reconfiguration dilemmas must tackle such complex questions as: When should a reconfigured "second-generation" product, service or process be introduced to replace an existing product, service or process? How large an investment in Research and Development (R&D) should be made in this second-generation product? Which characteristics of the product deserve priority in terms of their cost-value ratios? How can R&D resources - funds, manpower and even time - best be invested, in the most cost-effective manner, to improve the product's value-creating power?

With growing importance attached to strategic innovation, along with rising R&D costs, there is need for operational, quantitative decision-support models to guide strategic decision-making. Over a decade ago, Lee, Fisher and Yau (1986) asked rhetorically: "How are managers, many of whom are not themselves technically trained, to evaluate in real time the progress - and appropriateness - of [R&D] investments?" Managers who do have the requisite technical understanding face another challenge - allocating time. Gluck and Foster (1975) observed two decades ago that top managers spend most of their time - up to 95 per cent of it - putting out fires in marketing and production even though their ability to influence their firm's outcomes is far greater in the study, design and development stages - where CEO's invest perhaps five per cent of their time.

How can researchers help managers best carry out R&D for product redesign? Hauser (1996a) argues persuasively for the use of mathematical models in product development, and surveys a variety of them. Following his lead, the model proposed here is an attempt to provide a quantitative tool for optimal second-generation R&D. It builds on Hauser (1996b) and Meyer, Tertzakian and Utterback (1995), who have proposed a variety of "metrics", or quantitative measures, for managing R&D.

A number of attempts have already been made to construct quantitative operational models for evaluating R&D resource allocation. Scholefield (1994) notes that "the allocation of R&D resource in a multibusiness organisation is often based more on current operating performance than on the relative potential for technological development of the businesses." His model seeks to link R&D allocation to business strategy. Gittins (1994) proposes a planning model he calls "RESPRO" for new-product chemical research; Yin (1994) studies incremental improvements in petroleum refining.

Our model is based on standard economic cost-benefit logic that seeks to quantify and maximize the benefits of reconfiguration, relative to resource constraints on person-hours, capital funds and time alloted to the task. Emphasis is placed on integrating technological and engineering data with the "voice of the market" - data drawn from surveys of buyers, expressing their subjective evaluation of product attributes - and on "benchmarking" - the continuous process of measuring products, services, and practices against the toughest competitors or industry leaders.

1.2 An operational typology of innovation: Some basic theory

Technometric benchmarking

Lancaster (1991) observed that "the good, per se, does not give utility to the consumer; it possesses characteristics, and these characteristics give rise to utility" (p. 13). A product characteristic is an important feature of the product that satisfies needs or in other ways creates value for its buyers. Marketing researchers have long believed that no-one buys a "car", but rather, buys style, glamor, comfort, convenience, economy, status, and reliability.

It follows that the development, production and marketing of goods and services can best be understood and modelled, by focusing on key product characteristics or attributes. This is the foundation of a novel approach to product benchmarking known as "technometrics" (Grupp 1990, 1994, 1998; Grupp et al. 1986, 1988, 1994, and Koschatzky et al., 1996). It is also the basis of a huge literature in marketing on what are called "multi-attribute models" (Fishbein 1963, Fishbein and Ajzen 1975, Bass et al. 1972, Wilkie and Pessemier 1973, and Curry and Menasco 1983).

Technometric benchmarking builds comparative metrics of product quality and competitiveness by implementing the following four stages for a given product, process or service:

1. Choose the fundamental characteristics or attributes, that capture how the product, process or service creates value for customers. These attributes must be capable of being measured (though ordinal scales are acceptable), and usually number between five and 12.
2. Measure those attributes, and do the same for competing products.
3. Normalize each of the product's attributes on a [0,1] metric, where 0 represents the attribute's lowest value among all competing products, and 1 represents that attribute's highest value.
4. Graph, aggregate, and otherwise analyze, the product's strengths and weaknesses, across all attributes.

Here are two examples of the use of technometric benchmarking, "laser strippers" and medical-imaging printers. Laser strippers are devices for removing photoresistive materials from silicon surfaces used in semiconductor production; while *product* features are standard, the *process* technology (laser-based, rather than chemical or mechanical) is new. Thus, while the product itself is an example of incremental innovation (existing features are improved), the process could be regarded as a radical innovation (entirely new process features are created).

Table 1.1: L-Stripper vs. Four Competitors
*Values of key Attributes: Original Values ("**act**ual") and Technometric [0,1] Scale ("**tech**").*

	L-Stripper		Competitor 1		Competitor 2		Competitor 3		Competitor 4	
	act	tech	act	tech	act	tech	act	tech	act	tech
Process performance	40	0.6	50	1	25	0	30	0.2	35	0.4
Yield	*	1	77	0.97	55	0.6	19	0	79	1
Damage	*	1	*	1	*	1	*	1	*	1
Reliability	*	0	*	0.89	*	1	*	0.39	*	0.36
therein: MTBF	*		130	1	130	1	65	0	80	0.25
therein: MTTR	*		8.5	0.75	7	1	13	0	8	0.83
therein: UPTIME	*		92	0.93	95	1	85	0.78	50	0
Throughput	50	1	45	0.75	35	0.25	50	1	30	0
Particles	0.1	1	0.02	1	0.02	1	0.12	0	0.04	1
CV	100	1	100	1	100	1	0	0	0	0

* Confidential.

Process performance - test for quality of removal of photoresistors, scale of 1 to 100 points.

Yield - percent of total components usable, out of total number of components on the wafer.

Reliability - three characteristics: MTBF (mean time between failure), MTTR (mean time to repair),

UPTIME (% of time the device is operating).

Throughput - speed of operation, measured in wafers per hour.

Particles - test for presence of undesirable particles after completion of stripping process.

CV - test for presence of conductive ions (generated in the stripping process).

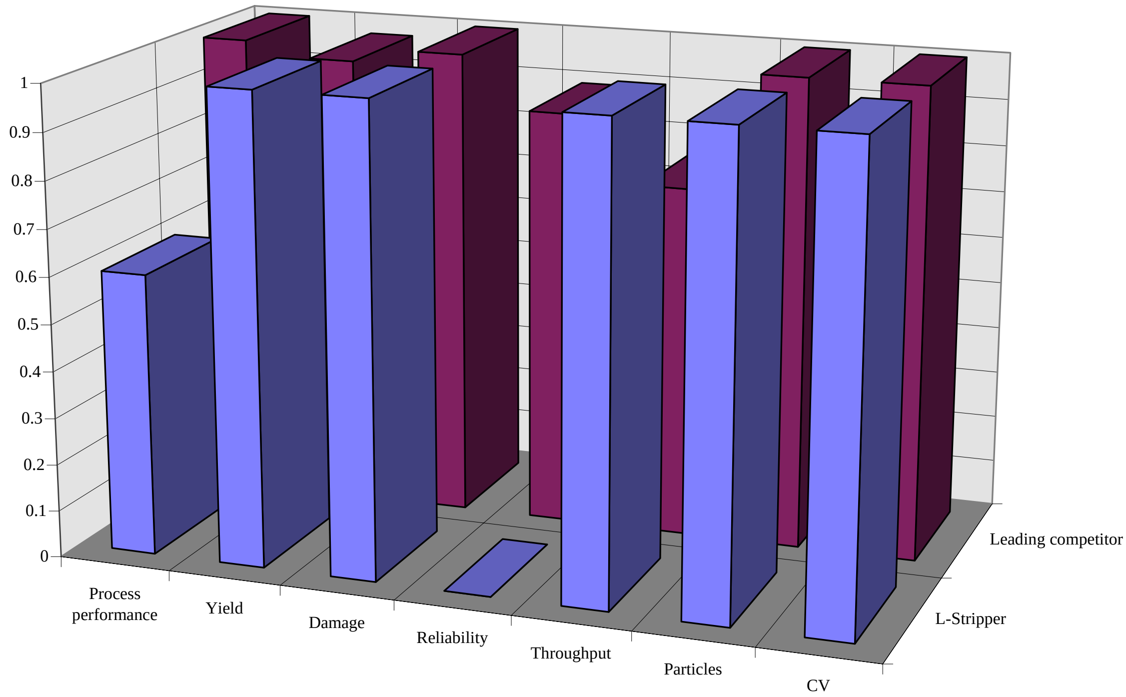

Figure 1.1: L-Stripper vs. Leading Competitor (#1).

Table 1.1 shows attribute values, and technometric scores for seven attributes, for the innovative laser-stripper and four competitors. The technometric scores are calculated as follows. Consider, for instance, the "0.6" value for the L-stripper's "process performance". This is computed as:

Technometric Score

$$= \frac{\textbf{(L-stripper value)} - \textbf{(Value for lowest-scoring competitor)}}{\textbf{(Value for highest-scoring competitor)} - \textbf{(Value for lowest-scoring competitor)}}$$

$$= (40 - 25) / (50 - 25) = 15 / 25 = 0.6$$

The new product excels in all but two characteristics: "process performance" (rated as highly important by customers) and "reliability", where it scores lowest. Its dismal reliability score make the product unmarketable in its current form. Further development efforts will focus on these two weak points. (See Figure 1.1). The current version now scores 1.0 in process performance, and is much improved in reliability; the product is now close to commercial production.

Figure 1.2 compares a leading medical-imaging printer (Agfa) with a new challenger ("X"). The challenger excels against all models, including Agfa, in film type, print time, size and weight - but falls short in other key attributes. The new product in its existing form failed. The technometric "silhouette" shown in Figure 1.2 helps us understand why. What appears utterly obvious, after carrying out the technometric benchmarking, is in our experience often *far from obvious* beforehand. Carrying out a characteristic-by-characteristic quantitative analysis forces the careful numerical benchmarking that decision-making demands.

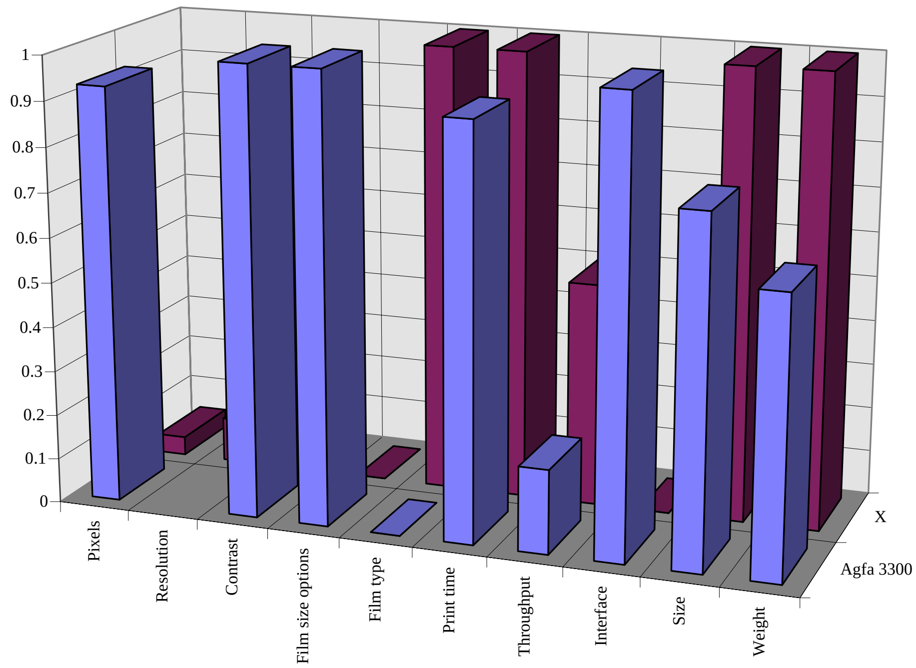

Figure 1.2: *A graphic technometric comparison of two medical imaging printers: Agfa versus "X".*

Typology of innovation

The technometric benchmarking approach can be used to construct a typology of innovation. In our view, no satisfactory operational definition currently exists of the various types of innovation (Dewar and Dutton 1986): incremental, standard and radical. Rosegger (1996) defines radical innovations as "clear discontinuities in economic activity" (p. 237), e.g. steam engine, computers; implying that incremental innovations are innovations that are neither basic nor major, arising principally when standard or dominant designs exist as platforms on which minor improvements are made. Yin's (1994) definition for radical innovation: "a revolutionary change that contains a high degree of new knowledge [while] incremental improvement is a renovation and adjustment of current technology with a low degree of new knowledge." (pp. 265-66).

These definitions rest on rather vague notions of "major", and "new knowledge". We now proceed to build a new operational typology of innovation, based on the Lancaster attribute model (see Grupp 1994, pp. 180 - 181).

We define a product, service or process as a finite collection of characteristics or attributes, all of them measurable in either physical or ordinal units (e.g. consumer satisfaction scales). For a given product, let those "n" attributes be x_i , where i = 1, ..., n . A product, then, is simply a vector of attributes:

$$[x_1, x_2, ..., x_n]$$

Definitions

1. An *incremental innovation* is one in which a new version of an existing product has some or all of its existing attributes improved. The new vector is:

$$[x^*_1, x^*_2, ..., x^*_n], \text{ all } x^*_i = c_i \, x_i, \text{ some } c_i \neq 1,$$

where x^*_i is the new post-development value of attribute i, and c_i is a vector of scalars, showing the proportion of change in each product feature.[2]

A hypothetical example of an incremental innovation is shown below in Table 1.2, for a large business jet, the Gulfstream IV. A reconfigured improved Gulfstream V may have better range, speed, payload, climb and cabin room. The new vector of attributes quantifies the degree to which the product was improved, in a way that permits easy benchmarking against competing products.

Table 1.2: Gulfstream IV vs. "Improved" Gulfstream.

	Range	Payload	Speed	Climb	Takeoff	Cabin room	Noise	Cost per mile
OLD	4141	3.66	459	4014	5280	2008	76.8	18.28
NEW	5000	3.66	480	4500	5280	2500	76.8	18.28

2 Note that this definition permits an incremental innovation, in which some product features are actually worsened, in order to save resources that can be directed toward improving other product features. This amounts to moving to a new point on the "production possibilities frontier", where production possibilities are defined not in product space but in product-feature space. An example: the French one-star hotel chain, Formule, dispensed with receptionists, room service and other amenities, while improving hygiene, quietness and bed quality. The incrementally-innovative product has been warmly received by business travellers, who mainly want a quiet, clean room with a comfortable bed. The economic logic of worsening a product is discussed in Grupp (1998, Chapter 10).

2. A *standard innovation* is one in which the vector of product attributes is:

$$[x'_1, x'_2, ..., x'_n, x'_{n+1}] , x'_i = c_i x_i,$$

where x'_{n+1} represents a new product attribute that did not previously exist.

The difference between a standard innovation and an incremental innovation is that one additional attribute is added to the product, that did not exist before (while existing attributes may or may not be improved somewhat). An example could be the addition of CD-ROM read-only drive to PC's.

3. A *radical innovation* is an innovation such that "k" significant new attributes are created, $k \geq 2$, which did not before exist - creating, essentially, a wholly new product:

$$[x^\circ_1, x^\circ_2, ..., x^\circ_n, x^\circ_{n+1}, x^\circ_{n+2}, x^\circ_{n+3}, ..., x^\circ_{n+k}], x^\circ_i = c_i x_i.$$

An example is a new pen-based computer, that stores handwritten material in its memory, then recognizes each character and transfers the material to standard computer files. Some of its attributes: pen size, memory size, accuracy of letter recognition, etc., are new and are thus not comparable to existing attributes of conventional computers.

Corporate decisions to launch R&D programs for radical innovation are often crucial, and often compete with less risky, less costly - and potentially less profitable - incremental-innovation R&D. An example is Intel's decision to continue developing SISC technology for its 486-successor chip, rather than develop a RISC chip, like the Power-PC of Motorola-IBM-Apple. In retrospect, the decision was a good one, aided by clever technological improvements leading to the Pentium and Pentium Pro.

We propose here a decision tool to aid managers in optimizing their incremental innovations, based on technometric benchmarking. With slight adaptation, our model could serve decision-making for standard innovations as well, and with considerable alteration, for radical innovation.

1.3 A mathematical programming model for evaluating incremental innovation

Consider a manager with limited labor, capital and financial resources, and especially limited time, managing an R&D project to create incremental innovation for an existing product. What attributes should be improved? How can the R&D investment best be utilized? Is the project worthwhile at all? How can one know? Our model supplies some answers.

Managers seek the most valuable feasible combination of improvements in product (or process) specifications, that meets a) cost; b) skill; and c) time constraints. "Valuable", in our model, means: The highest possible weighted average of product attribute improvements, where the weights reflect the value consumers attach to the improvement of each attribute.

We believe that senior management's ultimate objective is to supply the market with the most valuable, attractive package of attributes possible. Products that best create value, will best create sales, market share and profit.
Formally:

Terminology

i	-	product, service or process characteristic, $i = 1, ..., n$,
x_i	-	technometric specification for characteristic "i", based on [0,1] metric {0 is lowest performance, 1 is highest performance, among competing products},
Δx_i	-	change in x_i through R&D investment,[3]
c_i	-	cost of making incremental change in x_i,
t_i	-	time needed to make incremental change in x_i,
l_i	-	skilled labor-hour needed to make an incremental change in x_i,
w_i	-	market value of an incremental change in technometric specification x_i,
C	-	total R&D budget ($ million),
L	-	total number of skilled labor-hours,
T	-	time available for completing R&D.

Model

Objective function:
Choose Δx_i to Max $\Sigma\, w_i\, \Delta x_i$ subject to Capital, Labor and Time Constraints:

Capital: $\Sigma\, c_i\, \Delta x_i < C$

Labor: $\Sigma\, l_i\, \Delta x_i < L$

Time: $\Sigma\, t_i\, \Delta x_i < T$

3 Improvements are defined in terms of "one technometric unit", which is 0.1 on the [0,1] technometric scale (Maital and Vaninsky 1994); for instance, an improvement of 0.1 in the product feature "price" means development that enables a price reduction of $20,000 (from an original price of $200,000); the cost of such a price reduction, in terms of R&D investment, is $900,000, or a coefficient of 0.9. Hence, c_i is equal to 0.9.

That is: allocate labor, capital and time to R&D efforts, in order to improve the product's attributes, in a way that generates that highest-value "basket" of product attributes, where "basket" is a weighted average of the product attributes, with weights reflecting how the market (i.e. customers) values the improvements.

This is a linear-programming model. Incremental improvements are consistent with the assumption of linearity. But in many cases, the constraints may well be non-linear in nature. This can easily be handled by implementing quadratic or other non-linear programming techniques.

Standard linear programming algorithms provide solutions that include: the optimal improvement Δx_i for each attribute, and the way to achieve the improvement through investment of labor, capital and time.

Voice of the Market

A vital aspect of the model is the "w_i" weights, which can play a crucial role in deciding which attributes of the product should be improved: How can they be determined? One approach is through conducing "voice of the market" surveys among customers, who indicate on a questionnaire the relative importance of each of the product attributes. There are other several competing approaches to evaluating "voice of the market", apart from the "voice of the market" questionnaire, including the technique known as "hedonic price indexes" (in which product price is the dependent variable of a statistical least-squares regression, with product attributes as the independent, explanatory variables; beta coefficients then become the relative "weights" for the programming model's objective function).[4]

Finally, conjoint analysis can be used to evaluate "tradeoffs" of consumers among competing attribute improvements. Chan Choi and DeSarbo (1994) use a technique known as conjoint analysis: "In a typical conjoint-based product designing or concept testing procedure, estimated individual level part-worth utilities are used to simulate the potential market shares of proposed product concepts against existing competitors' brands. .... We compute equilibrium market shares and prices for each scenario of a concept profile versus existing brands" (pp. 451-454).

4 See, for example, Grupp and Maital (1998).

1.4 An example: The gamma camera - "Acu-Scan"

Background

The gamma camera is an imaging system intended to assist in diagnosis of illness by doctors. It produces images of the radiation generated by radioisotopes within a patient's body, with the objective of examining organ function and anatomy and to detect abnormalities. It serves as a diagnostic tool, in the hands of the physician, for evaluation and follow-up of disease and physiological problems. Initially a radioisotope attached to a chemical mediator is injected into the human body and targeted to a specific organ. When the radiopharmaceutical accumulates in the target organ, it emits radiation, which is detected and counted by the gamma camera detectors. The data collected is then processed by a computer, and can be rendered as a graphic picture, on a computer monitor. The nuclear radiologist can then provide his interpretation and diagnosis, and report his findings.

The customers whose preferences are decisive are those of the doctors, who use the camera's output, and the technicians who operate it. The market for gamma cameras is increasingly influenced by the trend to managed health care, which focuses attention on the camera's price efficiency: cost relative to its performance.

Six basic parameters characterize the camera's appeal to customers: price; downtime; connectivity to other systems and work stations; its ability to carry out optimally a wide variety of medical applications and ease of operation (extent to which operation is automatic); ability to carry out examinations using high-energy isotops (511 keV) and thus improve resolution; and transmission/emission.

Product

Acu-Scan is a pseudonym for an actual multipurpose gamma camera, produced by a mid-size firm that specializes in medical instruments. Acu-Scan has two detection heads positioned opposite one another, at a fixed 180˚. The heads are attached to a gantry and are placed on a large ring that rotates the heads around the patient. Patients are usually examined in a prone position, lying on a bed. The bed moves up and down, backward and forward. Acu-Scan is regarded as a highly sophisticated system, incorporating cutting-edge mechanical, electronical, and computer technologies. Its resolution is high, its automated operation provides ease of operation and reduces the need for skilled operators. Its conectivity with other systems is good, making it usable in modular form with other equipment in the clinic. However, Acu-Scan's price is regarded as above average in its market, and it lacks some attributes other cameras possess - like heads with variable, adjustable angles. Acu-Scan is unable to perform transmission of rays simultaneously with emission (of radiation), a method used to improve reliability and reduce artifacts, an attribute that now represents state of the art in nuclear medicine, specifically in nuclear cardiology (attribute no. 6).

Management Problem

As Acu-Scan completed its introduction and penetration of the market, a marketing need was discerned, to develop a more advanced dual-head camera, with only a 12-month development time and a limited budget. The Acu-Scan marketing department defined a number of improvements in the camera's performance attributes, that were perceived as vital to maintain market share and market leadership in the nuclear medicine marketplace.

The questions that faced management were:

- In which attributes should R&D resources be invested,
- what are the priorities,
- how much money, manpower and time should be invested, and
- what will be the value of the reconfigured Acu-Scan camera compared with its predecessor, relative to the resources invested in developing it?

In other words: what is the optimal R&D program for incremental innovation? The vital issue is, of course*: How do buyers perceive the value of improvements to the six key attributes?* Which feasible combination of such improvements would create the most attractive, marketable second-generation camera?

Model

The following mathematical programming model was employed. Six key product attributes were identified, together with the relative importance of each attribute, or weights. The weights were computed by consulting senior doctors and a leading professional journal; see Table 1.3.

Table 1.3: Nuclear Camera Attributes and Their Importance.

	Technometric value#	Weight**
1. Price	6.2	9.75
2. Down time	6.3	9.5
3. Connectivity	7.6	9.6
4. All-purpose*	8.5	9.0
5. Resolution	6.6	10.0
6. Simultaneous transmission, emission	6.0	8.0

\# for Acu-Scan camera, relative to competitors (= 10).
* Ability to perform all the nuclear medicine functions.
** On a scale of 1 to 10.

The sum of up to $X million was budgeted for the development; development time was not to exceed 12 months; and up to 20 man-years of skilled labor was made available.

The model itself is shown in Table 1.4. The linear programming solution is shown in Table 1.5.

Table 1.4: Programming Model: Optimal Incremental Innovation for Acu-Scan Camera.

Attribute	1	2	3	4	5	6
Vector of weights w_i	9.75	9.5	9.6	9	10	8
Cost coefficients c_i	0.9	0.1	0.1	1	0.6	0.3
Labor coefficients l_i	4	2	2	10	1	1
Time coefficients t_i	2	2	2.5	5.5	3	2

MAXIMIZE $9.75\ \Delta x_1 + 9.5\ \Delta x_2 + 9.6\ \Delta x_3 + 9\Delta x_4 + 10\ \Delta x_5 + 8\ \Delta x_6$

subject to:
a) financial constraint:
$0.9\ \Delta x_1 + 0.1\ \Delta x_2 + 0.1\ \Delta x_3 + 1\ \Delta x_4 + 0.3\ \Delta x_5 + 0.3\ \Delta x_6 < \$X$ m.[5]
b) labor constraint:
$4\ \Delta x_1 + 2\ \Delta x_2 + 2\ \Delta x_3 + 10\ \Delta x_4 + 1\ \Delta x_5 + 1\ \Delta x_6 < 21$ man years
c) time constraint:
$2\ \Delta x_1 + 2\ \Delta x_2 + 2.5\ \Delta x_3 + 5.5\ \Delta x_4 + 3\ \Delta x_5 + 2\ \Delta x_6 < 12$ months.

Table 1.5: Optimal Resource Allocation for Incremental Innovation: by Attribute.

	Capital	Labor	Time	Optimal value	Initial value
	$ million	Person years	Months		
Price	0.9 X	12	6	9.2	6.2
Downtime	0.1 X	2	6	9.3	6.3
Connectivity	0	2	0	7.6	7.6
All purpose	0	0	0	8.5	8.5
Resolution	0	0	0	6.6	6.6
Transmission/Emission	0	0	0	6.	6
Total	X	16	12		

Overall Improvement in the Objective Function: 15 %

5 The company with which we worked asked that we not disclose the R&D budget, which is noted above as $X m.

The linearity of the model moves the solution toward improving only two of the attributes - resources are directed toward where they contribute most to the objective function, and the system does not encounter the diminishing returns present if non-linearities were taken into account. Labor is a slack variable: 4 person-years are unused. The identification of slack resources is an important advantage of the model - skilled workers generally work long hours, are fully occupied, and the manager's naked eye has trouble discerning that their labor may in part be superfluous.

Capital and time are "scarce" variables, with non-zero shadow prices. From the high shadow price of time, we can see that this is the most severely-binding constraint - a common situation when a two-month reduction in time-to-market may mean the difference between market success and failure.

We found that if the time constraint were relaxed, adding three months to the 12-month period, along with $100,000 in additional capital, some of the resources would then be directed to improving "connectivity". The sensitivity of linear-programming models to small changes in parameters and coefficients make it vital to undertake sensitivity analyses - alteration of parameters to determine how the model's outcome reacts. *Another important reason for sensitivity analysis is the uncertainty that attaches to many of the underlying coefficients; it is always well to know how sensitive the solution is to possible estimation errors in key coefficients.*

The model directs managers to improve the Acu-Scan incrementally, by performing R&D that will permit a significant reduction in price (perhaps, by improving the process technology used in production), and result in a significant reduction in down time. Overall, the price decline achievable is 3 technometric units, or 3 x $20,000 = $60,000, and raise the downtime score from mediocre (6.3) to excellent (9.3). Both attribute improvements improve the cost-effectiveness of the gamma camera – an important competitive advantage in an increasingly price- and cost-sensitive market.

The optimal allocation of R&D resources leads to a 15 per cent improvement in the Acu-Scan's technometric objective-function score. About two-thirds of that improvement stems from price reduction, and one-third from improvement in down time.

Discussion

Management's R&D decision was not guided by the model, because it was not available to them at the time. Senior managers decided to invest R&D resources in improving the "All Purpose" attribute, and in "transmission/emission". This was a logical decision. The "all purpose" attribute has a reasonably high customer-preference weight, and it is the feature in which the Acu-Scan camera scores highest. It makes good sense to further strengthen the attribute that already provides strong competitive advantage, in anticipation that competitors will work hard to close the gap in this area.

The marketplace's demand for high "all-purpose" scores is interesting. This characteristic is kind of an "entrance exam" or "quality test" - cameras that lack it, flunk. Yet, doctors generally do not make use of it. "All purpose" is a buzzword that cameras must convey, or fail. Such knowledge is brought to the R&D lab from the marketplace. Knowing it can make the difference between success and failure in reconfiguration. Excess reliance on mechanical models is, for this reason, dangerous.

Resolution is a key characteristic; however, enormous investments are needed to improve it significantly enough to make a difference in the marketplace. The cost-value ratio is prohibitive.

Connectivity is driven in part by cost containment; buyers seek to purchase from suppliers their best instrument, then link them all up together, rather than buy the complete system from one supplier.

Transmission/emission was the Acu-Scan camera's weakest feature, and it made sense to work to improve it. However, the linear programming model showed that the cost-benefit ratio or return to investment in improving this attribute was dismal. In reality, a new camera that greatly improved this feature turned out to be a smash hit. We thus urge caution in using our quantitative model. While we believe it offers valuable insights, the inherent nature of the incremental innovation process require seniors managers to weigh the results of optimizing models against their own experience, intuition and intimate knowledge of their customers needs and wants – a caveat that applies to all decision-support optimization techniques in the area of R&D.

The model, therefore, focuses R&D investment on three attributes: price, connectivity, down time. The marketplace speaks loud and clear, that cost-effectiveness is a crucial attribute in the age of managed health care and cost-cutting. It also says, for similar reasons, that in order to be competitive gamma cameras must have minimal downtime - in nuclear medicine, time is literally money - and that the camera must link up seamlessly with a wide variety of peripheral equipment. These were the variables our model found gave the highest value/cost ratio for R&D investment.

In practice, considerable resources were invested in providing the camera with variable-angle capability, to make it All Purpose. Managers simply believed they had no choice in this matter. All-purpose capability was indeed perceived as a kind of "entry fee" gamma cameras needed, to prove credibility in the market.

1.5 Implications and conclusion

How does this model contribute toward integrating marketing and R&D (see Griffin and Hauser 1996) ? Managing incremental innovation is a matter of balancing cost and value. The value of incremental improvements to product attributes is a crucial input to the model, that can be obtained best from marketing managers in the field. The cost of those improvements is an input that the expertise of R&D managers can provide. Optimal R&D investment in incremental innovation results from obtaining the biggest bang for the buck – maximizing the value of incremental improvements, relative to their cost in terms of time, money and labor.

There is value in quantifying such decisions, even at considerable cost. It is sometimes surprising that managers who thoroughly explore investment options when engaging in financial investment, risk huge sums in R&D with very little effort to gather data or quantify and model the decision.

There will surely be occasions on which the results of a programming model deserve to be ignored - especially when high uncertainty attaches to its cost parameters. But the combination of mathematical programming, and intuition, is in almost all cases more powerful than pure intuition alone.

Incremental innovation is subject to the dangers of the "sunk cost" fallacy - the notion that because a product exists, with considerable investment of resources and time, it is necessary to continue to improve, market and produce it.

As Phillips et al. (1994) note:
"Dassault's decision to bring out the Falcon 900 as a follow-on to the Falcon 50 illustrates a second feature of the sunk-cost risks in a market characterized by continuing technological opportunities. The need to devote resources to the development of new products does not stop after successful innovation. The learning that occurs in the first element of the process leads to ideas about improving the product. This is augmented by developments in science and technology that occur outside of the firm in question. Great pressure exists to use that knowledge in creating yet another airplane, partly because of the urges characteristic of the Schumpeterian entrepreneur." (p. 133).

We simulated the Falcon 900 investment, for instance, using our model and found only an 18 % incremental improvement in the objective function in return for a large investment, even when the incremental innovation is managed optimally. It is generally believed that the Falcon 900 will not be successful in challenging the market domination of the Gulfstream Series V and VI.

Two decades ago, Gluck and Foster (1975) proposed that top managers participate earlier in the R&D process, emphasizing: 1. strategic performance parameters of products in each product/market segment, how they have shifted, how they may shift in future, and the product's position in each parameter compared with that of the principal competitors; 2. the improvements that customers would value most in each parameter; 3. changes in each parameter that could lead to competitive advantage; and

4. potential moves of competitors, government, consumer groups, or work markets, that could undermine the company's advantages in each parameter (pp. 147-148).

We believe that our typology of innovation, and the mathematical programming model based on it, can provide at least partial answers to the first three issues, by bringing the key input of the marketplace to the lab bench of the R&D engineer, perhaps via the desk of the chief technology officer.

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2 Creating New Products: Optimal Radical Innovation[1]

Main Ideas in this Chapter

In Chapter 1 we propose a new operational definition of incremental, standard and radical innovation, based on a multi-attribute model known as "technometric benchmarking". In this Chapter, we focus on radical innovation, defined as a product such that out of "n" product attributes, a significant subset "k" exists, comprising product attributes that did not exist previously. We outline a mathematical programming approach to optimizing R&D investment, which provides a systematic approach to integrating R&D and marketing to provide a decision-support system for guiding R&D for radical innovation. We make use of a basic economic tool - the production possibilities curve - to examine trade-offs between existing product attributes and radically new ones. As for the case of incremental innovation, we stress the value of the model in integrating market information ("psychology") and technological constraints and advances. Our Chapter addresses what we view as a key issue in radical innovation: How to avoid costly, unsuccessful "technology push" products which fail to find "demand-pull" markets. We illustrate our model with a case study from laser medicine.

2.1 What is radical innovation?

The theoretical "innovation" or "technical progress" construct has not been established unambiguously. Rather, literature contains a variety of partly contradictory designations and definitions of the term "innovation". Also, the views of economists ("world novelty") differ substantially from those of industrial and business management economists ("new potential suppliers to a market", i.e., new to the firm). Within the OECD, for many years work on guidelines for defining technological innovation has been proceeding for statistical purposes. The outcome is the so called "Oslo Manual" (OECD 1992). According to this source, the technological innovation concept embraces both substantially new products (designated "major innovations") and also significant technological changes to existing products and processes. An improvement in performance characteristics is termed incremental product innovation. "Minor" technical or aesthetic modifications to products, i.e., non–progress relevant product changes are not regarded as incremental innovation and excluded from the innovation concept.

1 This is an original contribution to this volume not published elsewhere.

The view is taken that radical innovation is a relatively coherent category within the usual spread of "minor" versus "major" concepts since it rarely occurs in practice, whereas the incremental innovation concept, when all is said and done, covers the vast majority of all other innovation events but is less conspicuous. Gordon (1992) contends that the "standard innovation" falls neatly into the large gaps between the radical and the more minor forms of innovation which in bipartition of concepts is wrongly disregarded.

Yet, products differ, according to how they are made ("process technology"), the benefits they yield consumers (attributes), how they are used or perceived (consumer behavior), or how the product is integrated with other products or systems (architecture). Thus, radical innovation can be defined by focusing on significant discontinuities or change in any or all of the above four aspects.

Henderson and Clark (1990) define radical innovation as fulfilling two necessary conditions: an "overturned" core concept of the product, and major change in the linkage among the core components of the product. Mansfield (1968) and Nelson and Winter (1982) focus on the competitive consequences of radical, as opposed to incremental, innovation. Moore (1991) focuses on how the product is used, and defines "discontinuous innovation" as products that require us to change our current mode of behavior or to modify other products and services we rely on. (p. 10). For the concept of discontinuity see also Ehrnberg (1995). In a simulation, Windrum and Birchenhall (1998) demonstrate that by learning effects of both producers and consumers of an innovation multiple as well as single designs configurations can occur.[2]

The one thing that all these theoretical constructs have in common is that they try qualitatively to keep the various types of innovation apart. The boundary line between them runs along verbally shaded distinctions like "large", "significant" or "substantial". The task remains to establish whether it is possible to measure all types of innovation with a formal, mathematical concept.

In Ben Arieh, Grupp and Maital (1998), we put forward new definitions of incremental, standard and radical innovation. Our taxonomy was built on the premise that products are best seen as combinations of features, or attributes – an approach developed independently, and somewhat differently, in three disciplines: economics (Lancaster 1971, 1991); management of technology and innovation (Grupp 1994; Saviotti and Metcalfe 1984); and marketing (Fishbein 1963; Fishbein and Ajzen 1975; Bass and Talarzyk 1972; Wilkie and Pessemier 1973; Curry and Menasco 1983). We went on to construct and illustrate a mathematical-

2 The latter design configurations are called "dominant designs" in innovation theory. For a recent review see Grupp (1998, pp. 13, 100).

programming model for optimal incremental innovation, based on optimizing the cost-value ratios of incremental improvements in product features.

In this Chapter, we outline a new conceptual approach to optimizing radical innovation. While the core of radical innovation is generally, and rightly, viewed as a creative, inspirational process not easily adapted to quantitative models, we maintain that it is both possible and desirable to model radical innovation, in ways that aid decision-making and reduce risk.

Section 2.2 presents our concept, Section 2.3 introduces the optimizing model, Section 2.4 illustrates a case in study, laser medicine (laser scalpels), which is a knowledge-based product, and Section 2.5 demonstrates how the optimizing model works in this case.

2.2 A model of radical innovation

We choose the conventional approach and focus on product features. We define a product, service or process as a finite collection of characteristics or attributes, all of them measurable in either physical or ordinal units (e.g. consumer satisfaction scales). For a given product, let those "n" attributes be x_i , where i = 1, ..., n. As we need metric scales, all the attributes measured in physical or ordinal units are converted into a [0,1] interval by the technometric algorithm (Grupp 1994, 1998). A product X, then, is simply a vector of attributes:

$$\mathbf{X = [x_1, x_2, ..., x_n]}$$

If we now integrate Henderson and Clark's (1990) distinction between product core or component technology and peripheral systems or linkage technology, we may differentiate between "modular" and "architectural" attributes. Suppose, our product has m modular and s systemic or architectural attributes, with m + s = n, we arrive at:

$$\mathbf{X = [x_1, x_2, ..., x_m, x_{m+1}, ... x_{m+s}].}$$

Let us stress here that the systemic part of the attributes may, but need not in any case, be related to standardization. Thus new entrants may be forced to fulfill certain systemic features with their innovative start-up products - eventually to the benefit of the incumbent market leaders by reinforcing the overall architecture of the systems.

As is well known (Swann et al. 1996), an industry standard does one or more of three things in innovation:

- It may allow products to work together (compatibility standard),
- it may define quality levels (minimum quality standard, e.g. for safety), and
- it may reduce the number of variants in a product system (variety reduction or scale economies standard).

Definitions

1. An *incremental innovation* is one in which a new version of an existing product has some or all of its existing attributes improved. The new vector is:

$$\mathbf{X^\circ = [x^\circ_1, x^\circ_2, ..., x^\circ_n], \text{ all } x^\circ_i = c_i\, x_i, \text{ some } c_i \neq 1,}$$

where x°_i is the new post-development value of attribute i.

2. A *standard innovation* is one in which the vector of product attributes is:

$$\mathbf{X' = [x'_1, x'_2, ..., x'_n, x'_{n+1}]\ , x'_i = c_i\, x_i,}$$

where x'_{n+1} represents a new product attribute that did not previously exist.

The difference between a standard innovation and an incremental innovation is that one additional attribute is added to the product, that did not exist before (while existing attributes may or may not be improved ot worsened somewhat in order to improve the others or fit with the new one). An example could be the addition of CD-ROM read-only drive to PC's.

Innovation typology	**Core technology reinforced**	**Core technology overturned**
Pheripheral interfaces unchanged	***Incremental innovation***	***Modular (standard) innovation*** ⇓
Peripheral interfaces changed	***Architec-tural (standard) inno-vation*** ⇒	***Radical innovation***

Figure 2.1: Innovation typology.

If the attribute n+1 adds to the m modular features, we speak of a modular (standard) innovation, if it adds to the s systemic proporties, we have an architectural (standard) innovation. The CD-ROM drive to a PC would certainly be a modular innovation.

3. A *radical innovation* is an innovation such that "k" significant new attributes are created, $k \geq 2$, which did not before exist - creating, essentially, a wholly new product (thereby the "old" $x_1, ..., x_n$ attributes may become obsolete):

$$\mathbf{X^* = [x^*_1, x^*_2, ..., x^*_n, x^*_{n+1}, x^*_{n+2}, x^*_{n+3}, ..., x^*_{n+k}], x^*_i = c_i\, x_i.}$$

We want to emphasize that radical innovation is thus defined as a continuum which can always be decomposed in a series of m^+ modular standard innovations and s^+ systemic standard innovations, if $m^+ + s^+ = k$. However, because standardization works at least in the architectural part of innovation, and because we adopted the economic definition of innovation (new to the world market, not new to the firm), we think confidently that in most cases cores and interfaces will be overturned to a large extent in radical innovation so that we need not study the case of few standard innovations as a separate issue.

An example of a radical innovation with a strong modular component is the laser scalpel that replaces the traditional knife scalpel of surgeons affecting the periphery in the operating room to some extent. Remote surgery by micro-manipulators whereby the doctor may be hundreds of miles away from the patient, is a radical innovation with a strong architectural component.

Another example for a modular radical innovation is a new pen-based computer, that stores handwritten material in its memory, then recognizes each character and transfers the material to standard computer files. Some of its attributes: pen size, memory size, accuracy of letter recognition, etc., are new and are thus not comparable to existing attributes of conventional computers. The transition from mainframes to PCs is an architectural radical innovation.

2.3 Optimization model

We now alter and adapt our mathematical programming model developed for incremental innovation (Ben-Arieh et al. 1998), to provide a decision-support system for guiding R&D for radical innovation.

Terminology:

- P_a - price of existing product "a"
- P_b - price of radically-innovative product "b"
- Q_a - total demand for product "a" (units)
- Q_b - total demand for product "b"
- X - vector of n attributes for product "a" as defined above

X^* - vector of n+k attributes for product "b" as defined above
FC_b - total fixed (R&D) costs for developing innovative product "b"
VC_a - total variable costs for producing product "a"
VC_b - total variable costs for producting radically innovative product "b"

The price of each product is assumed to depend on two factors: the product attributes, and other factors, such as advertising, brand name, etc.

$$P_a = A_o + A X \qquad (2.1)$$

$$P_b = B_o + B X^* \qquad (2.2)$$

where A is an (nx1) vector of coefficients a_1, a_2... a_n, where a_i is the subjective value of characteristic x_i as reflected in the product's market price, and A_o includes all factors that influence price other than product features. Similarly, B is an ((n+k)x1) vector of coefficients b_1,b_2, ..., b_{n+k} that reflect the mapping of product features into the innovative product's price.

The proposed approach has been considered sporadically in innovation literature here and there as far back as the 1960s and linked to the hedonic price concept.[3] The prime objective of the literature on hedonic pricing was certainly different from the present scenario. The method was originally developed in order to differentiate between a quality-determining price component and a quality-independent component. The question was raised as to whether price changes in an item can be viewed detached from quality changes. The use of hedonic pricing for measurement of technical change in later literature can therefore be termed "objective-estranged" (Dorison 1992, p. 68). As far as the neoclassical school is concerned, this approach is interesting in as much as, in so doing, demand forecasts are "sanitized" so that the effects of technical change can disappear. With (2.1) and (2.2), the opposite is intended.

Chow (1967) constructed such hedonic price indices for computers, presenting the price (the "net yield") of computers as a function of their memory capacity and their processing speed. He then adapted a logistic demand function to quality-sanitized

3 Griliches (1961, 1971) and Chow (1967). The new literature encompasses Saviotti (1985), Trajtenberg (1990) and Dorison (1992). A review of hedonics is provided by Silver (1996). Hedonism is a philosophical doctrine established in ancient times whereby the pinnacle of all endeavour is enjoyment. Such being the case, hedonic prices refer to prices arrived at by the consumers' sheer striving for enjoyment and do not represent anything but his wish. In particular, hedonic prices do not stem from the costs of capital and work input factors. Griliches (1971a, p. 4) comments that the value-loaded "hedonic" approach concept could be replaced by "property approach". Yet, in order to differentiate between other property approaches here, the original concept will be retained.

units of computer production and was able to show that the actual demand could be predicted satisfactorily by these means.[4]

We assume that demand for products "a" and "b" depends both on the price, and on the product's features.

$$Q_a = f(Pa, X) \tag{2.3}$$

$$Q_b = g(Pb, X^*) \tag{2.4}$$

We assume that managers seek to maximize profit. For the existing product "a", profit-maximization is formulated as:

$$\text{MAX} \;\; \Pi_a = P_a Q_a - VC_a(X, Q_a) \tag{2.5}$$

Correspondingly,

$$\text{MAX} \;\; \Pi_b = P_b Q_b - VC_b(X^*, Q_b) - FC_b - rFC_b, \tag{2.6}$$

where FC_b is the fixed (R&D) costs of developing the innovative product "b", and "r" is the opportunity cost of the FC_b capital, including a risk premium that reflects the degree of risk inherent in developing and marketing the radically-innovative product "b".

The standard first-order conditions apply – e.g., equate marginal cost and marginal price. However, a new set of conditions arise, that focus on product features:

$$Q_a \, \partial P_a/\partial x_i + P_a \, \partial Q_a/\partial x_i = \partial VC_a/\partial x_i \tag{2.7}$$

$$Q_b \partial P_b/\partial x^*_i + P_b \partial Q_b/\partial x^*_i = \partial VC_b/\partial x^*_i \tag{2.8}$$

Equation (2.8) states: a radically-innovative product should be so designed, that the marginal revenue from a new product feature is equal to the marginal cost of producing that feature. This condition, of course, applies equally to existing product features, and to the conventional product "a".

Finally, in order for the risk and expense of radical innovation to be worthwhile:

$$\Pi_b \geq \Pi_a. \tag{2.9}$$

4 As a byproduct, it became apparent that, virtually always, one of the two technical properties was price-determining, namely memory capacity. Technological limitations at that time in regard to expansion of memory capacity, according to Chow, were an obstacle to even faster market expansion (loc. cit.).

The model of optimal incremental innovation (Ben Arieh, Grupp and Maital 1998) is a special case of the above model, where production technology is assumed to be linear in time, money and labor. A key part of this model is the link between market prices P and product attributes X. ***Ex post***, this link can be explored through use of hedonic price indexes, which express market prices as linear functions of attributes and use statistical regression to estimate the coefficients; see Grupp and Maital (1998).

But in making vital, difficult decisions about whether to embark on costly, risky R&D programs to develop radically-new products, product managers must estimate the link between P and X ex ante. To do this, they must in some manner gain insight into consumer preferences of existing and potential buyers. Consumers are assumed to spend their income, in order to maximize utility. Assume consumers face a wide variety of products and product attributes. For a given consumer "j" and product "a", this implies:

$$\partial P_a/\partial x_i = \lambda\, \partial U_j/\partial x_i, \tag{2.10}$$

where U is utility and λ is the marginal utility of one dollar. (2.10) states that "optimized" products are such that the marginal utility value of an improvement in a product feature equals the increase in price stemming from that improvement. In competitive markets, where producers understand buyer preferences well, this condition will evolve and ultimately hold. The same condition must hold for the innovative product "b":

$$\partial P_b/\partial x^*_i = \lambda\, \partial U_j/\partial x^*_i, \tag{2.11}$$

A "trade-off" optimization condition can be derived from the above. Let $X(x_1, x_2, \ldots x_n)$ = constant be the product quality measured by the technometric concept and showing the various combinations of "x" attributes that are feasible resp. on offer, with existing technology and resources. Profit maximization therefore implies:

$$[\partial X/ \partial x_i] / [\partial X/ \partial x_j] = [\partial U/ \partial x_i]/[\partial U/ \partial x_j], \text{ all } i, j \tag{2.12}$$

Equation (2.12) states that the marginal rate of transformation among all pairs of product attributes must equal the marginal rate of substitution - i.e., the "cost" of improving attribute "i", in terms of worsening attribute "j", must equal the marginal utility of the improvement in attribute "i", relative to the marginal utility of attribute "j".

Condition (2.12) is the basis of the so-called "conjoint" model in marketing, which uses choice pairs presented to buyers to estimate marginal rates of transformation, then uses additional information to simulate market shares and profitability of existing and hypothetical combinations of product features, including those for radically-innovative products, ultimately zeroing in on the optimal configuration of features.

2.4 A case study from laser medicine

Laser medicine can be characterized by the fact that it is a comparatively new field in which physicists and engineers work alongside with doctors and which has a large and growing market potential. Thus, bio–medicine and medicinal physics is subject to specific interdisciplinary interests plus the market structures differ from many other markets. So, perhaps, competition between clinics, established doctors and manufacturers of medico–technical appliances is not typified by the conventional market relationships, but by checks and balances in health care. In the place of efficiency or price competitiveness, in many countries rivalries and questions of status are cogent factors. Against this background, laser medicine appears to be a highly worthwhile sample case.

Laser applications in medicine relate to both therapeutic and also diagnostic instruments. A very important and early application of lasers in medicine relates to eye operations. Laser opthalmoscopy, for instance, is used for treating detachment of the retina particularly in diabetic patients ("spot welding of the retina"). This possibility was published in 1965. As far back as 1964, another biomedical application of lasers became known: the treatment of carcinogenic skin diseases. In 1985, i.e., 20 years after description of the first capabilities, the number of annual patent applications in laser medicine was ten times greater than in 1975. Scientific publications have rocketed even faster. According to all innovation indicators, laser medicine seems to be a dynamic, comparatively new research area of substantial corporate and industrial relevance (Grupp 1998, p. 355).

The technometric comparison between the customary surgical scalpel and the laser scalpel points to a radical or greater innovation, since virtually all properties need to be redefined. In the terminology of Section 2.2, we find $k = 9$ new attributes: maximum power, durability, tuning, beam diameter, beam divergence, mode structure, high frequency trigger, cooling requirements, power supply (Grupp et al. 1987, p. 195). The first $m^+ = 7$ attributes relate to the modular part, the last $s^+ = 2$ attributes to the operating vicinity: a knife needs neither cooling nor electricity. Most of the n old attributes are obsolete (stainless steel etc.), but some are still important (weight, overall length etc.).

What is the relationship (2.2) between product quality and price on this radically new market? In marketing literature, conventionally the start point is falling marginal yields. The main theoretical relationship is illustrated in Figure 2.2. Shoham et al. (1999), however, point out that the implications are still similar if other functional types are taken as the basis. According to Figure 2.2, supplier B can calculate his additional profit margins from higher prices P as, in accordance with the graph, his product in the attribute rating is above A but does not approach that of supplier C.

According to the technometric data for 1985, the market was characterized by 20 predominantly American products (USA: 14, Japan, France and Germany 2 each). The 20 products on the laser–medical market in 1985 can be described by means of a characteristics bundle consisting of the mentioned parameters (power, beam diameter, beam divergence, etc). If we insert in (2.2) the technometric index X*, we find a positive relation (significant at the 5 per cent level) as expected.[5]

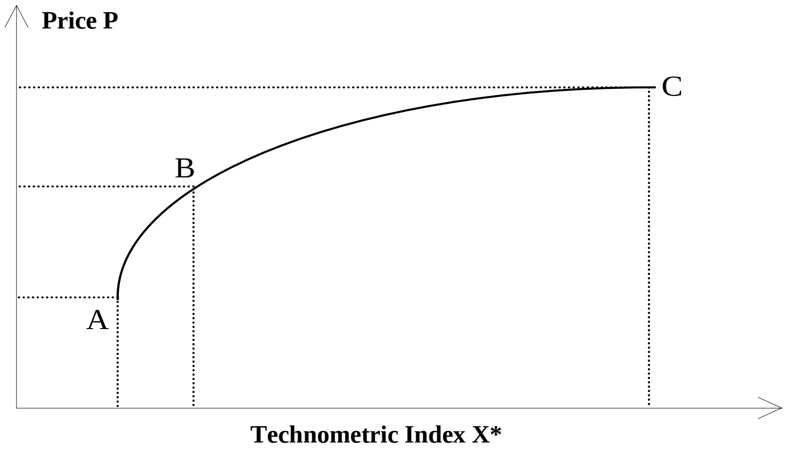

Figure 2.2: The relationship (2.2) between technometric assessment of product quality and price claimed by the marketing theory.

The hedonic prices b_i can be determined with the aid of the regression calculation. On this subject, Saviotti (1985, p. 312) observes: "Price equation coefficients ... can, therefore, be considered an approximation for users' judgement of the relative value of various characteristics." The regression calculation (with robust errors) can account for more than two thirds of the variance ($R^2 = 0.72$; see Table 2.1). This is open to different interpretations depending upon viewpoint. On the one hand, this means that more than two thirds of the price variation alone is explicable in terms of the physico–technical properties of the products. On the other hand, likewise one third is attributable to price variance which cannot be explained in terms of quality improvement but relies on the manufacturer's reputation or upon various marketing endeavours on service, maintenance, established practices or can be traced back to other preferences in certain market segments.

5 We use the rather dated feature values as it is sometimes difficult to get the permission to publish complete actual data.

An investigation of individual feature profiles by the vector X* in (2.2) and multiple linear regression, yields the finding (Table 2.1) that the power parameter (measured in watts) can significantly influence pricing (from heteroscedasticity robust errors, we determine the two-sided significance level at 0.3 per cent). This is shown in Figure 2.3, in isolation (without the other attributes). An exponential and a logarithmic approach is estimated. The exponential expression yields t = 3.48 at a significance level of 0.2 per cent, the logarithmic approach t = 3.58 from robust standard errors at the same level. The logarithmic approach is better than the linear one which explains only 13 per cent of the variance. The position can therefore be adopted that the other properties than maximum power play no part in price formation for this radical innovation. Why, then, do some prospective buyers prefer them?

First of all, the constant term in (2.2) is not significant (Table 2.1). This means, that the price variation is determined by the technical attributes of this radical innovation alone. The two peripheral features are neither; their sign is negative. The price seems to be determined by the core technology. We observe no multi-collinearity (all variance of inflation factors are below 6.2), thus our features are independent of

Table 2.1: Hedonic price analysis (OLS regression of (2.2) with robust errors).

Attributes	b_i	t (P > |t| in brackets)	
Constant	2746	0.72	(0.489)
Modular attributes:			
Maximum power	17558	3.96	(0.003)
Durability	-3499	-0.53	(0.607)
Tuning	-2007	-1.11	(0.292)
Beam diameter	5250	1.01	(0.335)
Beam divergence	9951	2.06	(0.066)
Mode structure	3251	1.22	(0.251)
High frequence trigger	-3586	-1.55	(0.152)
Architecture attributes:			
Cooling requirements	-2284	-0.69	(0.508)
Power supply	-6120	-0.78	(0.454)
Number of observations: 20 F = 43.3 R^2 = 0.72 Mean VIF = 2.6 Max VIF = 6.2 Max P = 25,000 US$ (1985) Min P = 3,450 US$ (1985)			

each other. Certainly, about 40 per cent of the variance between product prices is explained by the power parameter, but R^2 increases to 0.72 for all features. So the fact still remains that the specialists questioned consider the other technical properties important and reputable specialist journals publish these, since prospective buyers require information on the subject.

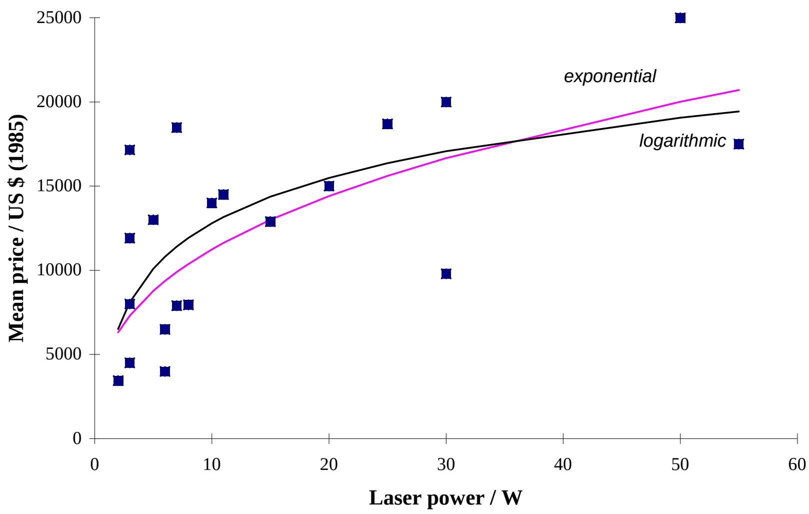

Figure 2.3: Relationship between one of the nine attributes of medical lasers (power) and the average price in 1985 (in US $).

There is one more core attribute, beam divergence, which contributes weakly significantly to the price (robust significance level 6.6 per cent). If taken alone, we again find that the logarithmic fit is better than the linear or exponential one.

2.5 Optimizing laser scalpels

In order to understand this and thus optimize our radically new product, we now model product quality from our empirical observations with only these two attributes all other ones being equal. If we use subscripts p for the power and b for the beam divergence attribute, we have to look for the empirical partial relation of x_p and x_b with X. We checked a number of well-known functions, among them the linear, the exponential, the logarithmic, the inverse, the quadratic, the cubic and the general power ones, and also the growth, S-shape and logistic functions. In the case of the power attribute, the most significant relation turned out to be the cubic one (see Figure 2.4)[6], for the beam divergence the best fit was obtained for the linear

6 Significance level α = 0.06 per cent, F = 9.86, R2 = 0.31. The next best fit is the logarithmic function with α = 0.5 per cent.

regression and negative coefficient (see Figure 2.5).[7] Inserting the empirical relations into (2.12), we arrive at

$$\partial X/ \partial x_P = p_1 + 2p_2x_p + 3p_3x^2_p \qquad (2.13)$$

and

$$\partial X/ \partial x_b = b_1 \qquad (2.14)$$

with p_i and b_1 being the estimated parameters.

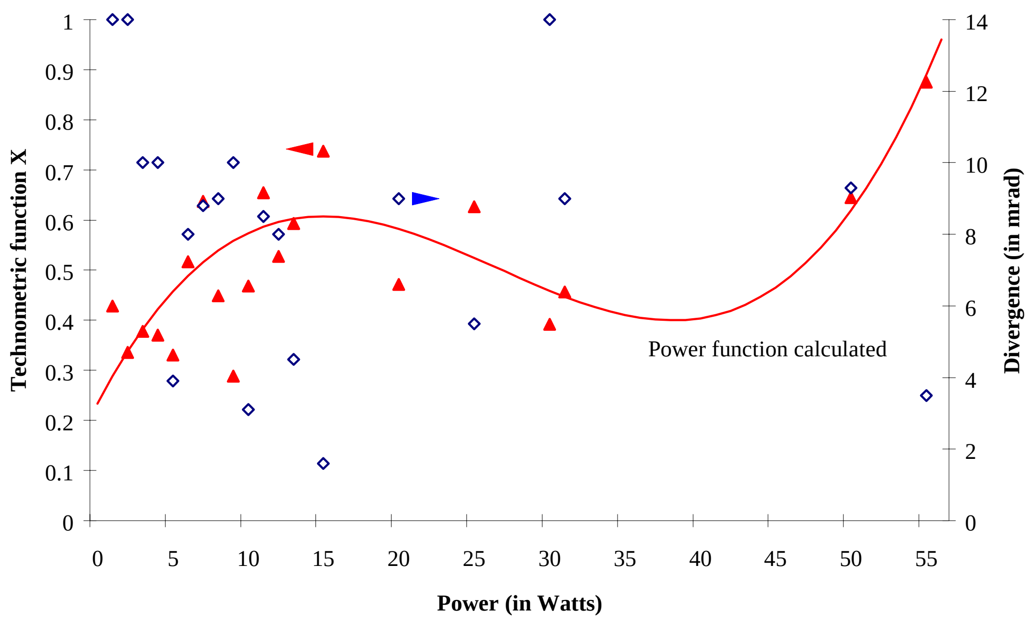

Figure 2.4: Empirical power characteristics and estimations.

At present, a conjoint analysis has not yet been performed but is planned for in order to determine the U function. However, we know from an expert survey, that customer preferences for laser light power is rated equally to beam divergence (see Grupp et al., 1987). Let us assume that the functional form of $U(x_P)$ is the same as for $U(x_b)$, and is, for simplicity, linear, then

$$\partial U/ \partial x_P = \partial U/ \partial x_b = a. \qquad (2.15)$$

---

7 Significance level α = 1.03 per cent, F = 8.21, R2 = 0.31. The next best fit in this case is again the logarithmic one with α = 1.30 per cent. The slope is b1 = -0.02. In Figure 2.4, for obvious reasons, not divergence vis-à-vis X can be shown but rather divergence vis-à-vis power. The pairs of data points belong to one brand each.

Condition (2.12) is then an equation quadratic in x_p which is roughly estimated at x_p = 26.6 (watts).

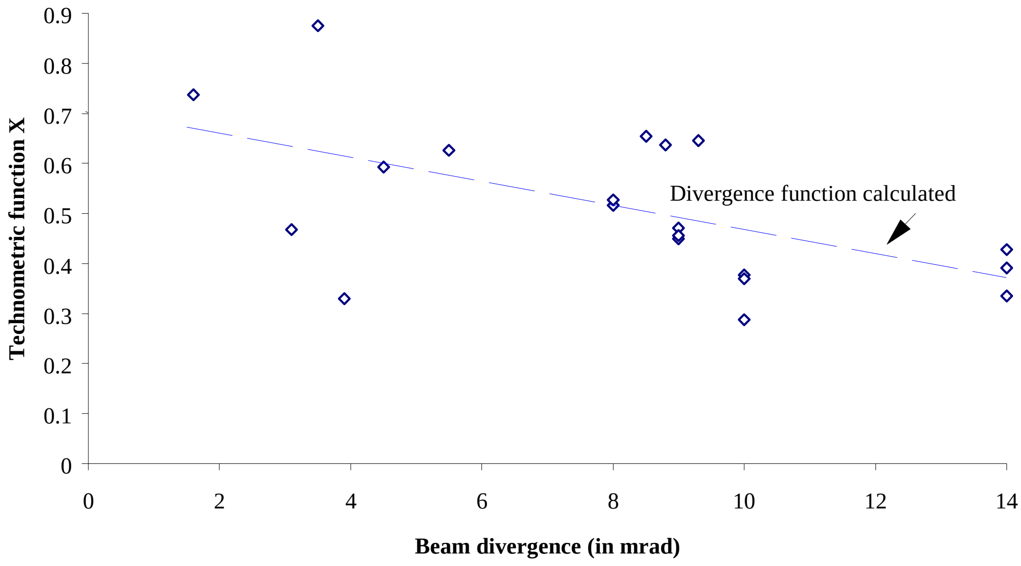

Figure 2.5: Empirical beam characteristics and estimations.

The innovative firm can conclude from this, if the coefficients are taken from the empirical investigation, that a laser scalpel with a light power of about 27 Watts will be preferred by customers over a scalpel with more light power as beam divergence will be enlarged accordingly. Note that the "voice of the market" asks for small beam divergence, and hence the divergences enter the technometric X function (quality function) inversely (compare Figure 2.5). So we find that in reality, i.e. for technical constraints, any improvements in laser power are not easily achieved without a loss in beam quality. We have no choice. Radical innovation is this case requires breakthroughs in laser light power not enhancing beam divergence too much. If we are not good enough in the core technology there are little alternatives to compensate for by incremental innovation in the beam array.

2.6 Conclusion

We believe that our typology of innovation, and the simple models based on it, can provide useful answers for a firm facing the situation of a newly developing market. Although several if not all attributes of the new product in comparison to the substituted one change - and must be mastered - the case study tells us that profit maximization implies the goal for the management of technology to be among the advanced firms in one feature only. Peripheral or architectural innovation does not matter. This need not be the case in radical innovation generally. More case studies will be required to draw general conclusions.

Radical innovators need to move to a different, from the buyer's point of view, better position on the features trade-off curves. This can imply to make some of the b_i worse or keep them moderate. Theoretical considerations and computer simulations show that one can understand technological innovation as a complex, second-order learning system comprising a population of consumers and a population of producing firms. In some special cases just one "dominant" design may occur, but in other cases a limited number of design configurations (Windrum and Birchenhall 1998). This is exactly the situation modeled above: there are several "optimal" positions on the feature treadeoff curves.

New approaches toward "emphatic design" (Leonard and Mayport 1997) can be embarked upon to find out by observing customers what they really want. But such types of new marketing should be complemented by optimization procedures as introduced above in order to get a systematic structure of the many possibilities which may be pursued in the laboratory.

How does this model contribute towards integrating marketing and R&D? What would be different in incremental versus radical innovation? Managing incremental innovation is a matter of balancing cost and value. In radical innovation, although many new features occur, not all of them seem to be equally important. There are limits for substitution of one achievement by another one if a core feature dominates. Even if the new market is young and may not yet be in equilibrium the model can help managers to concentrate on the most important aspects of radical innovation.

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3 Innovation Investment as Doors to the Future: A Real Options Approach[1]

Main Ideas in this Chapter

In the previous Chapter, a model for optimizing radical innovation was presented, based on a cost-benefit approach to adding new product features. That model argued that: a radically-innovative product should be so designed, that *the marginal revenue from a new product feature is equal to the marginal cost of producing that feature.* It can be argued that this first-order condition seriously understates the value of R&D investment in radical innovation, or provides only a lower-bound estimate, for the following reason: Radically new product features may in themselves have no market value at all (and therefore, have zero marginal revenue), but may provide learning, experience and technical expertise that enables the innovator to access new technologies, new markets and new products in the future. *Without the initial investment, that door to the future could never be opened*. The "option value" of this indirect benefit is often large, can be quantified, and must be taken into account to avoid underinvestment in promising, though risky, new technologies. We use a "real options" model to quantify the indirect benefits of innovation, and provide a numerical illustration drawn from lasers.

3.1 Introduction: A real-options model of radical innovation

In the previous Chapter, a model for optimizing radical innovation was presented, based on a cost-benefit approach to adding new product features. The essence of that model was a standard micro-economic optimization model, applied in a novel way, not to entire products, but rather to individual product features, with the decision focused on optimal R&D investment in new product features. The common sense meaning of the model: *innovate so that the marginal revenue from a new product feature is equal to the marginal cost of producing that feature.*

1 An earlier version of this Chapter, in the context of the pharmaceutical industry, was written together with Han Smit, Department of Finance, Erasmus University, Rotterdam, Netherlands. We are grateful to Han for sharing his expertise with us. This Chapter, in contrast with other Chapters in this book, focuses more on overall investment in new technologies, rather than on innovations in product features. Stefan Woerner, in his doctoral dissertation, seeks to substantiate of falsify our ideas.

It can, however, be argued that this first-order condition seriously understates the value of R&D investment in radical innovation, or provides only a lower-bound estimate, for the following reason: *Radically-new product features may in themselves have no market value at all (and therefore, have zero marginal revenue), but may provide technical expertise that enables the innovator to access new technologies, new markets and new products*. For example: The pharmaceutical company Pfizer invested in developing a new drug that seemed worthless, because it had "undesirable" side effects – until it was realized that those side effects were in some contexts highly desirable. The drug became the impotency treatment Viagra.

In this Chapter, we propose a model for evaluating ex ante innovative projects, in a manner that quantifies the option value of that project. In doing so, we build on an existing literature that has used the real-options framework to extend conventional net-present-value approaches to R&D project evaluation (Perlitz et al., 1999; Jaegle, 1999; Dixit and Pindyck, 1994; the standard textbook is Trigeorgis, 1996).

3.2 A real-options model

Dixit and Pindyck (1994) note that investment can create opportunities which may or may not be exercised; whether they are or not, these opportunities have value that can be measured. In the context of R&D, such options could be:

- *The Option to Start R&D*. Studies help identify prospective new features. Based on these prospects the development program can enter in the initial research phase.
- *The Option to Invest in Preliminary Development.* If a technology is discovered that might result in a promising new product or process feature, preliminary development work can begin.
- *The Option to Launch a Full-scale Development Project.* If initial work appears successful, a decision can be made to launch a full-scale development project.
- *The Option to Invest in Marketing and Production.* Following the R&D phase and test phases, it has to be decided to market the new features and start the production or to abandon operations.
- *The Abandonment Option*. At any stage, there exists the option to dump the new product features and revert to the old features or embark on R&D to develop new ones. We have found more than a few project evaluations, where the "abandonment option" has been left off the decision-tree analysis, significantly biasing the result in a negative manner.

Similarly, Perlitz et al. (1999) distinguish between six kinds of real options: option to defer; time-to-build option; option to abandon; option to contract; option to switch; and growth option.

By drawing a direct parallel between "real options" (i.e. options that involve real investment, products and R&D assets) and "financial options" (the right to buy or sell an asset for an agreed price on or before an agreed date), and by using the familiar Black-Scholes formula for pricing a financial option, the value of these real options can be determined.

In 1973, Black and Scholes published an article, unassumingly titled "The pricing of options and corporate liabilities", in which they solved a partial differential equation, in order to show that the market price of a financial option could be expressed as a simple equation, with only five variables: the stock price ("spot", or current price of the underlying asset; IBM shares, for instance); the exercise price (the price at which the asset could be acquired, or sold, under the terms of the option); the time to expiration (the time period during which the option to buy or sell can be exercised); the risk-free interest rate; and the variance of the rate of return of the underlying asset (i.e. its riskiness). This single paper was largely responsible for creating an enormous market in options and related financial instruments known as derivatives, because it created an agreed standard for valuing contingent claims that until then were hard to price.

Luehrman (1998a, 1998b) offers a useful simplification of the Black-Scholes equation, distilling its five parameters down to only two. In the body of this Chapter, we will follow Luehrman's approach, while in the Appendix, we offer a more full-blown mathematical model of real options, in the context of the pharmaceutical industry, where it is necessary to use the Black-Scholes equation itself to compute option values.[2]

3.3 An illustrative example: Lasers

For our illustrative example, we chose the laser industry (for a fuller history, see Grupp, 1998, pp. 338-344).

Laser is an acronym for light amplification by stimulated emission of radiation. Lasers are devices that amplify light and produce coherent light beams, ranging from infrared to ultraviolet. A light beam is coherent when its waves, or photons, propagate in step with one another. Lasers harness atoms to store and emit light in a coherent fashion. The electrons in the atoms of a laser medium are first pumped, or energized, to an excited state by an energy source. They are then "stimulated" by external photons to emit the stored energy in the form of photons, a process known as stimulated emission.

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2 This can be done using familiar software packages like Mathematica, for instance.

Stimulated emission, the underlying process for laser action, was first proposed by Einstein in 1917. The working principles of lasers were outlined by Schawlow and Townes in their 1958 patent application. The patent was granted, but was later challenged by the physicist and engineer Gould. In 1960 Maiman observed the first laser action in solid ruby. A year later a helium-neon gas laser was built by the Iranian-born American physicist Javan. Then in 1966 a liquid laser was constructed by Sorokin. The U.S. Patent Office court in 1977 affirmed one of Gould's claims over the working principles of the laser.[3]

Grupp (1998) notes that while the theory-to-first technical materialization of the laser took 43 years, in the 1960s a new laser medium was being discovered practically every year. The U.S. firm Spectra Physics launched the first laser onto the market; it became the model for a whole series of laser companies. But from 1968 on, many of those laser firms perished, finding that the original technical concepts on which commercial lasers were based were not marketable. Bankruptcies were recorded during 1973-75, as the industry went into a slump. Meanwhile, focus shifted from research to development; patent applications soared. Companies resumed their earlier laser-related development work. From $90 millions in total laser sales in 1970, the market grew to about $900 millions in 1977, $9 billions in 1986, and $13 billions in 1992.

Consider a hypothetical company, whom we shall call LaserWeld. LaserWeld is founded in 1972 by three creative solid-state physicists who think they can build a laser-based welder. They build a business plan, with a conventional spreadsheet, and are crestfallen to find that using a rate of discount that reflects the high risk of their venture, 18 %, their discounted cash flow (or net present value) is in fact negative (see Table 3.1). A $100 million initial investment in developing a laser welder (Mark I Model) generates a negative net present value of -$22 million, because the discounted cash flow during the planned five-year life of the product is insufficient to cover the $100 million total R&D investment. They reluctantly abandon their dream, because no-one is willing to invest in a firm with such bleak prospects.

Then, one of the firm's founders decides to rethink the analysis. He draws a decision tree (Figure 3.1A), and realizes that the "failure" branch of the tree is wrongly truncated. If our laser welder initially fails – sales double in years 2, 3, and 4, and triple in year 5, yet are not sufficient to pay back the initial large investment – LaserWeld will learn a lot during its R&D, sales and marketing. In year 3, the company has the option of investing another $100 million in a new generation of laser welders, building on the market experience and R&D knowledge acquired in the first two years. Will the new, improved decision tree (Figure 3.1B) give

3 "Laser," *Microsoft® Encarta® Encyclopedia 99.* © 1993-1998 Microsoft Corporation. All rights reserved.

LaserWeld better financials (see Table 3.2)? The answer is a resounding "yes"! The overall net present value is now strongly positive. This project will return an economic rent above the 18 % risk-adjusted cost of capital.

Table 3.1: Discounted cash flow for LaserWeld ($ million).

	Year					
	0	1	2	3	4	5
Cash Flow		0	$10	$20	$40	$120
R&D Investment	-$100					
Discount Factor (18 %)			0.718	0.609	0.515	0.437
Present Value	-$100	0	$7.18	$12.18	$20.6	$52.4
Net Present Value	-$100 + $92.36 = -$7.64					

Table 3.2: Revised discounted cash flow for LaserWeld ($ million).

Phase One						
	Year					
	0	1	2	3	4	5
Cash Flow		0	$10	$20	$40	$120
R&D Investment	-$100					
Discount Factor (18 %)			0.718	0.609	0.515	0.437
Present Value	-$100	0	$7.18	$12.18	$20.6	$52.4
Net Present Value (Phase 1)	-$100 + $92.36 = -$7.64					
Phase Two						
	Year					
	0	1	2	3	4	5
Cash Flow					$60	$200
R&D Investment				-$100		
Discount Factor (18 %)				0.609	0.515	0.437
Present Value		0		-$60.9	+$30.9	+$87.4
Net Present Value (Phase 2)	-$60.9 + $118.3 = +$57.4					
Total Net Present Value, Phase 1 and Phase 2: - $7.64 + $57.4 = $49.8						

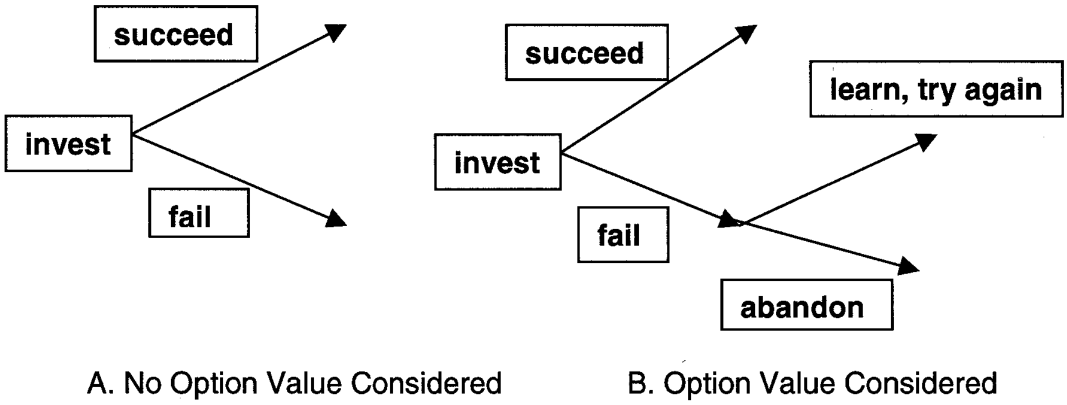

Figure 3.1: Decision tree analysis of investment in laser innovations.

Figure 3.1A shows a conventional decision-tree analysis, typified by net-present-value calculations of innovation investments. Figure 3.1B shows the result of considering the value of failing, but learning, and then using that knowledge to make another attempt. The "learn, try again" is an option – it need not be done, one can always abandon the project. But as an option, it has value; taking it into account can change an unprofitable project (3.1A) into a highly profitable one (3.1B).

3.4 A counter-intuitive result

The reader may protest, that this example is obvious, perhaps even trivial. We respond, that the learning value of initial failures in technology-based startups is enormous (Roberts, 1994) – and is often not taken into account in conventional project evaluations.

But consider a more counter-intuitive example. Suppose that the LaserWeld project's cash flow projections look like those in Table 3.3. In this case, the initial Mark 1 model is very profitable, with high net present value, while the Mark 2 model is not. Using Luehrman's (1998a,b) simplification of the Black-Scholes equation, it can be shown that the option value of the Mark 2 model is in fact large and positive, rather than - $2 million as net present value calculations indicate:

Option Value of Mark 2 Model is $19.4 million. The overall net present value of the project is therefore:[4]

[4] Option value is a function of five parameters: S, "stock price" (net present value of the project, phase 2), $73 million; X "exercise price" (the price of the option – in this case, the $100 million investment needed to "exercise" it, $75 million; t, the length of time the decision may be deferred (here: until year 3); r, time value of money, or the risk-free rate of return, 10 %; and σ^2, the variance of the returns on the project, which measures the riskiness, 40 %. Using Luehrman's

Net Present Value of Phase 1 + Call Option Value on Phase 2 = \$64.9 + \$19.4 = \$84.8 million.

Using the real options approach, the LaserWeld project appears far more attractive than using traditional net present value methods, and more attractive than the previous example, where initial learning led to later profitability. Why? What explains this counterintuitive result? There are several reasons:

Table 3.3: Revised Discounted Cash Flow for LaserWeld (\$ million).

Phase One						
	Year					
	0	1	2	3	4	5
Cash Flow		0	\$60	\$200		
R&D Investment	-\$100					
Discount Factor (18 %)			0.718	0.609		
Present Value	-\$100		+\$43.1	\$121.8		
Net Present Value (Phase 1)	-\$100 + \$164.9 = +\$64.9					
Phase Two						
	Year					
	0	1	2	3	4	5
Cash Flow		0			\$40	\$120
R&D Investment				-\$100		
Discount Factor (10 %)				0.751	0.515	0.437
Present Value				-\$75	+\$20.6	+\$52.4
Net Present Value (Phase 2)	-\$75.1 + \$73 = -\$2.1					
Total Net Present Value: + \$64.9 - \$2.1 = \$62.8						

- With the passage of time, the uncertainty inherent in technology-based companies tends to decline. As lasers were perfected, and additional scientific research, patents and development work accumulated, the degree of risk inherent in the technology tended to fall. Most net-present-value calculations use a constant risk-adjusted rate of return. Since interest rates are composed of risk-free rates plus a risk premium, this implies that risk premia are constant over the life of the project – something which is rarely, if ever, true. In Table 3.3, we have used a 10 % discount rate, rather than 18 %, to compute the present value of the second \$100 million investment, precisely for this reason – when the investment is undertaken, the degree of uncertainty associated with it has greatly

(1999) simplification, we get: NPV_q = \$73/\$75 = 0.97; and $\sigma\sqrt{3}$ = 0.693. The Black-Scholes value (expressed as a % of S, \$73 million) is (from Luehrman's table, Luehrman 1998, p. 56) 26.6 % ($NPV_q / \sigma\sqrt{3}$). In dollars, this yields an option value of 0.266 x \$73 million = \$19.4 million.

diminished.[5] For long-lived projects, lower discount rates imply higher present value.

- As time passes, investors have the ability to exert greater control over their expenditures and losses. Losing projects can always be truncated by closing them and selling the assets. Assets can be shifted out of declining technologies into burgeoning ones. This implies that for technologies that have large underlying "volatility" (very large potential profits, but also very large potential losses), the real options approach attaches a high value to the "call option" (right to invest) aspect of such technology. The reason: as with an option, you have the *right* to invest in the underlying, if you choose, but not the *obligation*. This inherent ability to truncate a widely-spread stochastic rate of return, captures the profitable part while discarding or avoiding the unprofitable part. As Perlitz et al. (1999, p. 267) explain: "The high volatility of the value of R&D outputs positively influences the option value, because high returns can be generated, but very low return can be avoided by reacting to the changing conditions. In Net Present Value calculations, high volatility leads to a risk premium on the discount rate and so to a lower NPV."

3.5 Conclusion

One of the most puzzling, and, for investors, anxiety-causing, phenomena is the enormous market valuations of technology-based companies. Companies, especially Internet-based ones, that have never earned a profit see their stock price soar, and their market valuation climb into the tens of billions of dollars. One camp argues that such stock prices are inflated. Another camp uses the real options approach to claim that for unprofitable but rapidly-growing companies, stock prices do not reflect past or current profits but future growth. Using the real-options model, Jaegle (1999) calculates that for industries like data networking, semiconductors, software and Internet businesses, the value of "growth options" comprise a large proportion of the companies' market value.

What this implies, is that capital markets may be somewhat ahead of capital budgeting techniques used for project evaluations. While capital markets understand the intrinsic value in "growth options", project evaluators often fail to take this into account. For management of technology, there is inherent value in the passage of

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5 This is because this sum is associated with zero uncertainty: you know what it will cost as an "entry free" into the Mark 2 Technology. In contrast, the cash flow numbers are still discounted at 18 %, because this is still highly uncertain – we do not know for sure what the Mark 2 Technology will bring in the marketplace, so the discount rate has to have a risk premium that reflects this uncertainty. This is in line with Luehrman's approach.

time; based on new learning and knowledge, losses can be avoided, while profits can be captured, as new opportunities arise and old misfortunes are shut down. Variations of the Black-Scholes option pricing method enable managers to quantify this value.

A word of caution is in order, however. The real options argument can be used, misleadingly, to justify almost any investment in high-risk R&D, simply by waving at some imaginary, huge future market to emerge at some distant date.

Like all quantitative tools, real options logic demands responsibility and integrity on the part of its practitioners. They must defend their numbers with the same rigor to which other conventional approaches are held to.

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Appendix 3.1:[6] *Mathematical Model for Evaluating Investment in a New Pharmaceutical Product.*

Consider a senior manager, weighing investment in a radically new technology-intensive product. At the initial phase of the investment program, scientific uncertainties are resolved and the production profile follows a fixed pattern over its useful life. For each state of the world, the net operating cash inflow for this product equals the yearly production, Q_t, times the current price, S_t, minus the operating costs and corporate taxes.

Future cash flows are assumed to follow a stochastic process, which is modeled in discrete time by a multiplicative binomial process (e.g., see Cox et al., 1979). In each sub period of one year, the project value may increase by a multiplicative factor u, or decline by a factor d. Equations (3.1), (3.2), and (3.3) are used to estimate the series of future cash flows over the total life of the project (research and production phase). In the following valuation process, the hedging (risk-neutral) probability, p, is used to estimate the present value of cash inflows

$$u = e^{\sigma}, \quad d = \frac{1}{u} \tag{3.1}$$

$$uV_t = V_{t+1}^{+} \tag{3.2}$$

$$dV_t = V_{t+1}^{-} \tag{3.3}$$

$$p = \frac{(1+r)V_t - V_{t+1}^{-}}{V_{t+1}^{+} - V_{t+1}^{-}} \tag{3.4}$$

where p is the hedging (risk neutral) probability and r the risk-free interest rate and σ is the standard deviation that result from commercial uncertainty.

In this fashion, commercial uncertainty results in a series of potential operating cash flows. The valuation procedure works recursively, starting at the terminal nodes of the tree and working backward in time to the beginning of the production phase. In the final production period the state project value equals the operating cash flow, CF_S. Equation (3.5) summarizes the state project cash inflows when stepping backward in time.

$$V_t = CF_t + \frac{pV_{t+1}^{+} + (1-p)V_{t+1}^{-}}{1+r} \tag{3.5}$$

where V = project value under continuous production

6 This Appendix draws heavily on an unpublished paper by Smit, and on his doctoral dissertation (Smit, 1996).

The option to "market" or to "wait and see"

Now we consider the valuation of a similar program in an earlier phase. Management must decide if and when to market the product. For production the corporation must invest in the marketing and production facilities. In pharmaceuticals, for instance, a company must typically spend $100-$200 million to market the new drug. When (if at all) is it time to market in light of commercial uncertainty?

The patent on the new product, in this stage, can be viewed as similar to a call option. The underlying asset is the present value to market the product, V. In Equation (3.6) the present value of the investment outlay in production and marketing, I, is equivalent to the exercise price. If at that time the value exceeds the investment outlay, management would invest and patent value equals: C = V - I. However, due to commercial, the NPV may turn out to be negative. In this case, however, management may decide not to invest and the net value would be zero.

Besides the wait and see advantage, deferment has certain disadvantages. For example, management may receive the net operating cash inflow later on. Again the question is: what would this call option be worth if it were traded on financial markets? The investment opportunity value, NPV*, equals:

$$C^{*} = MAX\left[V^{*} - I,\ \frac{pC^{+} + (1-p)C^{-}}{1+r},\ 0\right] \tag{3.6}$$

where C = the option value to commercialize the patent, and I = Investment necessary to market the product.

The procedure continues by working backward to the value of initial research, using the probability distributions of scientific success. During the research phase, the distribution of the quantity is updated several times: Initial research can lead to the discovery of new product feature, while the test phases provide additional information about the probability of market success. Starting from the values of the market potential, the value of the testing is calculated by using Bayesian updated probability distributions.

We consider now the valuation of a radical innovation, after uncertainty in the test phases is resolved with a sufficient success to proceed with the program. The scientific and clinical uncertainty is unrelated to the overall economy, and is therefore nonsystematic. Because this uncertainty can be fully diversified, we can estimate the value of the research program using both the risk-free rate and the actual probabilities of the distribution.

The value of the project equals the expectation over the expected commercialisation value or zero in case of abandonment using the updated probabilities of market success after two test phases. In order to estimate this value (using Equation 3.7), the quantity (market share) and corresponding values, including options, represent the potential values at the end of the program. To estimate the value of the program in case of approval the (producing and nonproducing) NPVs are multiplied by the actual probability of corresponding quantity, conditional on two successful test phases.

$$V^{FDA} = \frac{P_{reject}(0) + \sum\left\{P_{approval}(Q) = x \mid Q > 0\right\} NPV_Q^*}{(1+r)^{T-t}} \tag{3.7}$$

where V^{FDA} = value of potential commercialization before approval; NPV = net present value of the commercialization phase; P is update probability of approval after successful testing $\Sigma P_{approval} = (1 - P_{reject})$; and T - t = time lag of the Food and Drug Administration (FDA) procedure.

Now we step back in time to an earlier stage in the decision process of the R&D program, when the management has to make the expenditures for clinical testing I and II in order to acquire the proprietary option to proceed with the commercialization investment. Clinical tests maximize information on the compound and resolve the uncertainty with respect to the presence of harmful side effects. The commercial expectations must justify further investments. Since the test phases require the most outlays, the option value is most important.

The clinical test phase can be viewed as a set of two nested options. At the same time different types of uncertainty or risk are resolved in different stages. Consequently, the distribution is updated after each phase. Equation 3.8 takes the estimation over uncertainty in the second testing phase. The option value to start the second test phase equals is estimated by Equation 3.9.

$$V^{test\ II} = \frac{P_{failure}(0) + \sum\left\{P_{succes}(Q) = x \mid Q > 0\right\} NPV_Q^*}{(1+r)^{T-t}} \tag{3.8}$$

$$C^{test\ II} = MAX\left[V^{test\ II} - I^{test\ II}, 0\right] \tag{3.9}$$

In the same fashion, we can we now work backwards to valuing the first clinical test phase using equations (3.10) and (3.11).

$$V^{test\ I} = \frac{P_{failure}(0) + \sum\left\{P_{succes}(Q) = x \mid Q > 0\right\} C_Q^{test\ II}}{(1+r)^{T-t}} \tag{3.10}$$

$$C^{test\ I} = MAX\left[V^{test\ I} - I^{test\ I}, 0\right] \tag{3.11}$$

where $\{P(Q) = x \mid Q > 0\}$ = updated probability on quantity Q after successful testing I and II respectively; $V^{test\ i}$ = value of the test program i; $I^{test\ 1}$ = investment outlay of test phase i.

The basic logic of this model is identical to that of all dynamic optimization models: "Think ahead backward". We begin by valuing the final phase: sales and marketing. But of course we realize that an innovative product may well never reach this phase. So it must be treated as a "call option" – the right, not the obligation, to invest in it. This call option, in turn, becomes part of the value of an earlier phase, say, R&D investment, which is also a call option. So, the last phase, sales and marketing, becomes nested in a series of call options. The entire project is therefore evaluated, by beginning with the final phase, valuing it, inserting it into the call option value of the preceding phase, valuing that, and so on, until we reach the initial phase. This is very similar to the logic of dynamic programming.

4 Interpreting the Sources of Market Value: A Hedonic Price Approach[1]

Main Ideas in this Chapter

This Chapter presents an integrated model for evaluating purchasers' perceptions of science-based products that may be useful in the management of technology. The model combines a new approach to benchmarking, known as technometrics, that provides a quantitative profile of a product's key attributes, with direct and indirect methods for measuring buyers' perceptions regarding the relative importance of product attributes as a source of value. A new measure for the demand orientation is proposed, which shows the extent to which a product's "supply" of characteristics matches the "demand" for them in the market place. The model is illustrated using several types of industrial pressure sensors. The Chapter also demonstrates how the integrated model may be made effective for quality function deployment (QFD) during the R&D phase.

4.1 The sensor market as an innovation strategy and quality assignment

Companies working on innovations on a particular market tend to have commonality of scientifico-technical opportunity and, because of the specific nature of the technology concerned, the resulting potentiality for appropriation of innovation rents, see, e.g. Cohen (1995). This Chapter tries to examine the sensor market, a "conventional" market with monopolistic competition in which knowledge generation is largely uncoloured by state influence. It features both large and small companies, universal and special suppliers. At the same time this market for capital goods strongly depends on modern science.

The sensor market has been expanding over the last decade; characteristic growth rates for sensor sub-markets are between 10 and 30 per cent. The world market for sensors is currently worth over 5 billion[2] US $ per annum; methods of calculation and the estimates however deviate very widely. By the year 2001, as Arnold (1991) notes, growth rates are expected to be 8 per cent per annum; the 2001 market volume could be 43 billion US $. The uncertainty over sensor estimates stems directly from arbitrary drawing of sensor demarcation lines: Should supply lines,

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1 This Chapter was first published in *R&D Management* 28(2), pp. 65-77, 1998.

2 In this Chapter, by "billion" we mean "thousand million".

decoding electronics or calibration units be included or excluded? The price of a complete sensor system can deviate from that of the sensor element contained in it by one order of magnitude.

Extension of the sensor market is to some degree the outcome of the growing plant automation market; in this area, sensors plus certain other factory integration systems definitely reflect the greatest growth. In factory automation, in value terms, sensors however only account for a few per cent. In addition, the growth in the sensor market is linked with expansion of mass consumer products (motor cars, domestic appliances), the advancing technisation of medicine (biosensors) and linked with the legislation on protection of the environment (stack gas testers, probes in car catalytic converters, etc.). In all types, sensors thus play a part in capital goods marketing (product business, system business, plant business). Sensor miniaturisation has led to the incorporation of microelectronics. Modern sensor technology has therefore benefited from the huge advances made in semiconductor technology which are now spilling over into measurement technology. Sensor technology, cf. Grupp (1992), is therefore science-based like semiconductor technology.

This contribution deals with the *industrial sensors* sub-market. The medical area ought to be included in the industrial. Since sensors are very small commercial and technical units, in case of doubt, it must always be assumed that the sensor has not been shown separately in economic balances but included as part of a larger unit. There is a tendency for individual in-house production of sensors in the using company that siphons off some of the sensors from the statistical data sources. Contextually, the sensor market is virtually untrammelled by state intervention; restrictions are imposed, on the one hand, by environmental protection requirements which fuel environmental measurement technology, the pricing idiosyncracies in health care and a substantial commitment by state technology policy to microsystems engineering.

The sensor market is highly *segmented*. An overview by Grupp et al. (1987, p. 234) lists nigh on 90 measurands for which sensors are available commercially or which are in process of development. The number of types of sensors (in terms of product variants) however is clearly even larger since for each measurement parameter there are several if not many measurement processes available. Internationally, currently a total of approximately 10,000 different types of sensor are on offer; the number of brands is incalculable. In OECD countries, there are approximately 2,000 potential suppliers of sensors, most of whom are offering their own products.

Marked segmentation of the sensor market imposes one prime requirement on the R&D management of innovators: they must be stronger than others in *systematic early warning functions* and set up a strategic technology management. This is a defining parameter specific to the sensor industry and common to innovation behaviour in the intersectoral comparison. It would therefore seem apposite, prior to analysing technical properties (Section 4.4) and demand preferences (Sections 4.5 and 4.6), to set out one or two general considerations for technology management. According to the above analysis of the basic structures of the sensor market, the corresponding technology management in the intersectoral comparison is problematical from both aspects: technological analysis, owing to the many technical processes and measurement parameters used for sensors is just as complex as formulating a competitive quality strategy taking segmented markets into account.

4.2 A new benchmarking concept

The ability to develop and exploit new business opportunities, i.e. the *economic competence*, is generally difficult to determine quantitatively. One is tempted to "measure" economic competence by its outcomes - successful innovation. In a science-driven market, the firm's competences in various areas of activities, such as R&D, engineering, production but also general administration, have to be extended to monitor scientific achievements, co-ordinate learning from science and scientists outside the firm or to communicate problems to them, and to organise knowledge accumulation by appropriate risk taking, see Carlsson and Stankiewicz (1991, p. 94).

But how to measure successful science-based innovation? For measuring the tacit, embodied knowledge included in innovative products, measurement of technological characteristics is required. Here, the newly established technometric concept by Grupp (1994) may be embarked upon. It requires the consultation with technology experts and thus the handling of multi-disciplinarity in the management of technology.

At the beginning of the eighties a series of "metrics" for evaluating and comparing technological sophistication and quality were proposed. What was coined "technometrics" in 1985 is a procedure designed along Lancaster's (1991) consumer theory and is based on the observation that every innovative product or process has a set of key attributes that defines its performance, value or ability to satisfy customer wants. Each of these attributes has a different unit of measurement. Problems then arise in aggregating attributes to build a single quality index. Mathematical details of the general procedure are not discussed here as they may be found in Grupp (1994). Suffice to say that the technometric indicator surmounts this difficulty by converting each measured attribute into a [0,1] metric, enabling construction of weighted averages, etc., and permitting comparisons across products, firms, industries and countries. The "0" point of the metric is set as the technologically standard attribute; the "1" point is set as the most technologically sophisticated attribute in existence at a given point in time.

The j-th element of the characteristics of product (or service or process) i is the specification K(i, j). If monopolistic competition is assumed, one has to differentiate products k (or brands of the same firm) at time t_0. The measurement unit of this specification is u(j). The metric measure K* (for firm k') is obtained by the metric

$$K^* (i,j,k',k,t) = [(K(i,j,k',t) - K_{min}(i,j,k_{min},t_0))]/ [(K_{max}(i,j,k_{max},t_0) - K_{min}(i,j,k_{min},t_0))], \quad (4.1)$$

whereby K_{max}, K_{min} being the maximum and minimum specifications within subset k. k_{min} and k_{max} denote those brands k for which K is minimum resp. maximum with respect to the total subset. By this transformation, K*(k') is no more dependent on specific physical units, but expressed as a defined point on an interval scale spanned by the specifications of all competing brands (products) in each dimension j. If the scale of the specification is inverse, that is, if the minimum value of K represents the most sophisticated technological level, then an inverse formula holds

$$K^*_{inv} (i,j,k',k,t) = 1 - K^*(i,j,k',k,t). \quad (4.2)$$

From this micro-level, single-item definition, a technometric profile may be aggregated on the level of all j specifications per product i if functional characteristics or (revealed) preferences F are defined:

$$K^* (i,k',t) = \Sigma_j [K^*(i,j,k',k,t) \cdot F(i,j)] / \Sigma_j F(i,j). \quad (4.3)$$

The preferences may be derived from utility functions, by introspective or market observation, from expert knowledge or via hedonic prices.

Technometric profiles may be used for measuring the economic competence through the proxy firm-specific technological performance or quality level, one of the important determinants for innovation, which includes the tacit knowledge. Yet, the compilation of technometric data is time-consuming as the specifications are not accessible in data banks. The measure also does not differentiate between the sources of know-how. It may be created within the firm by R&D, in the science system, by learning by doing or learning by using or by adoption of innovative solutions developed by other industries or firms and embodied in capital equipment and intermediate inputs.

When conducting a technology-oriented competition survey, a relative competition analysis is recommended, cf. Backhaus (1992, pp. 135 onwards) or Shillito (1994,

p. 52 onwards). Usually, this is done by assessing the own position by reference to those of the relevant competitors. Owing to the lack of suitable metric data, competitor information is graphed qualitatively (e.g. "low" versus "high"). The technometric indicator is available, in competitor analysis, as a substitute for qualitative scales if the corresponding data are available from the rival company.

From competitor observation, portfolios can be compiled which just like financial business portfolios tend to be referred to in R&D management circles as *technology portfolios*. The use of portfolio procedures for technology evaluation is considered the best method in the field of corporate R&D management, see, e.g. EIRMA (1985, p. 27). In view of the few comments that can be made about industrial technology management, product quality measurement is still the final resort. The latest keyword of "benchmarking" is nothing other than the systematic comparison of the quality of products and services of a company in relation to those of the leading competitors, following Camp (1989) or Shillito (1994). Interest in benchmarking has grown enormously over the last 10 years. Technometrics applied in business management is nothing more than standardisation of product quality in terms of technical properties. Even now, technometric procedures still do not feature in benchmarking literature. First applications may be found in Shoham et al. (1998).

4.3 Data on technical characteristics of pressure sensors

In this Section, the problem of pricing of technically valuable goods and the effect of technical characteristics is tackled. The sensor market is thus regarded as a market with free and floating prices dictated by supply and demand factors. The first step must be to itemise the most important technical properties of sensors and then extract a selection from the wealth of conceivable measures. Koschatzky and others (1996) in a wide-ranging empirical survey were concerned primarily with pressure and temperature sensors (in addition to those for measuring acceleration, force and relative humidity). The inquiry related to earlier technometrics by Grupp et al. (1987) on sensors which reflected the 1986 market.

The primary data analysis thus involves large-scale gathering of exhibition material at the largest sensor fair in the world where not only exhibits, as is customary, are displayed but also specification sheets with the appropriate data.[3] Quite apart from the field survey conducted other companies were consulted so that in all 286 companies were approached in one way or another. Of these, 151 yielded

[3] This is the SENSOR Fair which took place in May 1991 in Nuremberg. The authors of this article are grateful to Frenkel and Koschatzky who conducted the data inquiry on the spot, see Frenkel et al. (1994) and Koschatzky et al. (1996).

comparable detailed information. Koschatzky and others (1996) also conducted 10 personal interviews with Israeli companies so that in all data from 160 sensor firms was obtained. When considering the breakdown of companies according to country, it should be remembered that European and primarily German speaking countries predominate since the fair in this year took place in Germany. Apart from companies from the United States and Israel, however, Japanese companies were also represented in the random sample.

The technical properties selected and compared were established by specialist discussions in the earlier investigation of the sensor market. In so doing, it became apparent that different specifications are important for different measuring principles and tasks. To illustrate the data, in this Section only pressure sensor analysis is spotlighted.[4] For pressure measurement, essentially three modern processes are in use. These are the piezo-electric and piezo-resistive principle plus the use of strain gauges.

The most important technical properties of a pressure sensor are the measuring range, accuracy, i.e. the maximum deviation of the instrument from the true measurand and the temperature range over which the sensor can be used (maximum and minimum working temperature). For concrete use, data on weight and diameter is important, particularly for built-in components. Apart from the accuracy of a particular measuring point, linearity is of interest, i.e. the maximum deviation over the entire scale, and the so-called hysteresis effect, particularly the maximum deviation which results from the delayed response of the sensor to changes in the measurand. For the hysteresis effect, non-linear physical principles are important. Apart from maximum and minimum temperature, temperature stability is of interest, i.e. the error that temperature fluctuations cause to the reading taken. Temperature stability at low and high temperatures can differ widely whence here usually two properties must be stated. Error tolerance in the event of mishandling, the overpressures which may occur without the sensor being damaged and likewise the maximum permissible electrical voltage tolerated without instrument damage are also of interest.

Among the twelve product characteristics specified are some upon which prospective customers prefer highest values (e.g. measuring range, maximum temperature, permissible overpressure, etc.) and also some at which preference is on low values (equipment deviation in temperature fluctuations, diameter, weight, etc.). In the technometric model, Formula (4.1) has to be used for the first group of properties, in the other case, in which technical advance progresses inversely

4 According to information from Arnold (1991), pressure sensors are much sought after. Their market volume in 1991 amounted to 3.2 billion US $ and is expected to double to 7.2 billion US $ by the year 2001.

relative to the measured variable and is expected to lead to the minimum value of characteristics, Formula (4.2).

Conceptually, if four products are deliberately chosen from the databank and the technometric indicators calculated, then a technological or characteristic profile will be obtained as per Figure 4.1. In such case, it should be noted that for certain products, isolated numerical values are missing (not divulged by the manufacturer).

Purely for the purposes of illustration, let us now refer to certain notable characteristics. The common denominator is that all four products have a comparatively small pressure measurement range. In this respect, they are similar and serve identically segmented sub-markets. The sensors compared differ little from one another in regard to hysteresis and temperature stability. Similarly, the linearity of the four products needs to be assessed and also their compactness. The maximum permissible temperature of the products is quite another matter. The British sensor (IMO) can only be used up to 80°C, while the American sensor (Kistler) tolerates operation up to 240°C. The position is similar for low temperatures (minus 20°C for the British one and minus 195°C for the American).

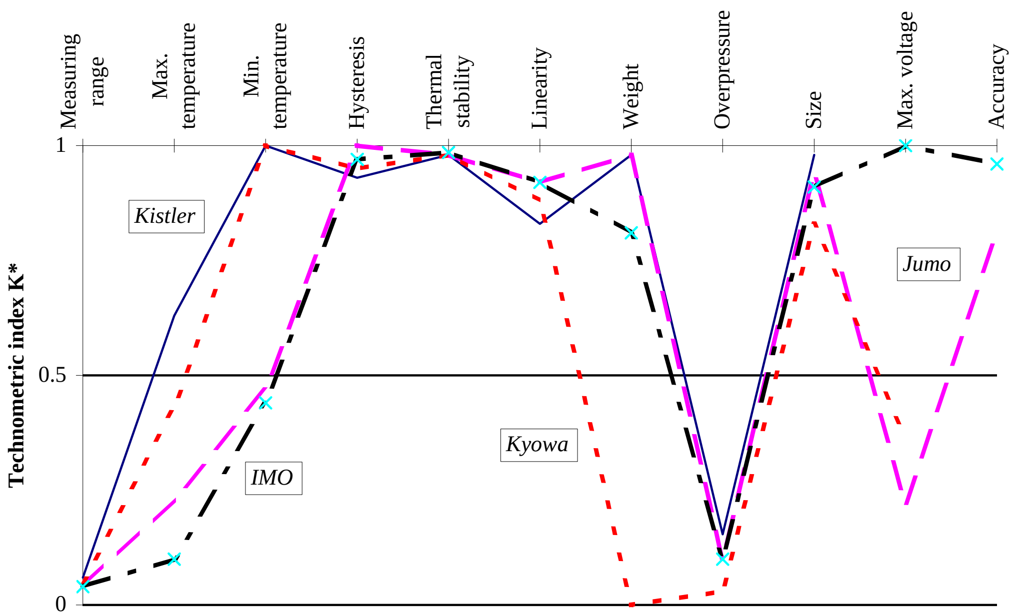

Figure 4.1: Technometric characteristic profile of four selected pressure sensors (1991).

The data on accuracy is fragmentary. The products differ considerably in terms of weight, the Japanese pressure sensor (Kyowa) at 530 g being substantially heavier than the German (Jumo) at 14 g. The error susceptibility at maximum permissible voltage must also be regarded as very divergent, while all four sensors react unfavourably to overpressure (in the world comparison).

Since the aggregated technometric indicator can be retained for product quality, the question arises as to what relationship exists between product quality and price. Before embarking on a systematic analysis of the relationship between technological performance and price structure, let us illustrate the problem by reference to 72 pressure sensors for which the technometric specifications are largely known. Figure 4.2 provides a comparison of the market prices of these sensors relative to the respective unweighted aggregated technometric indicators, i.e. according to Formula (4.3), F(i,j) = 1 for all j. The four products illustrated in Figure 4.1 are amongst these products selected from eleven manufacturers from six countries. The respective prices have been converted into US $.

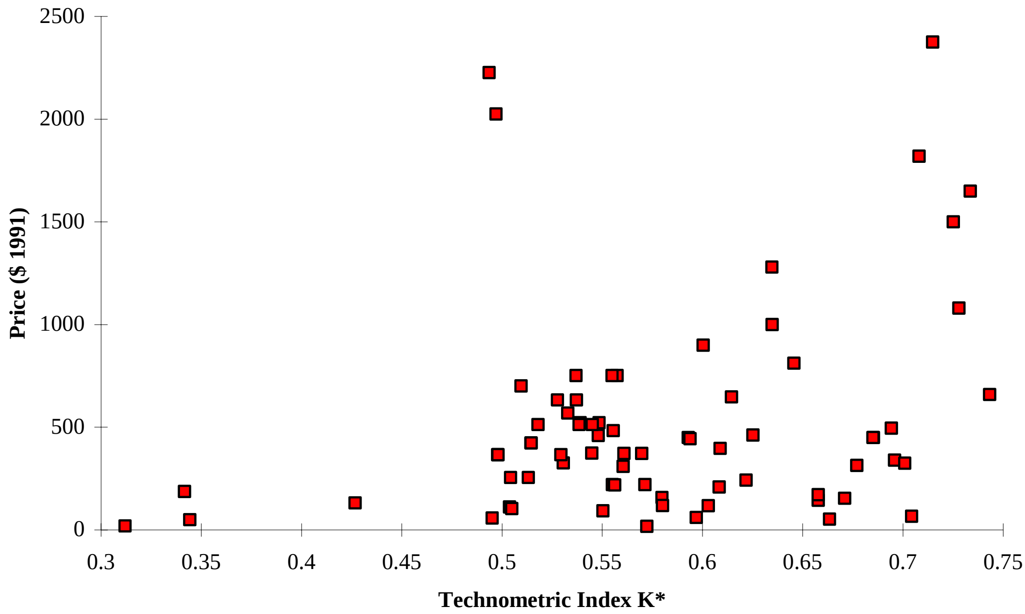

Figure 4.2: Comparison of market prices and aggregated technometric indicators for 72 pressure sensors from six countries (1991).

With certain exceptions, Figure 4.2 shows that apparently there is a consistently monotonic relation between technical properties and price. This intimates a weakly positive connection between (unweighted) technical quality and price[5], but does not show the pattern required by marketing theory: the start point taken cannot be declining marginal yields through higher technical quality but rather according to Figure 4.2 price variation will become broader on the market under investigation. Steenkamp (1989, p. 236) generally only establishes a weak quality-price correlation. Certainly, apart from two exceptions, a high price cannot be achieved with medium to low quality. Clearly a relationship must be found linking properties to demand preferences if important price-determining specifications are to be drawn

5 Official exchange rate for the randomly chosen date of December 13th, 1991.

up. The unweighted technometric quality index appears to be unsuitable for this purpose on a strongly segmented market.

4.4 Technical quality and hedonic prices

Before embarking on an appropriate systematic analysis, an attempt can be made, using *factor analysis,* to reduce the twelve technical properties via their relationship to one another - i.e. without considering price structure. For the total of 80 different pressure sensors incorporated in the sample, the following ratios emerge: a large proportion of the variance between variables is explicable by two main factors several variables respectively having high factor loadings. The first main factor relates to product properties which concern the *area of application*. Here, the measuring range and the maximum and minimum temperature have high factor loadings. The other main factor appears to represent properties connected with *accuracy*. Apart from the variables for accuracy itself, hysteresis plus temperature stability (for high and low temperatures) and to a lesser extent linearity are involved. Weight and diameter plus error tolerance appear to be stand alone items. Both main factors alone virtually account for half of the overall variance, thus suggesting that not all technical attributes contribute towards market price.

A systematic investigation of price structure must be extended, in the demand theory, in order to address demand for innovations in the capital goods field. Underlying the considerations is the approach developed by Lancaster (1991). According to this theory, "consumers are not interested in goods as such, but in their properties or characteristics" (p. 5). The theory deals with the optimum mix of properties required in order to meet a prescribed set of demand preferences and the relative values which the prospective purchaser awards to each characteristic property, prompting compilation of a matrix of functions linking preference and technical property.

For the sensor market, which, according to the assessment in Section 4.1, can be construed as being functional, i.e. intensively competitive and efficient, an empirical relationship should be discernible between the quantitatively measured attributes of the product and product prices. It should be possible to solve the problem by multiple linear regression (OLS), the dependent variable being market price and the independent variables being product properties. Thus, the absolute values of the coefficients show what value the market assigns to this property. The relative values of these coefficients when compared to the others can thus provide the relative weighting which the market demands and hence are interpreted as a functional characteristic per Formula (4.3).

The proposed approach has been considered sporadically in R&D management literature here and there as far back as the 1960s and linked to the hedonic price concept, see Griliches (1961, 1971) and Chow (1967). The new literature encompasses Saviotti (1985), Trajtenberg (1990) and Dorison (1992). The prime objective of the literature on hedonic pricing was certainly different from the present scenario. The method was originally developed in order to differentiate between a quality-determining price component and a quality-independent component. The question was raised as to whether price changes in an item can be viewed *detached* from quality changes.

In Saviotti's (1985) notation, product quality is modelled as follows, the variables already listed in this Chapter being retained:

$$K^*_k = \Sigma_j \, a_j \, K^*_{kj} \, . \qquad (4.4)$$

Here, k denotes the compared products and j the properties. In Formula (3), the aggregated technometric indicator K^*_k has been presented as a parameter deduced via a functional characteristic from the K^*_{kj} property profile. K^*_k is now interpreted as product quality reflecting a hypothetical market price M_k together with a quality-independent factor a_o (u_k thus representing the random statistical error term):

$$M_k = a_o + \Sigma_j \, a_j \, K^*_{kj} + u_k \, . \qquad (4.5)$$

The hedonic prices a_j can be determined with the aid of the regression calculation. On this subject, Saviotti (1985, p. 312) observes: "Price equation coefficients (...) can, therefore, be considered an approximation for users' judgement of the relative value of various characteristics."

In the regression analysis, it was felt expedient to omit sensors with many missing data. The hedonic price determination therefore related to 68 sensors and eleven properties. The regression calculation can account for precisely half of the variance ($R^2 = 0.50$). This is open to different interpretations depending upon viewpoint. On the one hand, this means that half of the price variation alone is explicable in terms of the physico-technical properties of the products. On the other hand, likewise one half is attributable to price variance which cannot be explained in terms of quality improvement but relies on the manufacturer's reputation or upon various marketing endeavours on service, maintenance, established practices or can be traced back to other preferences.

Of the eleven variables only two are significant. They originate from application of stepwise regression in which explanatory variables are arranged (according to an F - test) in order of their ability to raise the variance explained. The maximum coefficient occurs for the variable for maximum temperature; it is almost twice as great as the next largest coefficient for the weight. It can therefore be assumed that the maximum contribution towards price elucidation is made by the *maximum temperature* and *weight* of the sensor. These are the two decisive quality variables. Interestingly, both variables, on their own, virtually account for the entire quality-dictated price variance (R^2_{adj} = 0.46 in comparison to R^2 = 0.50 for all variables).

The hedonic price investigation for pressure sensors reveals that of the eleven technical properties two account, straight away, for the quality-determined part of sensor pricing, in all practically half of the price variation. The maximum permissible temperature has a direct bearing on the application potential in the industrial field. The supposition that lightweight versions would be among the most important consumer preferences does not hold. Higher prices are currently commanded by heavier weight sensors on the sensor market. This is presumably connected with the idea that the heavier units are more durable and can assimilate greater stress under extreme conditions.

The findings confirm the Lancaster (1991) new consumer theory according to which prospective customers are not interested in the goods as such but in their properties. From the sensor market analysis, this comment can be extended to: *"a particular handful of properties"*. It has thus been shown that for pressure sensors in 1991 questions of material saving or use of lighter materials are still not considered to be prime characteristics although this is generally postulated in literature for technical advances in sensors. Clearly, the properties associated with heavier units take precedence (durability, stability, etc.). A particularly lightweight sensor produced at high production costs which in all other respects does not differ from rival products commercially will not succeed in defraying the higher production costs. The only advice that could be given to a particular company which is bent on precisely this innovation is to "tune into the market" and at any rate so long as the demand for dearer lightweight sensors continues to be inadequate to refrain from embarking on a corresponding innovation venture. The use of hedonic prices in connection with technometrics appears to be a valuable analytical instrument for microeconomic as well as for business management use. Admittedly, there are more direct ways in establishing demand preferences which will be discussed in the next Section.

4.5 Preferences voiced by prospective industrial clients

In Section 4.3, it has been shown that product types, measurement processes, technical characteristics (specifications), manufacturing companies, sales organisations and prices can be known to manufacturers, their rivals *and* (industrial) users - e.g. via exhibits and trade fair documents. Information deficits on substitute goods may originate from the wealth of information and market segmentation - but this is no leading counter-argument merely a question of adequate information processing, i.e. a matter of cost.[6] It may also be that corresponding gratis information from customer-supplier relationships are available bilaterally in adequate measure to individual companies but in this case they are not recorded (formalised) in writing and hence, in principle, not accessible to *all* market participants which again leads to transaction costs.

According to current marketing literature, customer evaluations are measured with the aid of multi-attribute choice models. General articles have been written by Wilkie and Pessemier (1973) plus Curry and Menasco (1983). Attributes can, for example, be product quality, price *or* fashion externals. Attributes are therefore not identical to *technical* property profiles. Such models explain the formation of (internal) attitudes which lead to preference of one brand over another. At the same time, the tendency is for the capability of one attribute to be linearly compensated for by the other. The main disadvantage of this marketing model is the subjective nature of the evaluations. Consumers are guided by their own subjective assessments when making a choice and *in so doing assume* that a particular product *has* the relevant property. Such suppositions often provide no reliable information for the marketing division of a company on possible changes to marketing strategy. For example, it might well be that certain quality properties of a brand are regarded as poor by the users, although this is not confirmed objectively. If marketing experts want to know for sure that the customer evaluation is wrong in objective terms in comparison to the rival products, not product quality itself, but, for example, the communications strategy ought to be changed. Here, too, *technometric benchmarking* paves the way for more objective measuring processes in marketing and the management of technology.

Specifically the new consumer theory on the one hand and marketing literature on the other stress the importance of a demand-oriented corporate strategy, see Levitt (1993) or Maital (1994, ch. 8). At the same time, the missing information item relates not only to attributes such as price ranges which the prospective clients are prepared to pay (this matter can be left to market equilibrium force) or purely and simply product quality, but to detailed information about preferences for the optimal "basket" of product properties which the demander prefers. Precisely for company

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6 The costs of information procurement can be roughly estimated from the Koschatzky et al. (1996) and Frenkel et al. (1994) research projects, and thus from the preparation of the sensor data used in this Section. Indeed, this is a R&D management research project in which the research team was no market participant but the costs of a market participant with no large internal knowledge base, e.g. a medium sized enterprise, are of a similar order of magnitude. The costs of "manufacturing" as complete a set of data as possible on the sensor market *in a particular year* must be reckoned at US $ 20,000 to 35,000. In view of the size of this Figure, in the mid-80's, an attempt was made to set up a permanently updated sensor databank which all market participants could search on-line. The hosts STN SENSOR databank was not however a paying proposition and after an initial public launch expired in 1987 and ceased to be updated. See Grupp et al. (1987, pp. 248-249) and Koschatzky et al. (1996).

secrecy reasons amongst competitors it is questionable whether the manufacturer of an innovative product is aware of the functions in detail which his piece of equipment has to perform for industrial users and how appropriate the profile of product technical features is for this purpose. This information can be known bilaterally in adequate measure via customer-supplier dealings; other market participants are however excluded from this information. This information deficit is vital for elucidating innovation processes, since the technical properties of innovative products must be established prior to market launch and hence before sales discussions can be conducted with potential clients. This certainly applies to innovators new to the market.

It is possible to amass information about purchasers' preferences by direct market research. This is the usual and commonest way in practice for missing blocks of information to be obtained on free markets. An entire branch of the economy makes a living from this in market research. So, in order to include "appropriate" data on demand preferences in this context, here, too, a direct market survey has been conducted, see Frenkel et al. (1994). This was done by asking the purchaser of industrial sensors, via a questionnaire, to rate the importance of technometrically determined properties of sensors according to their importance on a scale of between 0 and 10.[7] The same questionnaire was also handed out to sensor manufacturers (R&D personnel, production manager, sales manager) in order to establish the preference rating of their industrial clients as perceived by the manufacturer.

In such a survey, firstly the problem of missing product data does not arise; the set of technical characteristics has therefore been extended beyond the twelve considered hitherto. The inquiry also sought to check whether the technometric information available was definitely relevant in terms of demand preferences. In all, in the case of pressure sensors, 22 possible technical properties were considered part of the sensor market. Fully completed questionnaires from 50 recipients of pressure sensors were evaluated; the data likewise relate to 1991.

Having amassed this data on demand preferences, answers could be given to the following hypothesis:

Hypothesis 1: The most important technical properties which manufacturers disclose to their customers are those which the demanders prefer.

Hypothesis 2: Manufacturers are perfectly aware of demand preferences.

Hypothesis 3: Potential customers on a market have identical or very similar preferences.

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7 If the resulting indices are divided by 10, then the results of the inquiry were referred to the same numerical interval between 0 and 1 as the technometric indicator.

Hypothesis 4: As far as the preferred properties are concerned, the technical quality of the products is higher in these characteristics than in others.

Hypothesis 5: Products whose technical quality perfectly matches the demand preferences achieve higher market prices.

The object of this Section is to check the above five hypothesis for the pressure sensor sub-market. Table 4.1 shows that, of the 22 quality properties examined, eleven are known from the technometric investigation whilst a further eleven were not considered important to the inquiry. The choice of technometric characteristics was made with the help of the R&D personnel of manufacturers having coherent ideas about the important technical features of their innovative products from the dominant technical design standpoint. From these assessments, sales and marketing departments formulate the corresponding specification sheets which they offer to their customers in the context of general business relationships and supply at fairs, for example. In expert circles, the other eleven properties are to some degree contentious, as far as their importance is concerned, or only represent the individual opinions of outsiders. In some respects, they have been designated by individual prospective clients as "unfortunately defective" in the specification sheets.

Table 4.1 shows two different things:

- in fact the preferences mentioned for technometric specifications are higher than for the rest,
- and what is perhaps even more interesting, the variances in regard to technometric characteristics are smaller than for the rest.

If this is not to be interpreted purely statistically, this means that the *notions* of the 50 industrial users of pressure sensors questioned in regard to technometric parameters are less divergent than for the rest. Consequently, it would seem to be confirmed that the technometric estimates are distinguishable from the rest in that they involve a larger consensus of the technical world. The technometrically chosen technical properties are consensual; this conceptualisation is already established in theoretical design according to which specialist technical circles during their social interactions over a period of time come up with a joint picture which is important to an innovation. Hypothesis 1 has therefore been confirmed, not surprisingly, tendentially; one criticism that can be levelled against it is that the random sample could be too small to produce significant results.

Table 4.1: Comparison of demand preferences for pressure sensors sub-divided into technometrically relevant and irrelevant properties (N = 50).

No	Characteristics	Average importance	Standard error
	Technometric properties:		
1	Hysteresis	0.915	0.114
2	Accuracy	0.894	0.151
3	Linearity	0.868	0.157
4	Measuring range	0.715	0.370
5	Overpressure	0.711	0.312
6	Maximum ambient temperature	0.702	0.226
7	Minimum ambient temperature	0.692	0.233
8	Thermal stability	0.656	0.345
9	Size	0.600	0.272
10	Maximum supply voltage	0.483	0.288
11	Weight	0.417	0.276
	Average	**0.696 ± 0.151**	**0.249 ± 0.082**
	Other properties:		
1	Repeatability	0.909	0.102
2	Response time	0.843	0.179
3	Sensitivity	0.764	0.256
4	Output signal	0.556	0.344
5	Minimum supply voltage	0.500	0.283
6	Insulation resistance	0.464	0.306
7	Resonant frequency	0.417	0.339
8	Bridge resistance	0.338	0.283
9	Maximum storage temperature	0.334	0.208
10	Minimum storage temperature	0.334	0.208
11	Output impedance	0.329	0.307
	Average	**0.526 ± 0.206**	**0.256 ± 0.071**

The second hypothesis relates to whether the manufacturers of the sensors perceive the lists of preferences in the same way as their clients. From supplier relationships, discussions at fairs and many other contacts ideally the manufacturer should have full information about the preferred technical features of his products as perceived by the customer. If the entire set of 22 specifications according to manufacturer and customer perceptions is correlated, the result is plain: both preference scales are entirely uncorrelated. Thus, the market tends to value highly technical characteristics such as linearity, repeatability and hysteresis, while the prospective supplier sets greater store by accuracy and error tolerance (overpressure).

Hypothesis 2 must clearly be discarded; no even remotely complete information can be obtained about purchaser-revealed preferences.

A further index for the non-existence of complete information about customer wishes within a comparatively limited sub-market such as pressure sensors is obtained from further observations which Frenkel and colleagues (1994) have conducted. The variances in perception between individual manufacturers show considerable scatter - much more marked than with prospective purchasers. Since anonymity was promised for the field research, no data can be supplied as to what type of companies can assess relatively reliably what prospective customers prefer. We might mention with some circumspection that amongst sensor manufacturers whose ideas deviate flagrantly from consumer preferences are also larger concerns so that the supposition of a specific problem with medium-sized companies is unsubstantiated.

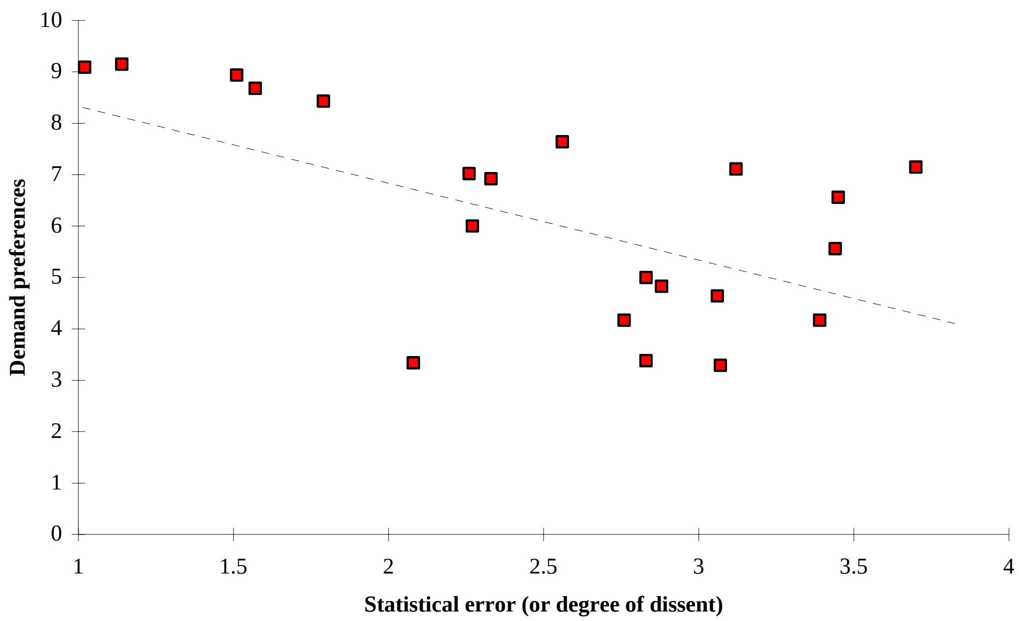

Figure 4.3: *Average consumer preferences for 22 technical properties of pressure sensors and the degree of dissent over the assessment (1991, N = 50).*

Hypothesis 3 takes the considerations on preference homogeneity a step further. Table 4.1 not only includes the revealed preference ratings of prospective purchasers but also standard deviations obtained from the answers. They relate to the preference ratings themselves and are not independent of them. The more important or the greater the functionality of a technical property is considered to be, the more convinced are the prospective purchasers as a whole of this conviction.

Figure 4.3 shows the high degree of concordance on highly preferred technical properties. There is a greater divergence of opinion over the generally less important quality features. The negative ratio proves to be significant and is robust. Hypothesis 3 can undoubtedly be considered confirmed which again points to the importance of consensus-forming processes amongst economic agents, in this case the prospective purchasing group for pressure sensors.

Since Hypothesis 2 cannot be confirmed and it is to be noted that manufacturers of science-based innovations (in this case, pressure sensors) are not adequately informed about the wishes or functional necessities of the user, it can be suggested that Hypothesis 4 is also untenable. It presupposes that the anticipated requirements of the industrial purchaser of innovative products are already considered at the R&D, design and construction stages of the technical specifications. Only with timely, adequate, relevant information can the innovating company so configure its R&D projects that in so doing the desired (in the literal sense) technical designs emerge.

Taking this a step further, technological inter-dependencies exist and not all somewhat contrary technical design requirements can be fulfilled simultaneously. As technical modifications are differentiated from factor costs, compromises would have to be struck between technical and cost practicability and the requirement profile presented by demand. Owing to the lack of information on product functionality, it must be assumed that also the gap between the resulting compromise solution and the ideal within the context of the R&D project is unknown. This does not apply to customer-specific developments in which *a* subsequent purchaser prescribes the specifications. Even in this case, it would however be interesting for corporate technology management to know how the list of market requirements thus claimed stands in regard to all purchasers other than the one customer.

For the 72 products chosen from eleven innovative companies in six countries which were analysed in greater depth in Section 4.3 and which are incorporated in Figure 4.2, it can be tested to what extent the technical quality of these products is in accordance with the disclosed demand preferences. This is based on the assumption that an efficient company with a good database on demand requirements sets greater store by highly preferred technical features which are reflected in a correspondingly high technometric index. With a view to arriving at a compromise between factor costs and mutually exclusive technical specifications the assumption must be made that the technometric indices for the properties less prized by the prospective purchaser (or as above, the more ambiguous ratings for the entire sub-market) are not endowed with correspondingly high quality. The technometric index must then be correspondingly lower.

If the technometric profiles are compared to the requirement profiles using the numerical values in Table 4.1 (taking only the technometrically relevant part of the assessments into account), then an index can be calculated for the *demand orientation (DO)* from the mean quadratic deviation of both profiles:

$$DO_k = \Sigma_j (K^*_{kj} - F_j)^2. \quad (4.6)$$

Here, F denotes the disclosed demand preferences; the other variables and indices have already been introduced. The demand orientation is large for small values of DO.

The distribution of the indices for demand orientation has the form of a continuum between good and less good orientation of the technical properties desired by the buyer. The optimum sensors from the random sample are likewise only configured in certain properties and not in all quality dimensions. By way of illustration, let us look at the best and worst sensor as oriented to demand wishes (Figure 4.4). The

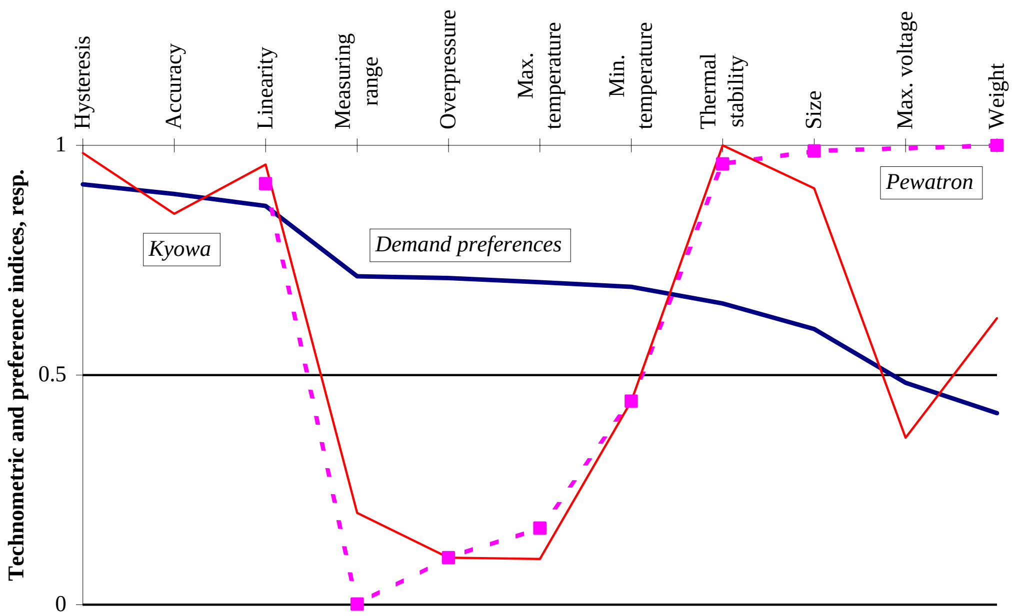

Figure 4.4: *Revealed demand preferences and technometric profiles for two chosen pressure sensors (the technical property configuration shows preferences in decreasing order).*

Kyowa (Japan) pressure sensor displays technometric specifications which in terms of the three most important properties (from the demand standpoint) are outstanding, but it is no longer appropriate for "average" preferences. In the next ranking properties, this sensor displays moderate qualities which consumers might accept. Of the 72 products chosen, this unit was the best match to demand requirements, at least, in regard to the most important features.

The reverse applies to the Pewatron pressure sensor whose best technometric characteristics materialise in the midst of those properties which users would put at the bottom of the list. This sensor shows high quality in regard to the less important properties. Also worth noting is the fact that the corresponding specifications in regard to both most important characteristics are hardly mentioned by the would-be supplier and might therefore be unknown to the user. This does not appear to be any general corporate marketing strategy because the corresponding data on hysteresis were produced properly for sensors other than the one considered here, from the same manufacturer. Figure 4.4 gives a visual impression of the technical quality dimension of the two contrasting products in regard to demand preferences, and thus refers to a method Pugh (1990) has described earlier. Whereas in a Pugh matrix scores are being used, here metric scales are involved.

Hypothesis 4, as already suspected, is untenable. Also a satisfactorily operating market such as the sensor market, insofar as the products considered are concerned, does not lead to premature inclusion of detailed requirements from later prospective customers in the technical quality characteristics of innovative products. Therefore, the sensor market can function with correspondingly sub-optimally designed products, since clearly no ideal products are available as these would otherwise drive the mismatched ones from the market. Industrial investigators choose what is for them the lesser of the various evils on offer. The marked segmentation has already been emphasised many times. To further check out hypothesis 4, the pressure sensor sub-market would have to be further segmented. Even without such segmentation it must be assumed that, essentially, attributes other than technical ones also play a part; let us cite confidential relationships, supplier relationships of long standing, incomplete awareness as to what is available on foreign markets, etc. by way of example. Also the hedonic price analysis in Section 4.4 has shown that the technical specifications can only account for half of the price variance.

4.6 Market segmentation and identification of niches

The purpose of the last hypothesis is to ascertain whether a better match to customer requirements leads to higher prices. However, first of all - since more detailed information on segmentation is not available - it must be checked whether, with the help of a similarity analysis of the property spectrum, an inherent pertinent product segmentation results. According to Backhaus (1992, pp. 158 onwards), the segmentation criterion must display a determinable relationship to procurement behaviour which again can be linked to characteristic functionality, if geographical and organisational partial approaches to segmentation (not explored here) are excluded. A multidimensional scaling of the 72 sensors in terms of eleven properties yields a *technometric portfolio* per Figure 4.5.[8]

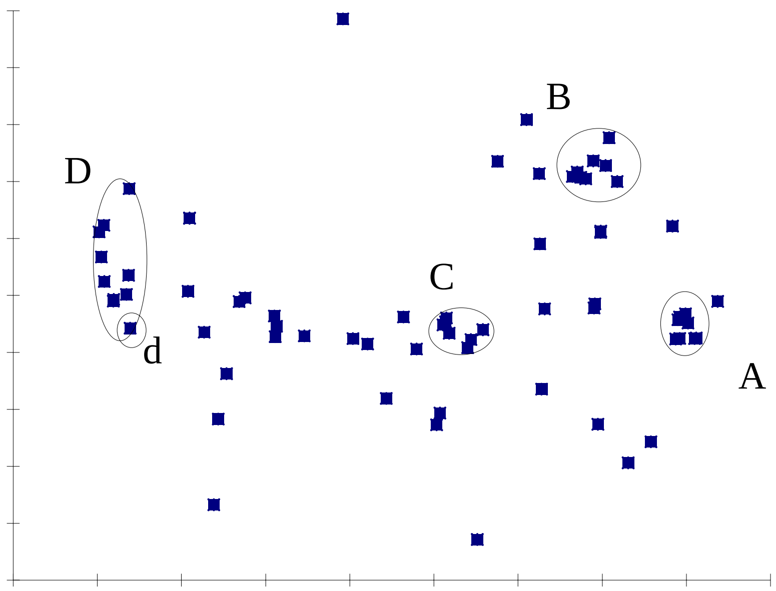

Figure 4.5: Multidimensional configuration of technical characteristics of the pressure sensor market 1991 (N = 72).

Figure 4.5 shows high scatter along the abscissa with certain clusters of homogeneous products. Most sensors with large measuring ranges lie in the left hand half, low pressure precision instruments are on the right hand side. Cluster A (deliberate visual demarcation) for example comprises eight products from three potential suppliers all with superlative accuracy and linearity but low temperature tolerance at high temperatures, light and perfect hysteresis. Manufacturers of products in Cluster B serve market segments in which moderate pressures are measured with high but not maximum accuracy, good display linearity is unimportant, but thermal stability even at higher temperatures is preferred. The Kyowa sensor from Figure 4.4, which meets customer requirements exactly in terms of top values (but not in regard to average), achieves a market price of 444 US $ (1991) and falls in Cluster C. The Pewatron product (d) has technical strengths in a few important properties and for which the specifications of the most important characteristics are scarcely known, achieves a market price of 18 US $ (1991) and falls in Cluster D. Sensor d is one of the cheapest, comparatively unreliable products, etc.

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8 The distance factor is calculated per the cosine measure; Figure 4.5 is unrotated, the stress at L = 0.166 is satisfactory, $R^2 = 0.87$ virtually explains 90 % of the variance, iteration was discontinued at $\Delta L < 0.001$.

Hypothesis 5 is likewise tested with the aid of the 72 products chosen. As we have now an empirical model of market segmentation, the hypothesis can now be formulated as follows: do sensors with a greater bias towards the technical properties desired by demand command a higher price? The answer is found by using a two-part TOBIT model which is not reported here (see Grupp, 1998, for details). According to this econometric test, higher technical quality along customer wants significantly explains whether a particular sensor belongs to the top price percentile. In the average and low price band, still, those sensors achieve a higher market price whose technological profile more closely follows the average preferences of all industrial buyers. But now manufacturing matters: with gauge strain technology, firms cannot sell expensive sensors. With these limitations, hypothesis 5 seems to be valid.

In the context of R&D and quality management, elucidation of the connections between technical change, demand preferences and prices would be out of order and inappropriate for individual cases and the pricing peculiarities. From the technical characteristics per Figure 4.4, in any case, it is apparent that the Pewatron product is not only cheap but also small and light. It is a modern miniaturised sensor whereas the products in Cluster A are many times larger.

The commercially lowly rated product appears to fit precisely into the much discussed mainstream miniaturisation of sensor technology whereby information technology and micro-electronics are making incursions into conventional instrument engineering. In 1991, the market was still not prepared, however, to acknowledge this price-wise and is still prepared to give preference to more conventional, larger duty units with higher accuracy and reliability. Similar findings are also obtained by the hedonic prices method (see Section 4.4).

4.7 Conclusion

In all, this Chapter results in unclear relationships and many current hypothesis do not provide confirmation of equilibrium markets. Whether the empirical findings proposed hitherto can be corroborated via further segmentation and larger random samples remains to be seen. The invalidity of the hypothesis on general information reliability is however not only supported by the empirical observations but also by the strength of theoretical considerations. Against the background of general market equilibrium, a proportion of the resource costs must be attributable to information procurement as it promotes the new microeconomics. As far as that goes, the justified hope remains that the technometric findings for the sensor market can be substantiated by further projects and are not a random event.

In the preceding Section, a temporary, rather anecdotal view of the modern sensor market supplies many informative insights into the sluggishness of this market in adopting a new scientifico-technological paradigm. Since an externally applied segmentation of this market is unknown, perhaps a bifurcation point is also available for this sub-market in which there is product differentiation between conventional products and semi-conductor products or the new paradigm must reinforce the first reactions before it becomes universally established. For the moment, the miniaturised product has objective disadvantages in the highly preferred properties evaluation. Consequently, for the time being for the technically more modern product cluster only those customers who do not set great store by it (earlier non-industrial applications) are considered. Investigation of the connection between technical quality and price would then have to resolve the corresponding case differentiations before plausible results can be obtained. For QFD, starting points to improve the quality of products under the new technical paradigm can immediately be derived from the technometric portfolio.

In the *management of technology context*, the technometric benchmarking acquires additional importance in identifying niches on capital goods markets. Validation with the aid of market surveys shows that the approach is valid; the characteristics contained in the technometrics index are deemed more important to some prospective purchasers than others. In this respect, this Chapter can also be viewed as an extension of the common benchmarking literature with relevance for quality function deployment (QFD).

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5 Estimating the Value of Brand Names: A Data Envelopment Approach[1]

"What's in a name?
A rose by any other name would smell as sweet".
- William Shakespeare -

Main Ideas in this Chapter

This Chapter uses a variant of linear programming known as Data Envelopment Analysis to measure the contribution of brand name to the determination of market price. Strong brand names generate higher prices than the quality of their product features alone implies, hence are 'efficient' in converting features into price. Weak brand names are 'inefficient', in that they give the consumer high feature value in the absence of brand-name value. This method generates quantitative estimates of brand-name value, as well as parameters showing substitution effects among product features. The empirical part of the Chapter deals with printers and executive jet aircraft. The examination of 36 printers reveals the existence of strong brand names that in and of themselves command higher prices. In contrast, no brand name effect is found for 18 executive jets. We interpret this finding as follows: For mass-market consumer products, amenable to brand-building techniques of marketing, there are clear, identifiable brand-name effects on price; but for investment goods (like jet aircraft) exhaustively evaluated by procurement managers, technology-based features alone drive price.

5.1 Introduction

With the rise of the global economy, greater importance now attaches to the establishment of strong brand names as a key element of competitive strategy. Ward et al. (1999) argue that "... it is precisely the volatile conditions (swiftly changing technology and high levels of uncertainty among buyers) that make the brand concept especially pertinent (for high-tech products). When things change quickly,

1 This Chapter is based on work which – in addition to the grant by GIF – was supported in part by a grant from the Technion V-P Fund for Research. We are grateful to Guy Levy and Irit Cohen, undergraduate students at Technion, for research assistance. We are indepted to Sharon Lifshitz for gathering data on executive aircraft. This Chapter was written while one of the authors, S. M., was Visiting Professor at MIT Sloan School of Management. It is an original contribution to this volume not published elsewhere.

and when buyers face great uncertainty, they want to deal with a company they perceive has a vision of their needs and interests that goes beyond price and performance." (p. 95).

A recent survey canvassed 106 firms in the United States and Europe (Troy, 1998). The study found that companies claiming to have a "highly successful brand" averaged earnings growth of 33 per cent yearly, compared with 22 per cent for other firms. Between 1991 and 1995, the value of "strong-brand" companies' stock price rose on average by 125 per cent, compared with 71 per cent for other firms. A consulting firm known as Corporate Branding Practice found that fully 5 per cent of Fortune 1000 companies' stock price was accounted for by Corporate Brand Image (Troy 1998, p. 28) – virtually equal to the contribution of "financial strength".

Yet despite the clear, high return to brand names, 40 per cent of the respondents reported that "they are minimally or not at all satisfied" (loc. cit.) with the measurement tools used to benchmark brand-building effort and investment. If indeed management begins with measurement, there is a clear need for improved methods for quantifying brand equity.

A Microsoft executive, Ann Redmond, defines brand equity as follows:

> "If a product Microsoft offers is equal to a competitor's in every other way – in its features and capabilities – what incremental value does our product have in the eyes of the customer? That value-add is the power of the brand name – and that's what we call brand equity".[2]

This suggests a multi-attribute approach to measuring brand equity, based on product features. Grupp and Maital (1998) applied a multi-attribute model known as "technometrics", commonly used to evaluate product quality, in order to measure the market value accruing to specific product features. That study showed that fully half of the variance in the market prices for industrial sensors was explained by only two key features: maximum temperature and weight. The question then arose: what factors underlie the other half of the variance in price not explained by product features? Is brand name a key variable in determining product price? If so – how can the "brand name effect" be quantified ?

This Chapter uses a variant of linear-programming known as DEA (Data Envelopment Analysis) to measure the contribution of brand name to the determination of market price. We estimate an efficiency frontier, in which the "decision making units" are similar, competing products; "inputs" are the objectively-measured qualities of product features (measured in interval scales); and "output" is the product price. The assumed objective of the company is to maximize

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2 Cited in Berman, 1998, p. 15.

price, for given product-feature inputs. Companies invest in R&D that improves product features, and/or in expenditures that build brand equity. Market prices are assumed to be generated by product features and by strong brand names. Efficiency scalars measure the brand-name effect. Strong brand names generate higher prices than the quality of their product features alone implies. A high ratio of price/feature input indicates the presence of value-adding factors other product features – specifically, brand name. This method generates quantitative estimates of brand-name value, as well as parameters showing substitution effects among product features.

The structure of the Chapter is as follows. The next Section reviews the literature on multi-attribute models in economics and business administration journals. Section 5.3 surveys methods for measuring brand equity and provides an exposition of our proposed method including a numerical illustration, based on our earlier study of pressure sensors. Section 5.4 introduces the DEA relations. Section 5.5 then applies DEA to the analysis of brand equity for 36 printers. Section 5.6 uses the DEA method for measuring brand equity for executive jet aircraft. The final Section summarizes and concludes.

5.2 A brief survey of multi-attribute product models

Multi-attribute models, which analyze products by breaking them down into measurable features or attributes, have been widely used in marketing and in the economics of consumer behavior and technical change, with relatively little interaction among them. This Section undertakes an integrative survey of these three branches of literature, to prepare the foundations for our new approach to measuring brand equity.

In marketing, multi-attribute models date back as far as Green and Wind (1973). In economics, Lancaster reinvented the economic theory of consumer demand by adopting a multi-attribute approach (Lancaster, 1971; 1991). In the literature on the economics of innovation and technological change, Grupp pioneered in the use of multi-attribute models for quantifying technological sophistication and measuring how it changes (Grupp and Hohmeyer, 1986; Grupp 1994, 1998). He termed his approach "technometrics". A natural development was to use the multi-attribute approach as the basis for optimizing investment in Research and Development (R&D) (Ben Arieh, Grupp and Maital, 1998; Grupp and Maital, 1998, 1998a), and for integrating marketing and R&D (Horwitch, Grupp, Maital, Dopelt and Sobel, 1999).

Multi-attribute Models in Marketing

Customer value is an important positional advantage and can be a key success factor (Day and Wensley 1988). Measuring customer value is based, in many cases, on multi-attribute models. Such models explain attitude formation, which underlies brand preference (Fishbein 1963; Fishbein and Ajzen 1975).

Fishbein's model (1963) arrived at attitude scores based on the multiplication of each brand's performance on an attribute and the same attribute's evaluation. Bass and Talarzyk (1972) replaced the evaluation component with an assessment of the importance of each attribute. Empirical evidence for the superiority of either model is mixed (Bettman, Capon, and Lutz 1975; Mazis and Ahtola 1975). Linear compensatory models have dominated (for reviews, see Curry and Menasco, 1983, and Wilkie and Pessemier, 1973; for exceptions, see Curry and Faulds, 1986, and Tversky, Sattah, and Slovic, 1987).

Given the importance of attribute-level information, it is not surprising that it has been used extensively in the marketing literature. Many texts use such models and suggest a variety of strategies to improve a firm's position in a perceptual map (e.g., Kotler 1991). Most prior research concentrated on the role of product attributes in determining perceived quality. For example, Chang and Wildt (1994) manipulated product attribute information and measured the impact of the quantity of attribute information on perceived value. They found that as more attribute information was given to subjects, the importance of price as a determinant of perceived value diminished. Zeithaml (1988) also recognized the importance of attributes and suggested that intrinsic attributes underlie an abstract quality dimension, which determines perceived product quality.

Other attribute categorization schemes have also been used. Attributes can be categorized on the basis of *accessibility*. Attribute accessibility is defined as the *availability and usefulness of attribute information to potential customers* and is similar to what Kotler's (1991) saliency of product attributes. Accessibility is important because it suggests which attribute information is available to and useable by potential buyers. For example, personal computer users may not know what a certain designation actually means. It may be inaccessible even to those who know what it means if they cannot assess the resulting computer performance. In a review of 42 empirical studies of multi-attribute models in marketing, Wilkie and Pessemier (1973) show that most such studies assume that their list only includes salient attributes without much substantiating evidence.

Another categorization is based on attribute *diagnosticity*. Diagnosticity is defined as *the extent to which an attribute can be used by customers to distinguish between competing alternatives*. Many product attributes lose diagnosticity with the passage of time and the maturing of an industry. This loss is explained by the three phases of product design (Watson 1993). Innovative performance is the first phase, where there exist truly innovative features that speak to real and, at times, unspoken customer needs. Watson (1993) uses the car coffee-cup holder as an example. Prior to the launch of the Ford Taurus, such holders were unsafe add-ons. In contrast, holders were designed into the Taurus model resulting in a diagnostic attribute for some buyers. The second phase is competitive performance, during which customers compare features that are available in most brands. Many car models incorporated the cup holders during this phase. Attributes at the first and second stage can be used to compare competing brands on the basis of what Pessemier (1977) calls "determinant attributes". In the third phase, an attribute that was innovative is expected by all buyers and loses diagnosticity altogether. Attributes at the final phase are not used to evaluate products because they are available in most existing brands (the situation in the car market for cup holders at this time). Consumer Reports groups such attributes under the heading "All Have". Utterback's and Abernathy's (1975) concept of the "dominant design" refers similarly to this convergence on a common set of attributes.

Finally, some product attributes are non-monotone. They cannot be compared across consumers nor ordered on a utility function. For example, product color is very important to some consumers (e.g., clothing), but a preference for one color over another cannot be compared across individuals. Most prior research included only monotonic product attributes for this reason.

The use of multi-attribute models in marketing has been subject to a number of critiques. Earlier critical work falls into one of three major types: choice of attributes, choice of weights, and allocation of performance scores. The first issue of choice of attributes involves their number (how many) and composition (which attributes). Wilkie and Pessemier (1973) show that the number of independent attributes assessed in previous research varied from 2 (of 9 original) to 8 (of 37 original). Consumer Reports uses an average of 6.8 attributes and the similar Danish Radog Resultater uses an average of 9.3 (Hjorth-Andersen 1984).

Second, the choice of attribute weights was the subject of much debate (Curry and Faulds 1986; Hjorth-Andersen 1984, 1986; Sproles 1986). Hjorth-Andersen (1984, 1986) argued that the process used by testing firms is flawed because it is based on subjective selection of attributes and, more importantly, on non-disclosed attribute importance weights. He argues that low correlations between price and quality may have been due to the use of summary, Consumer Reports-based quality ratings. Similar concerns were voiced by Archibald, Haulman, and Moody (1983) in their analysis of the running shoes market. Sproles (1986) uses Hjorth-Andersen's data to argue that consumer markets contain a high proportion of inefficient brands that can lead to financial losses. Curry and Faulds (1986) fault Hjorth-Andersen's summary methodology, but they agree that the proper choice of attribute weights is extremely important (see also Hjorth-Andersen 1986).

Third, multi-attribute models in marketing are mostly subjective with regards to brand performance scores on each attribute. Subjective assessments of evaluative criteria are important since consumers act based on their beliefs regarding performance of competing products (Wilkie and Pessemier 1973). Such beliefs can be assessed using competitive benchmarking (Bowman and Faulkner 1994; Camp 1989), but they sometimes fail to provide managers with the information needed to change strategy. For example, if a given brand is rated poorly by users on some attribute, say maximum speed of car, the major question is whether such ratings are justified. To the extent that objective quality is high, the firm may change its advertising strategy and attempt to convey a message of superior quality. If, on the other hand, low ratings are justified for a given product, the firm may invest in improving product quality. Another problem arises because not all users are aware of all brands and can only rate brands with which they are familiar. Their ratings are limited to known brands and evaluations are comparative only for these brands.

Furthermore, it is well known that attribute importance can vary by context (Bearden and Woodside 1977). For example, the importance of price and quality may vary by respondents' income. This is the basis for the use of multi-attribute models as segmentation tools in many marketing contexts (Wilkie and Pessemier 1973). Thus, it is important to either equalize the context of such studies or to divide the population into context-similar segments. Camp (1989) uses objective, benchmarked attribute measures – an approach adopted as well by Grupp (1998) in the innovation literature. Other studies deal with subjective, user-defined importance weights.

The use of objective measures at the attribute level is an important departure from most earlier research. As Hjorth-Andersen (1986) suggests, while the argument about choice of weights raged, no attention was paid to the choice of scales to measure each attribute. Hjorth-Andersen (loc. cit.) also argues that many such scales are, at best, ordinal and that the distances between points of these scales are not equal. The use of benchmarked technometrics, as discussed above, results in cardinal, interval-scaled measures of performance. Furthermore, Garvin (1983, 1987) argues that quality should be assessed on eight dimensions. Six of these dimensions (objective performance, features, reliability, conformance, durability, and serviceability) should be measured objectively. Only two incorporate subjective criteria (aesthetics and perceived quality). Technometrics result in measures that fit Garvins criteria.

In a "bicentennial" review of Chapters using multi-attribute models in marketing, Lutz and Bettman (1977) point out the significant impact of the existence of publicly available, objective attribute information. In their view, objective data or discrete attributes (see Hauser and Simmie 1981) do not apply to the standard models. Availability of public information has been shown to strengthen the positive relationship between advertising and quality (Archibald et al. 1983). Thus, after ratings are published, firms adjust their advertising levels. Archibald et al. (1983) argue further that advertising levels can help consumers locate good buys. Furthermore, as shown by Katz (1995), some product attributes are not directly observable, even after trial. She suggests that dependability and complaint-handling behavior fall into this important category. As a result of these problems, which are inherent in subjective assessments of quality, many researchers argue for the use of objective measures (e.g., Adelman and Griliches 1961; Lancaster 1991; Lucas 1972; Muellbauer 1974; Rosen 1982). Objective measures form the backbone of process benchmarking as popularized by companies such as Ford and Xerox (Zangwill 1993).

The use of benchmarked technometrics makes it possible to measure observable and non-observable attributes on the basis of publicly available attribute information (and, at a later stage, compare them to user-based attribute assessments). This is the basis of the technometric approach, which we now briefly survey.

Multi-Attribute Models in the Economics of Technical Change

Benchmarked technometrics is designed to measure product attributes (Grupp 1998, Grupp and Hohmeyer 1986; Grupp 1994; Frenkel et al. 1994). It is a quantitative, objective approach, which can provide profiles at brand, product-line, industry, or country levels. Its output is performance data for a given brand, compared to competitors'. Benchmarked technometrics has two advantages over existing methodologies. First, product or brand attributes are measured objectively. Thus, overall product evaluations are based on a combination of objective (attribute scores) and subjective (user weights) criteria, rather than a combination of subjective attribute scores and weights as in present approaches. Second, because it is based on readily available public sources, the benchmarked data can be used by firms to improve product management relatively easily. Existing methods require users to be knowledgeable about all available brands and their performance on the various attributes. As explained below, benchmarked technometrics requires that users provide only importance weights for the various attributes.

Because of the more objective nature of benchmarked technometrics and its use of readily available data, the technique has several practical advantages. These include the generation of objective, comparative attribute profile and perceptual maps of competing brands; a menu of possible attribute improvements; and a triangulation of manufacturer-based and user-based attribute importance weights. Interestingly, the technometric technique was developed in a policy framework to improve quantitative measures of progress, following a request by the German Federal Ministry of Science and Education for an assessment of the country's competitiveness in high-technology industries. It has originally been applied in the lasers, industrial robotics, and bio-diagnostic kits industries.

Technometrics is defined as a quantitative measurement of the quality or technological sophistication of attributes of a product, process, product line, or industry (Grupp 1998; Grupp and Hohmeyer 1986). Technometric measurement is based on relevant product attributes (we discuss this issue further when our empirical evidence is presented), which stabilize as products mature (Stankiewicz 1990). Industry experts usually agree on such attributes (Grupp 1994).

Theoretically, benchmarked technometrics builds upon the foundations laid by Lancaster (1971) in his modern consumer theory. This economic theory (Lucas 1972; Rosen 1974) views products as utility-generating bundles of attributes (much like the approach used in marketing). It has been used to assess the accuracy of consumer price indexes in accounting for changes in product quality from one period to another (Adelman and Griliches 1961). Such studies utilize the hedonic price index approach (Frenkel et al. 1993; Griliches 1961, 1971; Saviotti 1985).

Product attributes are typically measured in differing units of measurement, such as weight (kgs.) and length (cms.). The technometric technique circumvents these problems by normalizing product attribute-scores, say, to a [0,1] scale, or, alternately, a [1,10] scale (both are employed below, the latter in cases where zero values are to be omitted). The first step in assigning a technometric score is to identify the best performing and worst performing products in a product group on each attribute. These are assigned values of one (for the best) and zero (for the worst). Thus, technometric scores are normalized and become benchmarked. This normalization enables weighted and unweighted aggregation.

The approach so far yields technometric scores at the attribute level. The next step is to combine these scores to arrive at an overall technometric score. A simple summation of attribute-level scores ignores attributes' importance. A more complex approach weights attributes with their subjective importance, as perceived by buyers.

5.3 Methods for measuring brand equity: A simple illustration

Numerous studies in marketing have focused on the impact of brand-name on price for consumer products (Leuthesser, 1988; Srivastava and Shocker, 1991; Simon and Sullivan, 1993; Sullivan 1998). Brand equity is commonly defined as "the added value endowed by the brand to the product" (Farquhar, 1989), or, "the incremental cash flows which accrue to branded products over and above the cash flows which would result from unbranded products" (Simon and Sullivan, 1993, p. 29).

Simon and Sullivan (1993) list five techniques for measuring brand equity:

- changes in the market value of stock when a brand name is acquired or divested;
- the price premia that a brand name commands;
- the brand name's influence on customer evaluation;
- replacement cost: the cost of establishing a product with a new brand name; and
- brand-earnings multiplier: the product of "brand weights" multiplied by the average of the past three years' profit.

These authors themselves offer a new, sixth measure, based on financial market data, while noting serious flaws in the above existing five methods.

Troy (1998), in her survey of 106 firms, distinguishes between "performance-based" and "perception-based" measures, commonly used by firms. Among performance-based measures of measuring brand-building success are: market-share penetration; ability to attract a premium; customer satisfaction; market position; and brand leadership. Among perception-based measures are: brand awareness; value; and customer beliefs about brand.

While nearly all these studies focus on mass-market consumer products, it cannot be excluded that brand name plays a role for knowledge-based technology-intensive investment products as well. This Chapter proposes a new approach to measuring brand equity, one that is particularly suitable for technologically sophisticated products and services and may also be used for investment goods.

Our new method for quantifying "brand-name" effect is suggested by a "Lancaster" model discussed in Section 5.2.2, in which value for the buyer (based on utility) is an "output", produced by two types of "inputs": objective quantifiable product features, and intangible aspects, primarily brand name. This is the basic model of, for example, Hauser and Shugan (1983) and Hauser and Gaskin (1984). We estimate the price premium that brand names convey by partitioning the price into two components: that driven by product features, and that driven by the brand-name effect.

Consider the following simple example, based on Figure 5.1 in Hauser and Shugan (1983). Table 5.1(a) shows two key product features for three branded pressure sensors (data from Grupp and Maital, 1998).

Table 5.1(b) converts the basic product-feature data into "technometric" form, as follows (for formulae see Grupp, 1998, pp. 110 onwards): First, express "measuring range" in terms of a [1,10] metric scale, where 1.0 is the lowest quality (i.e. the 80 bars value for the Swiss Pewatron model) and 10 is the highest (the 1,379 bars range for the U.S. Kulite); and weight similarly, as a [1,10] scale (with the lowest weight, Kulite, as 10, and the Jumo, at 255 grams, as 1.0).[3] Finally, Table 5.1(c) computes Feature Score / Price (multiplied by 100).

Table 5.1: Product Attributes and Prices For Three Pressure Sensors.

a) Basic Data			
Product	Measuring Range	Weight	Price (1991)
German JUMO	400 bar	255 g	$373
U.S. KULITE	1,379 bar	13 g	$460
Swiss PEWATRON	80 bar	170 g	$112

b) Technometric Data:[1,10] Metric			
German JUMO	3.22	1	
U.S. KULITE	10	10	
Swiss PEWATRON	1	4.16	

c) Feature Score/Price x 100			
German JUMO	0.863	0.268	
U.S. KULITE	2.174	2.174	
Swiss PEWATRON	0.893	3.714	

Now, plot these value pairs for each of the three sensors, as "Feature Score/Price" (see Figure 5.1). The "isoquant" (feature per $ of price) on which the Jumo sensor rests is far inside the isoquant for Kulite or Pewatron. This means that the Jumo brand provides far less customer value, in the form of objective product features, per dollar of price, irrespective of the subjective weights customers may put on both attributes relative to each other. There must therefore be another component of value that Jumo conveys, apart from its product features. We may call this component "brand value". If buyers are rational, then 0b - 0a (the radius vector distance between the Jumo isoquant and the Kulite and Pewatron isoquant) must represent brand value. From the viewpoint of the firm, JUMO is "efficient" in generating the highest possible price for given features and a branded product; Kulite and Pewatron are inefficient.

The brand-name effect can be quantified as [PRICE (0b-0a)/0b]. In other words: only a small part of the $373 product price derives from the product features, while most derives from the strong brand name JUMO. While this result may seem exaggerated – indeed, the example was chosen for this purpose – in fact, strong brand names like SONY, TOSHIBA, IBM, bring significant price premiums, and in

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3 Note that in this case, the technometric scale is inversed as higher customer value results from lighter sensors.

mass-market consumer products like Coca-Cola, an enormous fraction of the product price stems from the brand name Coke.

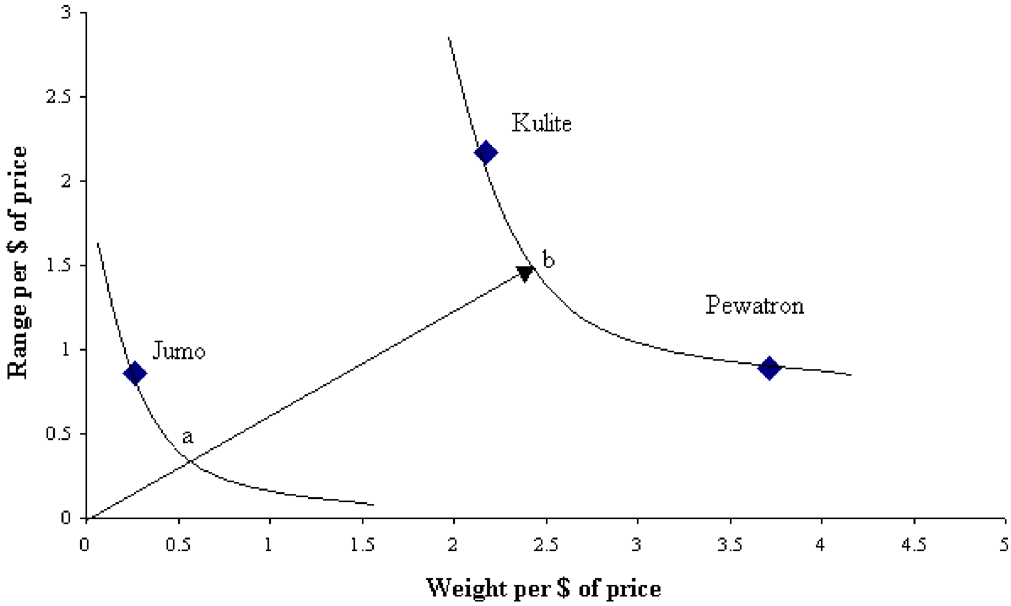

Figure 5.1: Efficiency Frontier for Three Piezo-Resistant Pressure Sensors.

This is just a simple illustration without detailing how the "efficiency frontier" for product groups can be estimated empirically, in order to make this method operational. Any of the various methods used to estimate efficiency frontiers – some based on stochastic regressions, some based on linear programming – can be used. We now proceed to propose a method based on the Data Envelopment Analysis (DEA) model, used widely to measure operating efficiency in organizations.

5.4 A DEA model for estimating brand equity

Assume a profit-maximizing company. It seeks to maximize the price P it receives for its product, for a given amount of "inputs", represented by product features vector **x** = $\{x_1, x_2, \ldots x_s\}$. Since features are costly to produce, and the better the feature the higher the cost, this model is simply a variation on the standard profit-maximization one. One way to achieve a higher P, apart from investing in product improvement, is by building a brand name. Another alternative is to invest in product quality by enhancing product features. Companies can therefore generate sales and profit by either building a national or global brand, while saving resources on product features per \$, or offering value by providing high features per \$, while saving resources in not building a national brand.

With the following terminology:

x - vector of features, $\{x_1, ..., x_s\}$,
x_i - feature "i", i=1 ... s,
b - brand name variable: $0 \leq b \leq 1$ (maximal brand name),
P - price
Q - quantity
TC - total cost
z - investment in brand-building

we can formulate our model of the profit-maximizing firm which becomes then: Invest resources in brand-building, until the marginal revenue accruing to improving the brand-name effect equals the marginal cost of such an effect:

$$\text{MAX}\ [P(b(z), \mathbf{x})\ Q\ (b(z), \mathbf{x}) - TC\ (Q, \mathbf{x}, z)] \qquad (5.1)$$

where z, the decision parameter, comprehends the quality and quantity of marketing resources invested in brand-building. The first-order condition for optimal investment in brand-building is:

$$Q\ [(\partial P/\partial b)(\partial b/\partial z)] + P[(\partial Q/\partial b)(\partial b/\partial z)] = \partial TC/\partial z \qquad (5.2)$$

In a full-blown model – beyond the objectives of this Chapter – additional first-order conditions would exist, showing that the "marginal profit" from the last dollar of brand-name investment equals the "marginal profit" from the last dollar of investment in product feature enhancement. We assume that in competitive markets, all firms seek to maximize profits, hence invest optimally in brand-name building.

Following Sullivan (1998), we assume an inverse demand function, for the utility-maximizing consumer:

$$P = f\ \{Q, \mathbf{x}, b\}, \qquad (5.3)$$

where the price of a product is determined by market quantity Q, the vector of features or attributes x, and the brand-name parameter b.

Other things equal, better brand names will command higher prices. In general (adapting Sullivan's equation [4]):

$$(P_1 / x_{1,i}) / (P_2 / x_{2,i}) = b_1 / b_2 \qquad (5.4)$$

where b_j represents the brand-name parameter for product "j" (j = 1, 2) and $x_{1,i}$ represents feature "i" for product 1.

That is, ceteris paribus, better brands will command higher "price per feature" values.

The question arises: how can b_1/b_2 be estimated empirically? Sullivan (1998) uses statistical regression methods, with "Price" as the dependent variable and brand name as one of the independent variables. Here, we propose a different method, based on a well-known technique for measuring efficiency known as DEA. The basic idea is to estimate an "efficiency frontier" for brand and non-brand products, using "price" as the "output" (to be maximized) and quantitatively-measured "features" (attributes) as the "inputs", and identify "efficient" and "inefficient" products, as in Figure 5.1.

Data Envelopment Analysis (DEA) considers a set of agents known as Decision-Making Units (DMU's; e.g. schools, bank branches, factories etc.) producing a set of outputs $\mathbf{Y} = \{Y_k\}$, k = 1, ..., r using a set of inputs $\mathbf{X} = \{X_i\}$, i = 1, ..., s; see Charnes et al. (1978); Banker et al. (1984); Seiford and Thrall (1990). DEA floats a hyperplane on the set of inputs and outputs, and thereby separates all of the DMU's into efficient and inefficient ones (Leibenstein and Maital 1992).

As mentioned in Seiford (1990), DEA may be viewed from two perspectives: "envelopment" and "multiplier". In the envelopment form of DEA, for each DMU taken in turn the linear combination of all DMU's is defined so that
(i) minimal inputs be achieved with outputs no less than existing ones, or
(ii) maximal outputs be obtained with inputs no more than actually used.

The first approach is called the input minimization DEA model, the second one, the output maximization.

Mathematically, the following problems are solved. Let r, s and n be number of outputs, inputs and DMU's respectively with $\mathbf{X}_j = \{X_{ij}\}$, i = 1, ..., s and $\mathbf{Y}_j = \{Y_{kj}\}$, k = 1, ..., r), j = 1, …, n being vectors of inputs and outputs of DMU_j, respectively. Given some DMU_0, consider the following restricting inequalities defining its possible production possibilities:

$$\alpha_{\mathbf{X}} \leq \sum \lambda_{\mathbf{X}};\ \beta_{\mathbf{Y}} \geq \sum \lambda_{\mathbf{Y}};\ \lambda_j \geq 0;\ j = 1, ..., n; \qquad (5.5)$$

and find vector $\lambda = (\lambda_j)$ providing one of the following:

min α with β=1 (input minimization problem) (5.6)

or

max β with α=1 (output maximization problem) (5.7)

In both cases an additional restriction may be added:

$$\sum_j \lambda_j = 1, \tag{5.8}$$

corresponding to variable returns to scale. If this restriction is omitted, constant returns to scale is assumed, see Banker et al. (1984) for details. In this study, we will omit [8], and assume constant returns to scale. This statement of the DEA problem was termed by Seiford (1990) an "envelopment DEA".

Suppose we now treat each individual product as a "DMU", characterized by one "output" (its price), and "inputs" (product features). By using DEA to compute the "envelope" of "efficient" products (those that secure the maximum price for a given level of product features), we can operationalize Hauser and Shugan's (1983) "Defender" model and its efficiency frontier (in "feature" space). We can identify efficient products, measure brand-name effect as an "efficiency" scalar for non-brand products, and identify how non-brand-name products overcome brand-names by strengthening certain features.

The maximization problem then becomes for a specific product labelled with subscript "0" to choose weights "w" that maximize the "feature efficiency" ratio:

$$P_o / \sum_i w_{io} x_{io} \tag{5.9}$$

subject to the condition that for all the other "n" products, this ratio does not exceed the value of one:

$$P_j / \sum_i w_{ij} x_{ij} \leq 1, \forall j, j = 1,..., n$$

where the subscript "j" represents the specific product.

Using Charnes, Cooper and Rhodes' clever transformation (1978, 1979, 1981), this non-linear program can be translated into a linear programming one. Hence, for each DMU – in our case, specific product – the above linear program is solved, and its brand efficiency estimated.

The essence of our model is this: Non-brand-name products charge prices commensurate solely with value inherent in product features. Brand-name products charge prices higher than feature values imply. If brand-name products comprise the efficiency frontier, then the "inefficiency" parameter – the % gap between the price of brand-name products and the price that would prevail in the absence of a strong brand name – measures the amount of value created by the brand, in contrast to the value created by product features.

In our model, the degree of "efficiency" measures brand equity, because it represents value created by the printer that is not attributable to physical product features. These parameters, therefore, are directly translatable into brand equity, using the formula:

$$P/P^* = 0a/ 0b = e \qquad (5.10)$$

where P is the "brand-less" price, P* is the actual price (including the brand-name effect), 0a/0b are as shown in Figure 5.1, and "e" is the efficiency coefficient compared to the least efficient hyperplane as defined and measured by the DEA procedure noted above. Note that in Figure 5.1 we did not specify the functional form of the efficiency frontier defining a and b. Now we specify that we mean the DEA envelope in the s-dimensional space.

Therefore the "brand value" per product is

$$P^* - P = (1-e)\, P^* \qquad (5.11)$$

The dollar value of brand equity – the fraction of sales accruing from the brand name, as opposed to product features – is therefore given by:

$$BE = Q\, P^*\, (1-e) \qquad (5.12)$$

where BE is "operating brand equity", Q is current units sold (annual), and P* and (1-e) are as given above. We can measure Brand Equity BE as a capitalized sum, KBE, by computing the net present value of BE measured over the product's lifetime t years:

$$KBE = \Sigma_t\, (BE) / (1+R)^t \qquad (5.13)$$

where R = risk-adjusted cost of capital.

Note that this concept of measuring brand effects does not assign a fixed value to an individual product, but derives the brand value from the actual competitive offer via the DEA envelope. If some non-branded products would disappear from the market, brand values of the remaining products are likely to change – this is exactly what we intended to model. Brand value is not independent from customers' preference scales with respect to an actual offer.

5.5 Case study of printers

We chose to apply our method to a set of 36 printers, based on objective performance benchmarking data published in 1994 in PC Magazine (see appendix). For each of the 36 printers (which range from inexpensive to very expensive), nine product features are measured. They are: color (0 for no, 1 for yes); pages per minute; speed in printing text; speed in printing graphics; speed in printing Word for Windows documents; speed in printing Lotus 1-2-3 documents; speed in printing Corel Draw documents; standard RAM; and power consumption when printing (lower values indicate better performance). The DEA analysis is performed on the basis of technometric [0, 1] values as the original data (see Appendix 5.1) are quite heterogeneous.

Table 5.2: Brand value of fully efficient printers (1994).

Name	Price	Brand Value
Canon LBP 430	799	564
HP L/J 4L	849	599
HP L/J HP	1229	868
Okidata OL400C	699	493
Okidata OL410C	899	635
Panasonic S/W KXP 4400	699	493
Lexmark 4037 SE	799	564
TI Microwriter PS23	799	564
TI Microwriter 600	999	705
Xerox 4505 PS	1629	1150
Canon LBP 860	1839	1298
Itoh ProWriter CI8Xtret	2099	1482
Itoh ProWriter CI-8XA	2299	1623
RMS Magicolor	9999	7059
Sharp JX9400H	599	423
TI Microlaser Pro 600	1599	1129
Apple LaserWriter Select 360	1599	1129
HP Color Laser Jet	7295	5150
QMS 1060 Print System	2699	1905
HP Laser Jet 4 Plus	1829	1291
HP Laser Jet 4M Plus	2479	1750
TI Microlaser Power Pro	1899	1341
Unisys AP 9312 Plus	1895	1338
Xerox 4900 Color Laser Printer	8495	5997

Table 5.2 shows the "brand value" parameters for each printer, interpreted in dollar terms, i.e. equation [11]. The efficiency measure is derived from the Iota measure of DEA programming.[4] It represents a scalar input efficiency score, interpreted as the proximity of the data point to the facet of the piecewise linear envelopment surface and equal to the total weighted distance between observed and projected points, standardized by the inputs. In contrast to other possibilities of measuring inefficiency, Iota measures the total amounts of inefficiency, not just the proportional distance along a radius vector.

At first glance at Table 5.2, many of the most powerful brand names being fully efficient can be found here. All models of Hewlett Packard are high brand equity products. However, closer examination of Table 5.3 reveals that some well-known companies cannot effectively maximize brand value. They face a key strategic decision either to exploit the brand name effect by charging premium prices or use the brand name effect for some of their products to create value for customers by charging prices that reflect only objective "feature value", hence increase sales and market share. Which of the two strategies is most effective may be determined only in the medium term if some brands are no longer major players in the printer business.

Table 5.3: Brand value and efficiency coefficients of the remaining printer (1994).

Name	Price	Efficiency coefficient e	Brand Value
Brother HL 630	499	1.00	0
DEC Laser 1800	779	0.43	440
Epson A/L 1600	1199	0.34	792
Sharp JX 9460 PS	849	0.32	574
Itoh ProWriter CI8Xtra	1799	0.34	1195
DEC Laser 5100	1599	0.37	1004
Lexmark WinWriter 600	1199	0.31	831
Mannesmann Tally T9008	1499	0.32	1020
Sharp JX5460PS	899	0.46	483
Xerox 4510 PS	2379	0.31	1632
Lexmark 4039 12R Plus	1749	0.33	1178
Lexmark 4039 12L Plus	2299	0.31	1588

4 We used two software tools (IDEAS 5.1 and Warwick DEA) which produced identical results with rounding differences in the third digit. More details on the Iota measure for innovation efficiency may be found in Grupp (1997).

It remains to clarify in a systematic way which features may explain the brand effect (if there are any). We have no variables for firms' strategy but only information on prices and features. This opens up the opportunity to explore whether the above key strategic decision between exploitation of brand name effect and value for customers matters. In what follows it will not be possible to learn in detail about the general brand management strategy of the corporations producing printers. Our method simply identifies and measures a brand name effect.

From the usual descriptive statistics it becomes clear that there are multi-collinearities between price and colour, as the colour printers are simply more expensive. Another multi-collinearity originates from the pages printed per minute and the speed in printing Word for Windows documents. After dropping these three features but keeping the price variable we find a very good mean variance of inflation factor of 3.1.

Table 5.4: Results of a Heckman selection model for inefficiency (coefficients and t values in brackets).

Variable n (uncensored)	Selection 36	Degree of inefficiency (12)
Price	-	-0.0003 (-4.56)***
Graphics speed	-	0.67 (1.62)
Corel Draw speed	-	0.45 (2.58)*
Text speed	5.16 (2.24)*	-
Lotus speed	9.07 (2.92)***	-
Standard RAM	-	0.87 (5.16)***
Power consumption	19.29 (3.13)***	1.07 (2.80)***
Constant	- -21.61 (-3.19)***	-0.97 (-2.13)*
Wald Chi^2	128.1***	

* significant at the 5 per cent level
** significant at the 1 per cent level
*** significant at the 0.1 per cent level
derived from heteroskedasticity-robust errors.

In a regression analysis we want to find out what makes printers inefficient, and secondly, what determines the degree of inefficiency (or brand effect). This situation resembles the classic example that explains the wages of women. Women choose whether to work and thus choose whether we observe their wages in a data set. If this decision is not made randomly the sample of observations is biased upward. A solution can be found if there are some variables that strongly affect the chances for observation (in the case of women the marital status or the number of children). In such a situation one may use a Heckman selection model (Heckman, 1976). We try to infer why some products are inefficient and which variables can explain the degree of inefficiency (that corresponds to little or no brand value). The results of a full maximum-likelihood calculation are presented in Table 5.4 (heteroskedasticity-robust errors). We also tried a two-step Heckman model which did not yield better results.

The above hypotheses are fully confirmed: The inefficient (no or little brand value) products offer distinct values to customers: They are highly significantly energy saving and quicker in printing (in general and in particular for printing Lotus documents). Not only the fact of being inefficient but also the degree of inefficiency is connected with energy-saving features, standard RAM and the speed of printing Corel Draw pictures. With little or no brand value, these products are offering too much customer value for low prices.

There is no doubt: In the consumer market for printers brand name is very important and the trade off between good features for little money (that is, good technology) and building up a brand name exists. As a complementary case study we now examine the same relations for an investment good, executive jet aircraft.

5.6 Case study of executive jet aircraft

The market for executive airplanes has several appealing characteristics. First, the products are complexly multidimensional (Phillips et al., 1994). Customers in the marketplace, i.e. corporations' procurement managers or CEO's, assess and compare performance on multiple attributes, such as range, speed, payload, maintenance costs, operation efficiency, and takeoff and landing requirements (Phillips et al., 1994). These are ideal settings for our study because the use of feature-based brand value is illustrated in a truly multi-attribute market environment.

Second, the market is extremely competitive. In a recent market analysis, Symonds and Greising (1995) estimated that the major aircraft producers are involved in fierce competition for a market that is estimated annually at 950 multinational corporations, billionaires, and heads of state. Competition is especially fierce between the two market leaders (Gulfstream and Bombardier). According to this report, the two firms have been spending an estimated $ 1.1 billion on the development of new airplanes (Symonds and Greising, 1995). This high level of competition increases the likelihood that competitors will seek to differentiate their products on multiple attributes.

Third, competition in this market requires major outlays for research and development. Bombardier is spending $ 800 million and Gulfstream $ 300 million in their respective development projects (loc. cit.). The risks involved in these projects are immense. Failing to respond to true customer needs may result in significant losses. Therefore, information about the value of plane attributes should be very useful. Additionally, this market is entry-unstable. New entrants have been reported to displace first-movers through rapid technological improvements (Phillips et al., 1994). Thus, attribute-level information is critical even after the introduction of true innovations to the market.

Finally, as discussed earlier, attribute weights can and do vary by context (Wilkie and Pessemier, 1973). The business aircraft market provides close to ideal settings in this respect as well because such aircraft are used similarly by all customers. Executive airplanes, also termed business aircraft, can be divided into four groups: Jets, Turboprops, Pistons, and Rotorcraft (Forecast International 1992). The world market is dominated by seven large manufacturers (Learjet, Canadair, Beech, Cessna, BAE, Gulfstream, and Dassault) with one smaller competitor (IAI). The data collection involved personal interviews with managers in a local manufacturing plant, pilots, and aeronautical engineers to identify a comprehensive list of jet attributes as they apply to business usage situations (Grupp 1998; Wilkie and Pessemier, 1973). These discussions resulted in the deletion of a few attributes. Attributes were deleted either because they lack diagnosticity or because they may not be salient for all business jet users (Watson, 1993). Attributes such as engine options, seating arrangement, documentation, warranties, or spare parts availability are comparable across the brands and offer no diagnostic information to potential buyers. Attributes such as political considerations and product line width were deleted because they may only be salient to users from some countries or large firms, respectively. The final list of attributes included 12 items: maximum fuel-load range, maximum useful load (the difference between non-fueled jet and the maximum landing weight), cruise speed, mach number, rate of climb, takeoff and landing distance, cruising-speed fuel consumption, cabin volume, cargo volume, noise level, total cost per mile, and resale value.

Information on attribute scores was gathered from published sources, such as industry magazines and manufacturers' brochures. Price information for the various jets was based on a well-respected industry publishing firm (Jane's, 1993). These prices are for what Jane's terms flyaway or standard versions. Scores were benchmarked at the sub-category level into the [0,1] range. The Appendix 5.2 lists the models, attributes, attribute measures, and prices.

Earlier, it was argued that it may be useful to compare manufacturers' and users' attribute weights. Therefore, both groups were sampled. It should be noted that manufacturers may have responded to the questionnaire with a "quality control" orientation whereas pilots may have been "usage" oriented. However, because of these differences, a comparison of both groups' weights may serve to identify production myopia of manufacturers. Four questionnaires were mailed to each of the manufacturers in the three sub-categories with instructions to distribute each copy to knowledgeable individuals in the firm. Additionally, each manufacturer was asked to provide a list of 20 customers for the user survey. Fifteen questionnaires from seven firms were returned. This represents a response rate of 34 % at the individual level and 67 % at the firm level. Table 5.5 lists average attribute weights for this group.

Table 5.5: Attribute Weights for Jets.

	Manufacturers' Weights	Pilots' Weights
Range (Nautical Miles)	7.786	8.338
Payload ('000 Lbs)	8.667	6.912
Cruise Speed (Miles/Hour)	8.000	7.718
Mach Number	6.667	6.422
Climb Rate	7.500	6.056
Takeoff Distance	7.929	7.549
Fuel Consumption (Miles/Gallon)	8.286	8.493
Cabin (Feet)	8.214	8.120
Cargo	7.357	7.408
Noise (EPN dB)	8.286	8.887
Cost per Mile	7.500	7.930
% Resale Value	8.000	7.422

None of the seven firms agreed to provide users' lists because such lists were trade secrets. Two groups of pilots were used to represent users since they are knowledgeable about the industry and approximate actual users' profiles. Forty pilots of a national airline and forty military pilots were asked to complete the questionnaire. Thirty-four of the former (85 %) and 39 of the latter (98 %) returned completed questionnaires for an overall response rate of 91 %. The differences between the two groups were not statistically significant and they were combined. Table 5.5 lists their average attribute weights.

As is evident from Table 5.5, manufacturers' weights are fairly similar to users' weights. However, two weights stand out in that the differences between the two groups are large. Manufacturers assign much higher importance to payload (8.7) and climb rate (7.5) compared to pilots (6.9 and 6.1 respectively). Decisions to change performance on these two attributes should be made with caution. Improving performance on the two will do less to improve overall positioning than what manufacturers probably think. Reducing performance on the two will harm overall positioning by less.

The technometric attributes were processed by a DEA model with exactly the same specifications as for the printers. However, because we have only 18 products here, we have to be conservative and avoid using too many inputs. While DEA is relatively insensitive to model specification, it can be extremely sensitive to variable selection. This is inherent in the nature of any method that identifies envelopes of frontiers. Moreover, given enough inputs, all (or most) of the DMUs are rated efficient because there may always be one dimension where they perform best. This is a direct function of the dimension of the input-output space (s + r = 12 + 1 = 13 in our case) relative to n (18 in our case). In practical applications, care should therefore be taken to ensure that the condition n ≥ (s + r) is fulfilled (Grupp, 1998, p. 237). This is similar to preserving sufficient "degrees of freedom" in statistical analysis.

In order to fulfill these conditions, three runs of the DEA calculation were performed, one with all attributes, one with the eight attributes ranked highest by the pilots (i.e. without payload, Mach number, climb rate, cargo) and one with the eight top manufacturers' weights (i.e. no Mach number, climb rate, cargo, cost per mile).[5]

All three runs yield the same results: All jets are efficient. Therefore no data table is given here. In fact 17 jets are fully efficient (at Iota = 1.000), one is close to being efficient (at Iota = 0.924 ... 0.935 depending on the run: it is Canadair 3 A). Therefore, we cannot observe any brand effect. All jets have equal brands or no brand value. That means, in this "rational" business market, brand effects do not matter. For mass-market consumer products, amenable to brand building techniques of marketing, there are clear, identifiable brand name effects on price. But for investment goods like jet aircraft exhaustively evaluated by procurement managers, technology-based features alone drive price.

5.7 Conclusion

Today's global economy can be defined in simple terms: "In today's global economy, you can make anything, anywhere, at any time, and sell it to anyone. Sentiment plays no role." (Thurow, 1998). With labor, capital and technology now widely available in all markets, product quality will tend to converge, as dominant designs emerge with increasing rapidity. The result is "commoditization" – the tendency of even sophisticated products to become standard commodity-like products with product features identical across various brand names, with resulting downward pressure on prices (see Pine and Gilmour, 1999; Shapiro and Varian, 1998). This is evident, for instance, in the market for PC's, with $ 1,000 PC's now common and a $ 500 PC, with strong product features, available. Managers are

5 Again we used two different software tools; see footnote 3.

rightly concerned about falling prices and the resulting shrinking profit margins (Berman, 1998). Perhaps the most effective strategy to fight "commoditization" is that of creating a strong, widely-recognized global brand name. This strategy has been successfully pursued by well-known firms. They have invested huge sums in building and supporting their brand name. They represent a handful of brand names that are recognized in virtually every country in the world. In contrast, companies with world-class products and technology that have neglected global brand-building investments have suffered enormous losses in recent years.

With growing investment in brand-name creation, managers and shareholders alike will rightly demand quantitative measures for determining the returns to investment in brand creation. We believe the approach suggested in this model can help companies both measure the presence, or lack of, a brand-name effect, and then portray visually the market position of their products relative to those of competitors, in terms of a brand-efficiency frontier. Unlike most efficiency models, the objective here, of course, is to attain the highest market price possible for given product features, by supplying consumer utility through the brand-name perception and not solely through costly product feature improvements. Ward et al. (1999) note on this issue: "Most customers' evaluations of price and performance include multiple definitions and dimensions, and the tradeoffs individuals make in their buying decisions reflect different definitions of value and different needs. Through strong brands, high-tech companies can make it clear exactly which aspects of their offerings' price and performance benefit their customers."

Our model suggests that brand-name equity is not a charlatan's marketing trick that extracts money from buyers without creating corresponding value. As Berthon et al. (1997) note, "for buyers, brands reduce search costs, reduce perceived risk and provide sociopsychological rewards" (p. 21). In a sense, the DEA model proposed in this Chapter seeks to measure the value brands create, in parallel with conventional value-creating sources like technological features.

Our model could possibly find use not only in economic analysis, but also in new-product business plans, by supplying a tool that can measure the degree to which the new product's innovation and feature superiority – with zero brand name – can compete with inferior products that have the advantage of a strong, recognized brand name. It may also help indicate the magnitude of resources necessary to help an "anonymous" non-branded new product, with superior product features, build brand recognition.

To conclude: Brands help companies improve competitive positioning, battle against falling prices and shrinking profit margins. Some 38 per cent of large firms brand *all* their products and 46 per cent brand *most* of their products, while 43 per cent of companies have initiated a new corporate brand strategy since 1995 (Troy, 1999, p. 8). With new emphasis on building brand equity, growing importance attaches to developing new benchmarking methods for quantifying the return on investment in brand building activities. In consumer markets, for many products a no-name product is nearly worthless (at least it is so for our printers being cheaper with the same utility). But, at the same time, our method has revealed that there is a class of products for which brand effects are zero. Managers seeking to create strong brands, through large investments, must know which products are amenable to creation of brand equity, and which products are inherently and solely feature-driven.

References to Chapter 5

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Appendix 5.1: Printers: Features and Prices (1994).

	Name	Price	Color	Page/ Min.	Text Speed	Gra-phics Speed	Word for Win	Lotus 1-2-3	Corel Draw	Stan-dard Ram	When Printing Power Consump-tion Watts
1	Canon LBP 430	799	0	4	3.4	1.2	3.1	1.1	1.0	1	138
2	HP L/J 4L	849	0	4	3.8	1.3	3.4	1.9	1.1	1	118
3	HP L/J HP	1,229	0	4	3.8	1.3	3.5	1.5	1.2	6	121
4	Okidata OL400C	699	0	4	4.1	1.6	3.8	2.2	1.2	0.512	127
5	Okidata OL410C	899	0	4	4.0	1.8	3.6	1.7	1.1	2	121
6	Panasonic S/W KXP 4400	699	0	4	4.2	1.3	3.8	1.1	0.6	1	94
7	Lexmark 4037 SE	799	0	5	4.7	1.5	4.2	2.0	1.2	0.512	168
8	TI Microwriter PS23	799	0	5	4.6	1.5	4.2	1.1	0.6	2	130
9	TI Microwriter 600	999	0	5	4.6	1.1	3.0	1.3	1.1	2	134
10	Xerox 4505 PS	1,629	0	5	4.9	1.5	4.5	1.8	1.3	6	132
11	Brother HL 630	499	0	6	6.0	2.6	5.1	3.3	1.3	5	
12	DEC Laser 1800	779	0	6	6.2	2.3	5.5	2.4	1.5	1	137
13	Epson A/L 1600	1,199	0	6	6.0	2.6	5.9	2.9	1.9	2	185
14	Sharp JX 9460 PS	849	0	6	6.0	2.5	6.3	2.6	0.7		158
15	Canon LBP 860	1,839	0	8	8.0	1.6	5.4	1.7	1.6	2	140
16	Itoh ProWriter CI8Xtra	1,799	0	8	7.1	2.0	5.3	1.8	1.4	4	161
17	Itoh ProWriter CI8Xtret	2,099	0	8	7.2	2.1	5.4	1.8	1.3	4	197
18	Itoh ProWriter CI-8XA	2,299	0	8	7.2	2.8	5.9	2.5	1.8	4	199
19	DEC Laser 5100	1,599	0	8	8.1	2.0	6.6	2.6	1.6	6	183
20	Lexmark WinWriter 600	1,199	0	8	9.0	2.3	5.6	2.1	1	2	158
21	Mannesmann Tally T9008	1,499	0	8	7.9	2.3	7.1	2.6	1.6	2	182
22	RMS Magicolor	9,999	1	8	6.8	1.4	5.4	2.0	0.9	12	294
23	Sharp JX9400H	599	0	8	8.0	1.2	5.5	1.0	0.9	1.5	145
24	Sharp JX5460PS	899	0	8	8.2	2.5	7.3	2.0	1.3	2	167
25	TI Microlaser Pro 600	1,599	0	8	3.6	3.1	3.1	2.3	1.6	6	123
26	Apple LaserWriter Select 360	1,599	0	10	7.2	2.2	3.6	2.0	1.7	7	190
27	HP Color Laser Jet	7,295	1	10	8.6	0.8	6.8	2.3	1.3	8	440
28	QMS 1060 Print System	2,699	0	10	9.7	3.0	8.7	3.0	2.0	8	240
29	Xerox 4510 PS	2,379	0	10	9.7	2.7	8.7	3.4	1.7	6	208
30	HP Laser Jet 4 Plus	1,829	0	12	11.5	2.9	9.7	3.3	1.8	2	287
31	HP Laser Jet 4M Plus	2,479	0	12	11.3	2.7	10.0	3.2	1.9	6	273
32	Lexmark 4039 12R Plus	1,749	0	12	10.7	2.7	8.8	3.4	1.9	2	202
33	Lexmark 4039 12L Plus	2,299	0	12	10.7	2.7	9.0	4.0	1.7	4	200
34	TI Microlaser Power Pro	1,899	0	12	12.1	4.4	7.0	1.6	1.9	6	213
35	Unisys AP 9312 Plus	1,895	0	12	11.1	2.7	9.1	3.5	1.5	2	265
36	Xerox 4900 Color Laser Printer	8,495	1	12	8.2	1.8	5.7	1.6	0.9	12	130

Appendix 5.2: Business Jets: Features and Prices (1993).

	Range	Payload	Cruise Speed	Mach	Climb Rate	Take-off Distance	Fuel Con-sumption	Cabin	Cargo	Noise	Cost per Mile	% Resale Value	Price (Millions)
Citation 550	1507	2.45	335	.71	3070	3450	.47	263	77	71.6	4.6	62	3.47
Learjet 31A	1577	1.80	424	.81	5100	3280	.528	268	40	81	5.1	51	4.78
Citation 560	1717	2.70	350	.75	3684	3160	.473	296	67	83.7	5.32	67	4.84
Learjet 35A	1924	2.98	424	.81	4340	4972	.428	268	40	83.7	5.31	52	4.92
Learjet 36A	2543	2.98	415	.81	4340	4972	.413	227	34	83.9	5.31	52	5.12
Beechjet 400A	1480	2.61	419	.78	4020	4290	.467	305	57	88.9	5.4	62	5.31
Astra SP	2727	2.77	412	.855	3700	5250	.422	365	53	82.3	7.20	69	7.54
Citation VI	1852	2.50	404	.835	3699	5030	.381	438	61	84.6	7.69	65	7.99
Learjet 60	2440	2.19	420	.81	4000	5560	.404	453	64	83	7.68	53	8.30
Citation VII	1808	2.30	409	.835	3921	4690	.351	438	61	77.1	8.09	65	8.95
Bae 800	2427	2.22	401	.800	3500	5600	.333	604	40	80.9	8.58	63	9.95
Bae 100	3095	2.70	402	.800	3577	6000	.352	675	45	81	10.35	77	12.90
Falcon 50	3071	3.64	410	.86	3430	4700	.278	845	115	84.3	12.73	75	14.75
Canadair 601-3A	3288	5.00	424	.85	4443	5400	.231	1415	115	79.4	12.9	76	16.95
Canadair 601 RJ	1973	12.20	424	.85	3210	6125	.172	2415	196	81	12.9	76	16.98
Canadair 601 3AER	3503	4.75	424	.85	4259	5875	.227	1415	115	79.8	12.9	76	17.39
Falcon 900	3845	3.56	430	.87	4000	4930	.264	1862	127	79.8	17.58	78	22.50
Gulfstream IV	4141	3.66	459	.88	4014	5280	.169	2008	169	76.8	18.28	90	25.00

Part II

Linking Innovation and Performance

6 The Relation between Perceived Innovation and Profitability: An Empirical Study of Israel's largest Firms[1]

Main Ideas in this Chapter

Innovation is understood as a chain-linked, non-sequential process in which research and development may be embarked upon at various stages. Therefore, there are various ways to measure innovation; there seems to be no single catch-all index. One approach is not to attempt to measure *actual* innovation but to assess the *perceived* innovativeness by trained business observers. This Chapter reports data on perceived innovativeness among the largest Israeli firms, measured by surveying a group of experienced managers. The posited links among innovativeness, sales revenue, the growth in sales revenue and profitability are examined statistically. It is found that perceived innovation is neither a cause nor an effect of growth in sales revenue, with some industries being notable exceptions. However, perceived innovation may be explained by the visibility of firms. Those firms whose shares are traded on U.S. stock exchanges are more frequently perceived as innovative.

6.1 Introduction

"When you see a successful business," Peter Drucker once wrote, "Then know that someone once made a courageous decision." Nearly always, those decisions involve bold change and innovation. There are numerous examples.

- When Robert Haas became ceo of Levi Strauss & Co. in 1984, he found a company in crisis, with dropping sales, bloated work force and excess production capacity. He quickly moved Levi's out of the 18-to-25 age group (the "baby bust" generation) and into the 25-and-over "aging baby-boomers". Between 1987 and 1990, Levi's added $ 1 billion in annual sales, and added $ 300 million in annual profit.

- In the same year Haas took over Levi's, Andy Grove met with Intel founder Gordon Moore. Together, they decided to dump Intel's DRAM (dynamic random access memory) chip business, and venture into newer products. Intel today is

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1 This Chapter was first published in *Technovation* 20, 2000. The research outlined in this Chapter was supported in part by a grant from the Technion Vice-President's (Research) Fund in addition to the GIF support.

America's 38th largest firm, with $ 25 billion in sales, a staggering $ 7 billion in profits (second in the Fortune 500 only to Exxon and GE), and a market value of its stock equal to General Motors and Ford combined.

- John D. Rockefeller dominated the oil business in the 1860's and 1870's, by dictating to the railroads the prices they could charge for shipping his oil. But in the late 1870's, oil pipelines began replacing trains. Rockefeller saw far ahead and built his own pipeline. By 1911, his wealth - $ 900 million - was fully 3 per cent of America's entire Gross Domestic Product.

- Sears, Roebuck head Robert Woods moved Sears out of the catalog business into retail stores in the 1920's, moved it from the cities to the suburbs in the 1940's, then to the booming Far West from the lagging East in the 1950's. The result: Sears dominated the retail market for decades (Slywotzky 1995 and Shapiro et al. 1999).

A basic principle that has prevailed for generations (Schumpeter 1911) is: Successful innovation generates "advances", i.e. profits, market share increase and sales growth. MBA students all know that, on average, more than 25 per cent of corporate profits accrue from only 10 per cent of company products - the innovative 10 per cent. Cooper (1993; see also Cooper and Kleinschmidt 1996) has demonstrated empirically the close link between innovation, growth and profitability.[2] Kim and Mauborgne (1997) observe that, in their five-year study of high-growth companies and low-growth ones, one key difference emerged: low-growth companies tried to stay ahead of their competition, while high-growth companies made their competition irrelevant by "value innovation".

How valid is the assumed link between innovation, on the one hand, and growth, market share and profitability, on the other, for an entire economy? This is not an easy issue to tackle empirically. The main difficulty lies in quantifying innovation. In principle, it is simple to measure sales revenue, sales growth, and profitability. But how can the degree of innovativeness prevailing in a company be measured?

In this Chapter, we chose to focus on Israel, a country famed for its high-tech industry and entrepreneurial energy. We decided to measure innovation subjectively, as "perceived innovativeness", by surveying experienced managers. Before describing the data (in Section 6.3), we begin with some conceptual considerations (in Section 6.2). The results are dicussed in Section 6.4 before we conclude (Section 6.5).

2 Cooper and Kleinschmidt (1996) is based on a study of 161 business units.

6.2 Theoretical framework

A review of the literature[3] on the innovation process reveals the following basic characteristics (Grupp 1998):

- the innovation stages are characterized by feedback,
- research and development (R&D) is not a unified whole but is divisible into various, specifically identifiable processes,
- the interplay between R&D and innovation processes should be regarded as functional,
- the time dimension is the key to understanding innovation; various stages (also named paradigms, cycles, phases) of innovation are an important aspect of the literature.

The functional reference scheme in Figure 6.1 meets the stated requirements and thus embodies the approaches and concepts known from the literature. The scheme can be characterized as a heuristic working model whose purpose is to structure the measurement issue. Depicted on the vertical axis are four idealized innovative stages, the premise being that the interfaces between them are not always clear cut. Under no circumstances can they always be expected to follow one another sequentially (Freeman and Soete 1997). Arranged at right angles to it are various types of R&D processes. Their basic role is to expand the knowledge stocks which are likewise an important source for innovation. Between them and the innovation stages numerous individually intangible functions may exist that couple the random fluctuations in the knowledge base in a "chain-linked" (Kline and Rosenberg 1986) way to innovation.

The function of R&D may be to provide new knowledge-based technology or the production of technically operational designs. It is true that not every technical design leads to a commercially viable innovation. Often a particular project "terminates" once certain prototypes have been constructed. While much technical design never reaches the commercial marketing stage, other designs lead to industrial product design and innovation.

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3 For a fuller list of references, see Grupp (1998), Kline and Rosenberg (1986) or Freeman and Soete (1997).

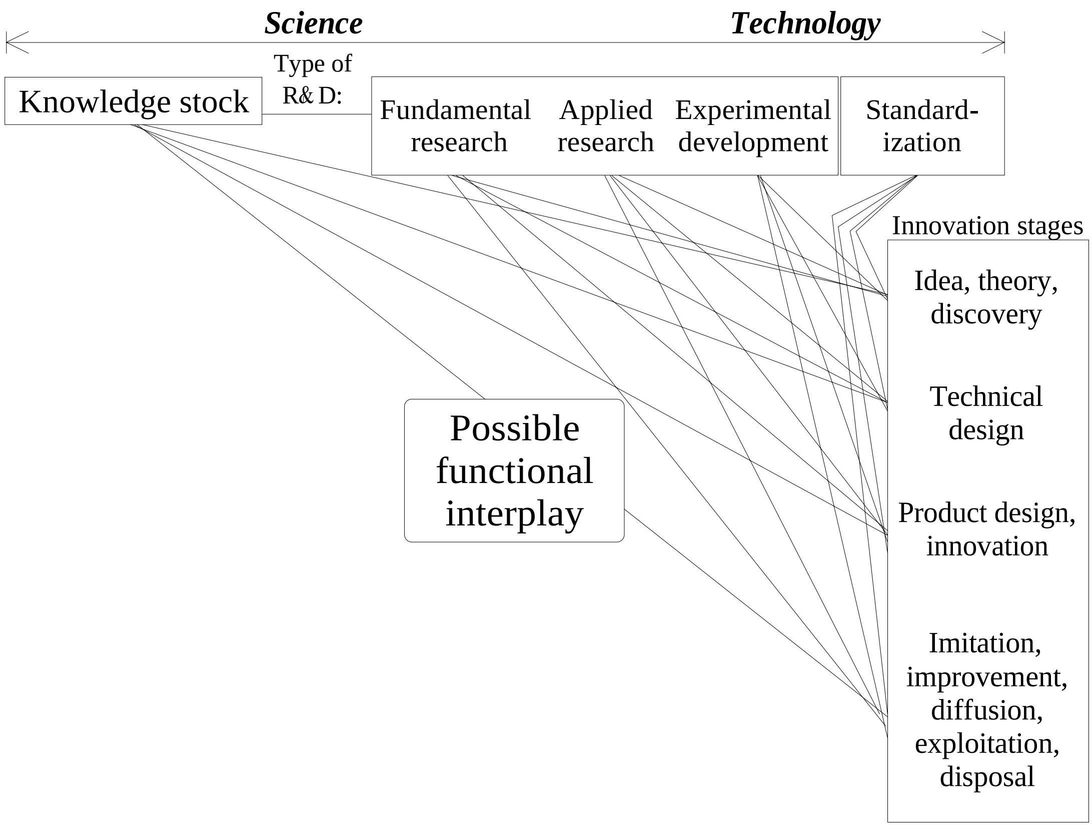

Figure 6.1: Reference scheme for chain-linked innovative functions.

Conceptual establishment of exploitation and disposal of new products as an innovation stage requiring R&D support as in Figure 6.1 may appear unacceptable in the microeconomics and management literature of the past. So, some explanation of this stage is necessary. To economists, R&D processes only come under scrutiny if and insofar as their results are actually marketed, that is, become innovations. The economic importance of innovations is clearly greater, the more pervasive they become, which is essentially a matter of dissemination. From the macroeconomic standpoint, at any rate, the *diffusion* of innovations is thus more important than the initial innovation *process*. With all the significance supply factors have in the emergence of innovations, ultimately utilization alone, that is, utility, determines the scope for diffusion. In addition, escalating environmental problems will orient innovation processes towards the utilization and disposal areas.

Despite all the differences discussed in the innovation-oriented stages and types of R&D shown in Figure 6.1, they have much in common. All stages of knowledge-based, technological innovation are brought about by scientifically or technically trained people, and as such are inextricably linked to the supply of knowledge and hence to the education and training system. On the other hand, potentially all types of R&D are required to generate innovations whether these relate to fundamental research, applied research or experimental development. In the functional reference scheme, R&D is regarded as a kind of problem-solving in which innovation processes can become involved at any time. A company has an internal knowledge base which it scans for solutions to problems that inevitably materialize during the gestation of innovations. Some innovations can be organized from the stocks of knowledge and need no R&D input. The science and technology system tackles long-term problems which cannot be solved via the company's internal knowledge base and actually helps to broaden this knowledge base. Transactional processes are taking place between the company's internal R&D area and public institutes which are not always easily arranged.

From the structure of the theoretical reference diagram (see Figure 6.1) it becomes clear how important it is to differentiate between R&D activities and innovation stages. Input indicators are subsets of innovation indicators accounting for resources. Some resources will be wasted. It is therefore important to comprehend output-oriented indices relating to R&D processes as a specific subset and to call them "R&D results" indicators. What is known in the literature as "byput" or "throughput" (Freeman and Soete 1997) - because these measure "attendant" or "partial" effects of technical progress - is thus regarded as the *result* of R&D activities and not always as a prerequisite for innovation. It is also not always sufficient for this purpose. The output-oriented measurement processes which seek to cover economically relevant innovation effects, are the "economic" indicators and should be called "progress" indicators. Progress indicators derive from quantity or value-related or even quality modifying effects on production, but not from achievements in R&D alone.

"Resource indicators" should be regarded as a generic term embracing every possible means for measuring personnel, monetary, investive and other expenditure on research, development and innovation. These include for instance R&D outlays, R&D personnel statistics, investment statistics, the royalties paid and many more besides. Amongst the R&D results indicators should be all results from research, development and standardization in the direct sense, that is, irrespective of whether or not they are important for the success of innovation, market launch, and so on. The most important result indicators come from publication, patent or standards statistics and their citations. Progress indicators relate not to detailed R&D activities but to the characteristics and micro- or macroeconomic effects of innovation. Progress indicators commonly encountered in the literature as those relating to the innovation counts recorded in corporate questionnaires, measurement of high technology markets or calculation of total factor productivities and other macro- and foreign trade indicators. A relatively new concept consists in analyzing statistics on product performance and its improvement.[4]

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4 These concepts are known as "technometrics" (Grupp 1994).

Figure 6.2 shows schematically the posited links among innovation, sales revenue growth, market share and profitability. It is widely believed, and taught, that successful innovation leads to rising sales revenue (1) and higher market share (2). Market share, in turn, is a key variable in the rate of return on investment, or in profit margins (3). Higher profitability drives or simply finances even more innovation inputs and so on (4). The link between market share and profitability is often mediated by the learning curve, which shows how average variable costs decline rapidly with higher cumulative output.

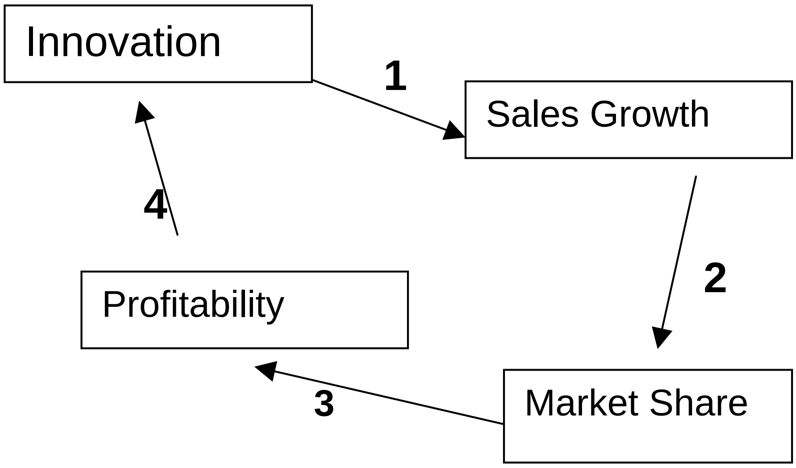

Figure 6.2: Innovation, sales revenue, growth and profitability.

This model can easily be made more complicated, and more realistic. Innovation can generate large sales revenues, in absolute terms, which in turn affect profitability through economies of scale and monopoly effects. However, there may be negative, as well as positive, feedback loop effects. As they become larger, companies may become less innovative and less entrepreneurial. Higher profitability may encourage complacency. The positive feedback loop described in Figure 6.2 can change its direction in a remarkably short period of time - witness IBM's U-turn in profits, between 1990's record year and 1992's record losses. Now, in 1999, IBM again is running near-record profits.

The dynamics of Figure 6.2 could be explored through system dynamics However, we chose to examine the innovation-growth-profitability linkages empirically by quantifying each of the variables in the four boxes and examining the links among them by statistical regression. The difficult part, of course, was measuring innovation.

There have been numerous attempts to measure a company's degree of innovation. A product-based measure of innovation, known as "technometrics" (Grupp 1994) would be desirable. But data on product specifications are available only for rare case studies.[5] In most industrialized countries, R&D input statistics and questionnaire-based innovation output statistics for businesses are available - not so in Israel. Patent statistics as a somewhat "hard" and established indicator would be a good choice for Israeli companies, but would cover manufacturing companies only, not banks and other service firms as in our sample.

In this study we chose to measure innovation subjectively, by surveying experienced managers and asking them to grade each of the largest firms on an innovativeness scale. The advantage of this approach is that it permits a very broad definition of innovation, which includes not only process and product innovation (traditionally the focus of empirical studies of innovation and innovation metrics) but also innovativeness in marketing, distribution, human resources management and globalization. "Perceived" innovativeness, as we term the indicator, need not to be related significantly to actual innovation performance. The precision of this relation cannot be checked for the time being, given the poor innovation database on Israeli firms.

6.3 Data

We asked participants in Technion's[6] MBA program - mainly engineers, aged 30-40, working in leading high-tech firms in the greater Haifa area - to grade each of Israel's 73 largest firms, according to their "degree of innovativeness", where innovativeness was explained to apply in a general sense to the firm's new products, services and processes; improvement of existing products; marketing, advertising and overall business strategy. Innovativeness was rated as "high" (=3), "moderate" (=2) or "low" (=1). *Respondents were asked not to grade firms with which they were not sufficiently familiar to provide an informed estimate*. The result was a measure of "perceived innovativeness", according to the 47 respondents (about a 60 % response rate), for 50 publicly-owned industrial firms, eight non-traded firms, five holding companies, five banks, and five real estate firms and contractors - a total of 73 firms in all.

Data on 1997 Sales Revenues, annual % change in sales during 1997, Profit as % of Sales in 1997, and Assets were obtained, for those 73 companies, from The Jerusalem Report's first annual ranking of Israeli companies, compiled together with Solid Financial Markets of Tel Aviv and New York (Sher 1998). For 23 of the firms (mainly, the non-industrial ones) only limited data were available. (See Appendix 6.1 for the data).

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5 See, for the example of Israel Frenkel et al. (1994). This article is reproduced in Chapter 11.

6 Technion – Israel Institute of Technology, Haifa, Israel.

In addition we tried to add some "hard" evidence; we checked which Israeli top companies are listed on U.S. Stock Exchanges and for those companies, gathered data on the companies' stock price (in U.S. dollars) for January 7th, 1999, together with the lowest and highest stock price in 1998.

Because of the subjectivity of the "perceived" innovation measure, advertising strategy, visibility and information policy may influence the innovation measure. In order to check this, we constructed two dummy variables: No stock listed (on U.S. exchanges) and No profit data (in Israel) for those firms either *not listed* on U.S. stock exchanges or which *do not publish* their profits, respectively. Because of the close links of Israeli firms with the U.S. (for historical and geopolitical reasons), the U.S. stock listings are a good indicator of visibility. Generally, Israeli firms able to do so list their stocks in the U.S. as a way to generate liquidity and raise new funds.

Further dummy variables are introduced to control for the various industries: chemical firms (11 enterprises), electrical and electronics firms (15), other manufacturing firms (17) and service firms (20). The remaining ten firms are pure trade houses (export-import firms) or holdings.

It must be stressed here that the firm sample is not a random sample nor representative of Israeli business firms. It is the top part of Israeli businesses as measured by size, and hence represents the majority of Israel's business activity.

6.4 Results

We first proposed to check whether the perceived innovativeness of Israeli enterprises simply reflects what business analysts read in the newspaper: stock ratings. To test for this, we regressed the innovation index on the stock prices (in U.S. $) as of January, 7th, 1999, and on the 1998 minimum and the 1998 maximum prices. All three regressions are positive, but, judging from heteroskedasticity-robust errors, largely insignificant (error probability being between 22 % and 46 %). We can, thus, test for more complex explanations of perceived innovation.

Table 6.1 summarizes the results of the weighted statistical regressions using the inverse standard deviation of the innovation index as analytic weights.[7] Our main finding: While innovation may be the main driver of business success for a part of Israeli industry - technology-based firms - for the mainstream part of Israeli industry, *there is no clear link between innovation, as a cause, and economic*

7 The calculations were done using STATA 6 software. The reason to use weights is the subjective character of the innovation index. If standard deviation is large, we assume dissenting votes of the respondents and attribute lower weights to the respective firms.

success, as a result - nor between economic success as a cause and innovation as a result. Here are the detailed results.

- Innovation: There is no statistical link between the degree of perceived innovativeness and the change in sales revenues (1997 vs. 1996) (see Table 6.1, columns 2 and 3). Agan Industries, a chemicals firm, with $ 370 m. in annual sales, showed 46 % growth in 1997, but was rated far below average in innovativeness - 62nd out of 73 firms. Scitex, in contrast, a high-tech firm that makes pre-print products, rated 7th highest in innovativeness, but its 1997 sales actually declined. Nor is there any link between innovativeness and firm size, as measured by sales revenues. The scatter appears virtually random. Among the ten largest firms in sales revenues, five scored well above average in innovativeness (Bezeq, Teva, Tadiran, ECI and Scitex), and five scored well below average (Israel Chemicals, Blue Square, Supersol, Makhteshim, Delek).[8] This is true for those 50 out of 73 firms that publish data on sales changes. For the full sample (Table 6.1, column 3), findings are not any different.

- Significant explanations of perceived innovativeness originate from the branch structure (Table 6.1, columns 2, 3 and 4). Electrical and electronic industry is rated highly innovative, followed by chemical industry (including plastics and pharmaceuticals). Other manufacturing industry is naturally quite heterogeneous (food, drink, tobacco, metals, construction products, textiles, paper etc.) and includes some innovative firms. Service companies are definitely not innovative. The "hierarchy" in branch innovativeness is also visible from Figure 6.3. Most electronic firms are positioned in the upper part of Figure 6.3; the chemical ones are somewhat lower, but in general are recognizable above services.

- Otherwise, Figure 6.3 represents the relation between profits and perceived innovativeness. One notes that, overall, the relation is positively significant (Table 6.1, column 1) in the multiple regression without branch structure. If we control by branches (Table 6.1, column 2), however, the profits variable loses significance as the branch disparities explain the different levels of innovativeness.

- An interesting feature is the differentiation between firms that are listed on the U.S. stock exchanges and those that are less visible in the large U.S. market. The listed firms are more frequently perceived as innovative than the less visible ones; this effect is highly significant, statistically. This does not mean that our respondents derive their assessment from the stock price (the respective tests are negative; see above) but it points to the central role of the information policy of

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8 Part of the reason for these results may be the focus on a single somewhat atypical year, 1997 - a year of recession for Israel. In that year, GDP grew only 2.7 per cent and unemployment rose to 7.7 per cent of the labor force.

firms. Firms that are visible all over the world, and disseminate easily accessible and repeated information on their business development including new products are assumed to be more aggressive and more innovative. This was recently found for a large sample of German firms (Schalk and Taeger 1998, p. 247). If we take the stock listings as one important proxy of information available to everybody, it comes as no surprise that non-listed firms are perceived as less innovative whatever their actual innovation performance may be.

Table 6.1: Statistical regression results: Weighted heteroskedasticity-robust Ordinary Least Squares (t values in brackets).

	(1)	(2)	(3)	(4)	(5)
Dependent:	Innovativeness	Innovativeness	Innovativeness	% change, sales	Profit %
constant	1.484*** (14.63)	1.757*** (9.30)	1.930*** (10.36)	14.649 (0.70)	4.518 (0.86)
Innovativeness	--	--	--	-1.214 (-0.12)	1.627 (0.59)
Sales Revenues	0.0002 (0.70)	0.0001 (0.71)	-0.00004 (-0.63)	--	--
% change in Sales	-0.001 (-0.23)	-0.002 (-0.42)	--	--	--
Profit %	0.033** (2.15)	0.009 (0.93)	--	--	--
Assets	0.0001 (0.85)	-0.00001 (-1.08)	0.000004 (1.10)	0.00003 (1.29)	-0.0021** (-2.46)
Industries					
Electrical	--	0.593*** (3.56)	0.921*** (7.20)	-0.707 (-0.06)	0.177 (0.04)
Chemical	--	0.313** (2.11)	0.335 (2.03)	17.805* (1.74)	4.411 (1.07)
Services	--	0.008 (0.06)	1.647 (1.65)	-0.159 (-0.02)	-0.553 (-0.15)
Other Mfg.	--	0.243* (1.75)*	0.180 (1.43)	-0.974 (-0.12)	-1.624 (-0.42)
No stocks	--	-0.473*** (-3.00)	-0.309* (-1.822)	-12.287 (-1.51)	-3.254 (-1.58)
No profit data	--	--	0.323** (2.63)	--	--
N	50	50	73	55	50
R^2 (adj)	0.19	0.73	0.64	0.24	0.29

* Weakly significant at the 10 % level.
** Significant at the 5 % level.
*** Highly significant at the 1 % level.

- Profitability and growth: There seems to be a somewhat stronger link between innovativeness and the rate of profit on sales for 1997 for top firms (Table 6.2). Six of the eight most profitable firms score above average or well above average in innovativeness. ECI, the second-most innovative firm, has the highest profit rate, at 19.5 %, with Orbotech (six-highest in innovativeness) close behind at 18.1 %, and Teva, fourth in innovativeness, with a 9.1 % profit rate. However, Israeli Petrochemicals, Feuchtwanger, and Elco Industries all scored below-average in innovativeness but had high profit rates. For the whole sample, there is no significant relation (Table 6.1, column 5). The only significant relation is the negative influence of large assets on profits. Growth of sales can neither be explained by innovation in the actual year (Table 6.1, column 4).

- Innovation and High-tech: Expectedly, nine of the ten most innovative firms came from technology-driven areas: Intel, ECI, Motorola, Teva, El, Orbotech, Scitex, Elbit Systems, and Elscint. Intel leads the list of all 73 companies in innovativeness, with a remarkable score of 2.94, implying that nearly every respondent gave Intel a score of 3.0. Close behind is Motorola. The only non-high-tech firm to make it into the Top Innovative Ten was the First International Bank (see Table 6.2). The "electronics" industry dummy as a statistically significant variable in predicting innovativeness catches this effect of the top electronic firms listed in Table 6.2.

Table 6.2: Ten Most Innovative Firms: Israel 1997-8.

COMPANY	1998 innovation index	% rate of profit	% change in sales	std. dev. of inno-vation	1997 sales $ m	assets $ m
Intel	2.94	--	--	0.24	363	363
ECI	2.87	19.5	15.1	0.34	677	869
Motorola	2.77	--	--	0.50	946	946
Teva	2.64	9.1	17.1	0.53	1116	1188
Elbit Medical	2.64	1.0	-6.1	0.53	493	540
Orbotech	2.57	18.1	28.7	0.60	191	190
Scitex	2.51	0.1	-2.8	0.54	675	669
Elbit Systems	2.46	6.0	21.1	0.55	372	321
First Int. Bank	2.33	9.0	13.5	0.73	143	11178
Elscint	2.31	0.2	-2.7	0.56	303	357

- Innovation in service firms: Remarkably, all but one bank - Israel Discount - scored above average in the respondents' perception of innovativeness, although the service industry dummy points to the low or no innovation situation of this sector of the economy. The reason is that the other service firms are less innovative. Israel Electric rates below average in innovativeness - perhaps not surprising, considering that this company is a government-sanctioned monopoly. Among the Real Estate and Contractor firms only Dankner scores average in innovativeness; the remaining five firms were perceived to be at below-average innovativeness. A surprising position, ranked by innovativeness, is taken by Tnuva, once a hide-bound dinosaur that has been completely revitalized by new management. Three of the five holding companies ("other") in the sample scored below average in innovativeness: Elco, Clal and the Israel Corp. Only Koor and IDB scored slightly above average.

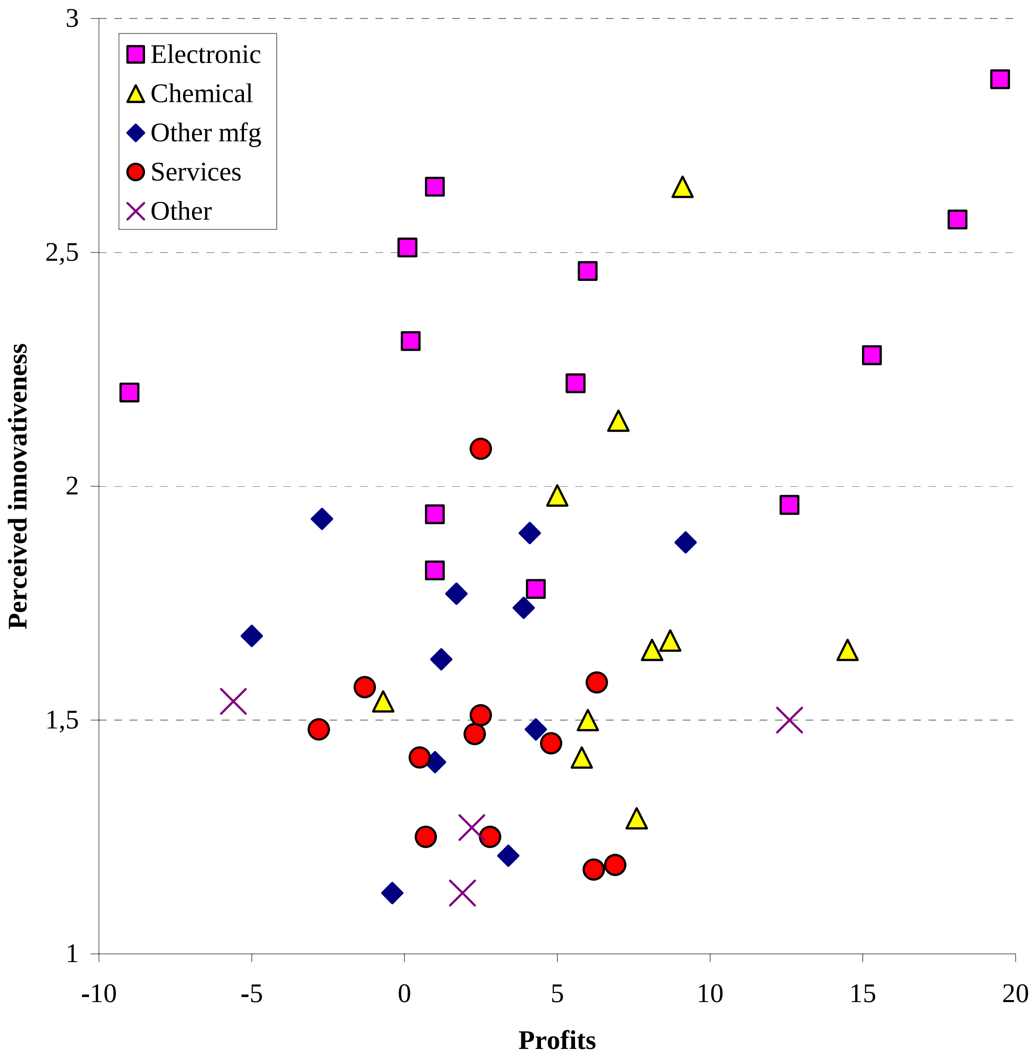

Figure 6.3: *Relation between profits and perceived innovativeness by Israeli industries.*

- Another interesting observation relates to the fact that 23 firms do not disclose their profitability data on the Tel Aviv Stock exchange, although sales, assets, and, for five of these, sales changes are published. From this we created a "no profit data" variable. The companies not disclosing profits are significantly perceived as more innovative than the others. How can we explain this? We are well aware that these data may be subject to the vagaries of accounting procedures (van Reenen, 1996, p. 205). On the other hand, a favourable profit-turnover ratio (or net operating margin) is always an indication of competitiveness (Hanusch and Hierl 1992). So why not publish it? We offer two explanations: First, for the accounting systems, R&D and innovation expenditures are costs and thus directly diminish the operating result. Secondly, R&D projects are risky and some are not successful. If we assume that profits are negative or low for some highly innovative and risky high-tech firms they may decide to hide this information. Also Israeli subsidiaries of very innovative international trusts may prefer not to publish local profits in Israel which may be fed strategically into the consolidated balance sheet. The indications that for some companies a negative relation between innovation and profits may be the case may be disappointing, but we are concerned here with short-term profits - our findings contribute nothing to medium-term growth and they relate to individual firms not disclosing their profits, not to welfare effects of industry branches, spillover or the whole economy springing out of innovation. For most of the firms we confirmed a positive relation of perceived innovativeness and short-term profits (Figure 6.3).

6.5 Conclusion

While the innovative, globally-competitive high-tech companies attract headlines, a large part of Israel's business sector remains strategically conservative. This will likely continue, as long as profits, sales and sales growth are not associated by senior managers with change and innovation, and as long as large parts of Israeli industry enjoy a monopoly or semi-monopoly position. This is reflected in the World Competitiveness Index of the Swiss business school IMD, which ranks Israel only 25^{th} (out of 47 countries), despite Israel's strong high-tech sector.

From the methodology perspective, on our agenda is research to validate and cross-check subjective measures of perceived innovation with some "harder", i.e., well established indices. For reasons given above, this is not possible at the moment for Israeli firms. We do hope that Israel will ultimately establish a better statistical base for innovation studies, like that of the OECD countries. To study the dynamic, real growth effects, it would also be required to study time series instead of cross-section data, which are, a fortiori, not yet available.

We anticipate that when this study is done again ten years from now, the results will show significantly tighter links between business performance and innovation. As Israeli capital, goods and labor markets become more closely integrated with world markets, and as the flow of goods, services, labor, capital and technology to and from Israel increases, the established connection between innovation and performance shown to be true in truly competitive markets abroad will become true in Israel as well. This connection clearly exists for the electronics industry. As Israel globalizes and other sectors become open to global competition (for instance, the banking sector), we should find that the feedback loop shown in Figure 6.2 will become operative and powerful.

The principle that innovation is vital for building profits and growth, taught in Israeli business schools, is only slightly ahead of its time.

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Appendix 6.1: Data Tables.

COMPANY	innovation index	std. dev. of innovation	1997 sales $ million	% change in sales 97 vs. 96	profit as % of sales	assets $ million	Branch*
Intel	2.94	0.24	363	--	--	363	E
ECI	2.87	0.34	677	15.1	19.5	869	E
Motorola	2.77	0.50	946	--	--	946	E
Teva	2.64	0.53	1116	17.1	9.1	1188	C
Elbit Medical	2.64	0.53	493	-6.1	1.0	540	E
Orbotech	2.57	0.60	191	28.7	18.1	190	E
Scitex	2.51	0.54	675	-2.8	0.1	669	E
Elbit Systems	2.46	0.55	372	21.1	6.0	321	E
First Int. Bank	2.33	0.73	143	13.5	--	11178	S
Elscint	2.31	0.56	303	-2.7	0.2	357	E
Tower Semic.	2.28	0.60	126	28.6	15.3	218	E
Tadiran	2.22	0.59	1112	-0.4	5.6	930	E
Tnuva	2.21	0.65	895	--	--	895	S
Bezeq	2.20	0.65	2467	-1.6	-9.0	4837	E
Agis Indust.	2.14	0.69	236	14.2	7.0	283	C
Home Center	2.08	0.82	129	56.6	2.5	65	S
Israel Aircraft	2.04	0.77	1467	--	--	1466	M
Tambour	1.98	0.73	179	-0.6	5.0	186	C
Bank Leumi	1.97	0.64	703	10.0	--	41029	S
Formula Systems	1.96	0.69	153	41.8	12.6	192	E
Koor Indust.	1.95	0.79	3565	--	--	3565	O
Tadiran Appl.	1.94	0.65	151	-15.4	1.0	96	E
IDB Holding	1.94	0.77	684	--	--	684	S
Elite	1.93	0.62	537	-12.4	-2.7	342	M
Israel Military Ind.	1.93	0.77	509	--	--	509	M
Osem	1.90	0.71	446	12.1	4.1	364	M
Elco Indust.	1.88	0.55	119	-15.4	9.2	95	M
Bank HaPoalim	1.87	0.73	843	18.6	--	45312	S
Bank Mizrahi	1.84	0.85	180	5.2	--	12132	S
Electra	1.82	0.67	297	-14.9	1.0	210	E
Electra (Israel)	1.78	0.71	240	10.4	4.3	160	E
Tzamancal	1.77	0.83	133	8.0	1.7	57	M
Dankner	1.77	0.69	152	--	--	152	O
Elco Holdings	1.75	0.58	861	--	--	861	O
Delta-Galil	1.74	0.78	319	8.0	3.9	205	M
Israel Electric	1.73	0.63	2167	--	--	2167	S
Israel Discount Bank	1.71	0.53	306	5.7	--	23662	S
Kitan	1.68	0.61	204	-5.8	-5.0	192	M

Dead Sea Works	1.67	0.75	453	26.7	8.7	984	C
Malibu	1.67	0.77	199	--	--	199	M
Dead Sea Bromine	1.65	0.78	493	7.2	8.1	604	C
Israel Petrochemical	1.65	0.69	150	13.3	14.5	249	C
Azorim	1.65	0.81	323	--	--	323	M
Clal (Israel)	1.64	0.66	1238	--	--	1238	O
Polgat	1.63	0.62	181	0.1	1.2	144	M
Maa-ariv	1.58	0.65	125	4.1	6.3	161	S
Dan Hotels	1.57	0.73	131	-.9	-1.3	279	S
Clal Trading	1.54	0.51	289	-20.0	-5.6	267	O
Electrochemical Ind.	1.54	0.52	132	17.8	-0.7	162	C
Solel Boneh	1.52	0.70	568	--	--	568	M
Supersol	1.51	0.60	1269	21.7	2.5	784	S
Israel Chemicals	1.50	0.64	1685	3.0	6.0	3126	C
Feuchtwanger	1.50	0.71	137	7.4	12.6	103	O
Shekem	1.48	0.63	224	-34.6	-2.8	185	S
Jaf-Ora	1.48	0.65	127	-1.3	4.3	86	M
Blue Square	1.47	0.50	1392	12.0	2.3	752	S
Knafaim-Arkia	1.45	0.55	189	6.1	4.8	281	S
Makhteshim	1.42	0.50	740	35.3	5.8	943	C
Israel Lighterage	1.42	0.66	156	-10.7	0.5	173	S
Tempo	1.41	0.59	157	10.1	1.0	120	M
Tashloz	1.36	0.50	164	--	--	164	O
Israel Corp.	1.33	0.49	971	--	--	971	O
Agan	1.29	0.47	370	46.0	7.6	422	C
Dorban Inv.	1.27	0.47	209	17.0	2.2	187	O
Granite HaCarmel	1.25	0.55	520	-3.4	2.8	499	S
Israel Cold Storage	1.25	0.45	155	-10.8	0.7	174	S
Amer-Israel Paper	1.21	0.41	347	2.4	3.4	242	M
Delek Auto	1.19	0.40	372	-3.4	6.9	98	S
Oil Refineries	1.19	0.51	2063	--	--	2063	C
Delek	1.18	0.38	652	-4.9	6.2	653	S
Nesher	1.14	0.36	535	--	--	535	M
Israel land Deve.	1.13	0.35	228	0.0	1.9	761	O
Israel Steel	1.13	0.45	137	-4.1	-0.4	139	M

Branches: E – electrical and electronic, C – chemical, M – other mfg., S = service, O – other

7 Total Factor Productivity as a Performance Benchmark for Firms: Theory and Evidence[1]

Main Ideas in this Chapter

In this Chapter, we propose using Solow's macroeconomic approach and the concept of Total Factor Productivity (TFP) as a microeconomic tool for analyzing individual firms. TFP long used in analyzing macroeconomic growth among countries, is a useful strategic performance benchmark for individual firms. TFP calculations permit managers and investors to partition labor productivity growth between two sharply different underlying causes: capital-deepening (higher capital per worker), and exogenous technological change. The TFP benchmark can be computed from readily-available information in financial statements. The structure of the Chapter is as follows. Section 7.2 presents a simple version of Solow's model, suitable for use in individual firms, and provides a numerical example. Section 7.3 gives detailed total factor productivity calculations for the 20 largest firms in the world. Section 7.4 provides three case studies of total factor productivity growth, for Intel, YPF (Argentina's largest energy company) and Merck. The final Section summarizes and concludes.

7.1 Introduction

It is widely accepted that productivity is a key performance benchmark for firms. Rising productivity is related to increased profitability, lower costs and sustained competitiveness. The most widely-used productivity indicator for firms is labor productivity – units of output, or value added, per employee. However, this measure has serious shortcomings. The main one: It fails to show why labor productivity has risen.

Consider, for instance, productivity among banks. Value added per worker among U.S. banks rose by 3.5 per cent annually, in the 1990's. In contrast, overall labor productivity in the U.S. economy rose by less than half that rate. Why did labor productivity in banks outpace that in the overall economy? Was it because of massive investments in information technology, as some believe? Or because of

[1] Research for this Chapter was supported by a grant from the German-Israel Foundation. This Chapter was written while the second author was a Visiting Professor at the MIT - Center for Advanced Educational Services and MIT Sloan School of Management. We also acknowledge partial support from the Technion Vice-President's Fund for Research. This Chapter is an original contribution to this volume not published elsewhere.

economies of scale (in part due to mergers, downsizing and improved efficiency). The 3.5 % labor productivity figure itself offers no clue. Clearly, for a particular bank, benchmarking its productivity performance in a way that leads to strategic managerial interventions is vital. Labor productivity is not in itself sufficient.

A possible solution lies in the macroeconomic research of Solow. Solow (1957, 1969) found that a majority of nations' economic growth was attributable to technical change, or "total factor productivity growth", which he proposed measuring as a "residual", based on a so-called "production function approach". This "production function approach" has been extensively used to measure the rate of return to net investment in R&D for firm or line-of-business level data (Mansfield, 1965; Clark and Griliches, 1984; Link, 1981; Griliches, 1986) and industry aggregates (Terleckyj, 1974; Griliches, 1979, 1994; Griliches and Lichtenberg, 1984; Scherer, 1982).

In this Chapter, we propose using Solow's macroeconomic approach and the concept of total factor productivity as a microeconomic tool for analyzing and partitioning labor productivity change in individual firms. The result is insightful because it shows whether companies' labor productivity gains are driven principally by capital investment, or whether they are driven by technology and knowledge. For outside observers and analysts, TFP can be estimated using publicly-available information contained mainly in balance sheets and pro-forma income statements. Within firms, confidential data can be used to build disaggregated measures of total factor productivity and its rate of change, for individual business units or subsidiaries.

We will argue that total factor productivity, a powerful tool in the armoury of macroeconomists, should also be added to the day-to-day toolbox of senior managers and investment analysts, keen to benchmark productivity change within the firm in an operational manner.

7.2 Theory

In his classic 1957 paper, Robert Solow showed how technical progress could be measured by using a production function. In his method, the change in labor productivity was caused by two separate factors: a) capital deepening, i.e. a rise in the amount of capital per unit of labor, and b) exogenous "technical change", i.e. improvements in knowledge, methods, etc. While (b) could not be directly measured, it could be inferred as a residual, by subtracting the contribution of "capital deepening" from the overall change in labor productivity. This method was widely applied to analysis of countries and industries.

In this Chapter, we argue that Solow's method can be equally useful for benchmarking productivity change within individual firms. For countries, aggregate value added is simply Gross Domestic Product (GDP). For firms, value added is the difference between sales revenue and the cost of material inputs.

Value added per employee for firms, as for countries, grows either because a) capital investment makes workers more productive, or b) better methods, technology, methods, incentives, motivation, etc., makes workers more productive without additional capital investment. It is vitally important for managers, investors and for stockholders to know why labor productivity (value added per employee) has risen, or why it has not.

Solow has shown that countries grew wealthy mainly through factor (b). If this is true, it must therefore be the case that for such wealthy countries, a significant number of the firms in these countries also have significant increases in factor (b).

To adapt Solow's measure of technical progress to the individual firm, define "total factor productivity" as total value added divided by a "representative bundle" of labor and capital – a geometric average of labor and capital, with the exponential weights reflecting the contributions of labor and capital to overall value added:[2]

Terminology

TFP = total factor productivity
VA = value added ($): Sales revenue minus cost of materials
K = capital (generally, shareholders' equity, which is "net assets", or gross assets, taken from the balance sheet)
L = number of employees, or total annual labor hours
α = fraction of value added attributable to labor, equal to [L VMP_L]/VA, where VMP_L is the value of the marginal product of labor
$1 - \alpha$ = fraction of value added attributable to capital, equal to [K VMP_K]/VA, where VMP_K is the value of the marginal product of capital.

Model

$$TFP = VA / [L^{\alpha} K^{1-\alpha}] \tag{7.1}$$

Equation (7.1) simply states that total factor productivity is defined as value added per "basket" of labor and capital, where the basket is the geometric mean of Labor

2 Craig and Harris (1973) develop a measure they called Total Productivity by using the algebraic sum of the value of factor inputs (capital, labor and materials) as the denominator. This approach, however, does not take into account differences in the relative importance, or marginal productivity, of labor and capital and treats them unrealistically as equal.

(L) and Capital (K), weighted by their respective importance or contribution to output, as measured by α and 1-α.

Dividing by L yields

$$TFP = [VA/L] / [(K/L)^{1-\alpha}] \qquad (7.2)$$

Total Factor Productivity is now seen as value added per worker, divided by an exponential function of capital per worker. The exponential function in the denominator represents the part of labor productivity (VA/L) generated by capital intensity K/L.[3]

Taking logarithms of both sides provides the form

$$\log TFP = \log [VA/L] - (1-\alpha)\log [K/L] \qquad (7.3)$$

Derivating with respect to time (d/dt) finally gives

$$d\log TFP/dt = d\log [VA/L]/dt - (1-\alpha)\, d\log[K/L]/dt \qquad (7.4)$$

Since 100 dlogx/dt equals 100 [dx/dt]/x, i.e. the % change over time in x, (7.4) can be expressed as

% change in TFP = % change in Value Added per employee
- (1 - α) (% change in capital per employee). (7.5)

Equation (7.5) is the key tool for TFP benchmarking. In terms of the Solow (1957) paper, (7.5) states that whatever part of the change in labor productivity is not attributable to capital deepening (higher capital per employee), must be caused by exogenous non-capital factors like better management, knowledge, motivation, etc. Therefore, the change in Total Factor Productivity, when computed for individual firms, partitions the underlying factors that drive labor productivity between expensive capital-deepening and inexpensive "free lunch" technological change factors. It is of course understood that technological change is often embodied in capital equipment; this fierce debate, about the "embodiedness" of technical change, is the subject of a large number of studies, and will not be addressed here.[4]

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3 To see this: Let VA/L = F[(K/L, A(t)], where A(t) is exogenous technological change, not associated with physical capital K. Assuming certain properties for F( ) permits us to write this expression as: VA/L = A(t) F(K/L). Finally, assuming a Cobb-Douglas (exponential) function form for the production function yields: $VA/L = A(t)\,(K/L)^{1-\alpha}$. It is therefore true that $A(t) = [VA/L] / [(K/L)^{1-\alpha}]$, which is precisely equation [2].

4 See Grupp and Schwitalla (1998) for a recent treatment.

Numerical Illustration

Consider two firms. Each has experienced a 20 per cent rise in net after tax profits in 1999 (see Table 7.1). A deeper analysis is required, to understand why profits rose. Data are collected on operating profits, value added, shareholders' equity (net capital, or assets minus liabilities) and number of employees.

Table 7.1: A numerical illustration.

	Firm 1		Firm 2	
	1998	1999	1998	1999
Value Added ($ million)	100	110	100	110
Capital ($ million)	40	45	40	40
Labor (persons)	1,000	1,000	1,000	1,200
NOPAT* ($ million)	10	12	10	12

* NOPAT = net operating profit after tax

Table 7.2: Partial measures of productivity and profitability.

	Firm 1			Firm 2		
	1998	1999	% change	1998	1999	% change
Economic Value Added*	$2 m.	$3 m.		$2 m.	$4 m.	-
EVA as % of Capital	5 %	6.7 %		5 %	10 %	-
Labor Productivity**($000)	100	110	+10 %	100	92	-8 %
Capital Productivity*** ($)	2.5	2.44	-6.1 %	2.5	2.75	+ 10 %

* Economic Value Added (EVA) = NOPAT minus the opportunity cost of capital. Here, we assume that shareholders can earn 20 % on their investment in equally-risky alternatives; hence EVA = NOPAT - (0.2) (Capital)

** Labor Productivity = Value added per employee

*** Capital Productivity = Value added per dollar of capital

These data permit calculation of standard, partial measures of productivity (see Table 7.2). Such measures reveal

a) Firm 1 enjoyed a 10 % rise in labor productivity in 1999, while Firm 2 had an 8 per cent *drop* in labor productivity.
b) Firm 1 suffered a 6 % drop in capital productivity, while Firm 2 had a 10 % increase in capital productivity.

Evidently, this results from Firm 1 maintaining its labor force unchanged while increasing capital investment; while Firm 2 kept its capital investment constant, while boosting its labor force by 20 %.

Moreover,

c) Firm 1 increased its economic value added as a % of shareholders' equity from 5 % to 6.7 %, but Firm 2 raised the same measure to 10 %.

While all three of these benchmarking measures have value, what is missing is an overall summary statistic showing what part of labor productivity gains were due to what may be termed an "economic free lunch" (not related to capital investment), and what part were due to relatively costly (though doubtless necessary) capital investments, i.e. equation (7.3). This is computed in Table 7.3.

Table 7.3: Per cent change in total factor productivity.

	Firm 1	Firm 2
% change in value added per employee	+ 10 %	- 8 %
- (0.4) (% change in capital per employee)	- (0.4) (12.5 %)	- (0.4) (-16.67 %)
equals: % change in total factor productivity, 1998 - 1999*	+ 5 %	- 1.67 %

* % change in total factor productivity = % change in value added per worker minus (capital intensity coefficient) (% change in capital per worker). See equation (7.3).

From Table 7.3, we learn that Firm 1 experienced a 5 % gain in total factor productivity, while Firm 2 had a 1.67 % decline in this key measure. Thus, even though Firm 2 has managed to boost its economic rent to 10 % of shareholders' equity by avoiding additional investment, its performance in the realm of productivity has been substantially poorer than that of Firm 1. Even though the short-term profit picture may be bright, the TFP numbers raise issues related to management performance.

Economic Value Added (EVA) – return on shareholders' equity after deducting the opportunity cost of capital - has become a widely used measure of firm performance. Strategy experts have criticized this measure, on the grounds that it narrowly measures the productivity of capital alone. The advantage of the TFP measure is that it takes into account both labor and capital in measuring productivity, as well as, of course, sales and output.

A Macro Example

Consider now a real-world example: two "firms" we shall temporarily call HK Ltd. and SG Ltd. (Table 7.4). Both entities experienced similar, rapid growth in value added per worker over the two decades 1971-1990; in each, labor productivity doubled every decade. But HK Ltd. showed profitability (rates of return on capital) twice that of SG Ltd. Why? SG Ltd. attained growth in labor productivity by massive capital investments. For instance, in 1980, SG Ltd. did not produce any computer components or peripherals whatsoever. By 1983 SG Ltd. was the world's largest producer of disk drives. Such investments were profitable initially, but encountered rapidly diminishing returns. In contrast, HK Ltd. used its high quality human resources and entrepreneurial energy to drive total factor productivity growth with far less capital spending, achieving therefore higher profitability.

HK Ltd. is, of course, Hong Kong. SG Ltd. is Singapore. While Singapore's conservative economic policy has left it relatively unscathed by the Asian financial crisis, nonetheless the concomitance of massive investment, diminishing returns to capital and shrinking profitability, are seen by some as the underlying causes of Asia's 1997-98 financial crisis, in Thailand, Indonesia and Malaysia, anticipated in Young's (1992) paper. Had managers and investors been tracking total factor productivity for firms, as well as for whole countries, the impending crisis might have signalled its coming years before it happened.

Table 7.4: HK Ltd. and SG Ltd., 1971-1990.

	Proportion of Growth in Value Added per Worker Caused by: TFP Growth	Capital Deepening	Real Return on Capital (%)*
Hong Kong	56 per cent	44 per cent	22 % - 24 %
Singapore	- 17 per cent	+ 117 per cent	7 % - 13 %

* HK: 1980-86; Sing.: 1980-89. Source: Young (1992).

7.3 Application of TFP analysis to global firms

In this Section, we provide some calculations of TFP growth for a selection of large global firms drawn from the Fortune 1000 list. Data are given in the Appendix 7.1.

Rates of change in Total Factor Productivity were computed for the largest 20 firms in Fortune magazine's Global 1,000 (see Table 7.5). They reveal several firms, like GE and WalMart, with large positive TFP gains, and several (mainly Japanese) with large declines in TFP (with Mitsubishi the exception). ATT is also notable for poor TFP performance, as is Mobil.[5]

5 Significantly, Mobil has since been acquired by Exxon.

To determine whether TFP change indeed provides new information about the firm beyond conventional measures – like the change in the price of its shares and the change in profits – we computed the Pearson correlation between % change in TFP and a) % change in stock price during the following year, and b) % change in profits in the same year. None were statistically significant, and in fact none exceeded 0.13. This suggests that TFP change does provide a new dimension of information about firm performance, largely independent of – and behaving differently from – share performance and profit. Of course, because the % change in revenue is a key part of the TFP formula, TFP change is highly correlated with revenue gains. This is not only a statistical artifact but also a management principle – nothing is more helpful to productivity than strong revenue gains, generated with more or less the same capital and labor resources as the year before.

An interesting, marginally-significant relation was found between "rank by firm size" and TFP change. The Pearson correlation of -.390 ($p > 0.089$) was negative, indicating that smaller firms (i.e. higher rank numbers) have smaller rates of growth in TFP.

Table 7.5: Top 20 firms in the fortune 1000 global list: % change in TFP 1997 vs. 1996.

Company	% change in TFP $1-\alpha = 0.4$	% change in TFP $1-\alpha = 0.3$	Mean % TFP change
GM	2.51	3.33	2.92
Ford	0.98	1.86	1.42
Mitsui	0.57	0.03	0.30
Mitsubishi	12.34	11.25	11.80
Itochu	-6.36	-6.42	-6.39
Royal Dutch Shell	4.80	3.60	4.20
Marubeni	-7.38	-8.13	-7.76
Exxon	2.78	2.71	2.74
Sumitomo	-8.94	-10.25	-9.59
Toyota	-10.78	-11.21	-10.99
WalMart	14.68	14.11	14.40
GE	16.04	15.71	15.88
Nissho Iwai	7.45	6.54	6.99
NTT	-1.55	-1.58	-1.56
IBM	3.37	3.38	3.37
Hitachi	-7.05	-7.64	-7.34
ATT	-31.38	-30.66	-31.02
Nippon Life	-17.61	-16.41	-17.01
Mobil	-14.81	-15.36	-15.08
Daimler Benz	0.27	0.45	0.36

Source: see Appendix.

7.4 Three case studies: Intel, YPF, Merck

The following three case studies of total factor productivity growth are drawn from publicly-available data in annual financial statements. Use of such public data necessarily requires some assumptions, in order to compute TFP. Of course, when internal company data are available, no such assumptions need to be made.

Intel Ltd.

Table 7.6 summarizes productivity data for Intel, for 1993 and 1994. They show a decline in labor productivity of 3 %. The TFP equation (7.5) can help us understand why.

Table 7.6: Balance sheet data for Intel.

	1994	1993	% change
	- $ billion -		
Net Revenue	$11.5	$8.8	
- Cost of Goods Sold	5.6	3.3	
= Value Added*	5.9	5.5	+ 7.2 %
Labor (employees)	32,600	29,500	+ 10.5 %
Value Added per Worker	$180,982	$186,440	- 3 %
Capital (Shareholders' Equity)	$9.3 b.	$7.5 b.	+ 24 %
Capital per Worker	$285,276	$254,237	+ 12 %

Assume value of $(1-\alpha) = 0.4$

Source: Intel Ltd. Annual Financial Statements, 1993, 1994.

* Value added is not technically the difference between net revenue and cost of goods sold (as derived from the income statement), because cost of goods sold includes the cost of labor as well as materials. However, if we assume that the proportion of cost-of-goods-sold comprised of labor costs does not appreciably change in 1994 compared to 1993, then the % change in value added computed by using cost of goods sold will be the same as the value computed by using the technically correct measure of value added (not computable from publicly-known information).

Applying the "Solow equation" (7.5) yields a % change in TFP = - 7.8 %.

Intel experienced a decline in labor productivity in 1994, despite a large increase in Intel's capital, owing to "negative technological change". Closer investigation would doubtless reveal Intel's massive shift from 486 microprocessors to the new 586 ("Pentium") microprocessor, and attendant loss of output and production time, as fabrication plants transitioned to new technologies and workers underwent training.

The data indicate the costliness of such transitions, in terms of lost productivity and inefficiency, but further exploration may have led investors to conclude that the productivity decline is likely temporary. Indeed, in following years, Intel's value added per worker grew impressively, driven largely by its technological change, and its stock price rose sharply. Poor TFP numbers do not in themselves prove a bleak outlook, or establish poor managerial performance, for firms. They may be temporary.

YPF Ltd.

YPF is Argentina's leading energy company. In 1991 the company was privatized, and slimmed its employment rolls down from over 50,000 employees to around 6,000 (although many of the 50,000 became private outsourcers for YPF). It provides one of the world's most dramatic examples of efficiency gains through privatization. YPF recorded very large gains in productivity in 1996. Was this due to gains in total factor productivity (higher value added per unit of resources), or capital investment?

Table 7.7: Balance sheet data for YPF.

	1996	1995	
	Billion $	Billion $	Increase
Revenues	5.9	5.0	
Cost of Sales	3.6	3.2	
Value Added	2.3	1.8	27.7 %
Labor: (employees)	9,700	9,300	4.3 %
Value added per employee	237,000	194,000	22.16 %
Capital	6,734	5,839	15.32 %
Capital per employee	694,000	628,000	10.5 %

Assumption: the contribution of capital to value added ($1 - \alpha$) is 0.4,
typical for a capital-intensive firm. Source: YPF Annual Financial Statements.

Solow's equation provides the answer: The % change in TFP equals 22.2 % - (0.4) (10.5 %) = 18 %.

This tells us that YPF's impressive increase in value added per worker was largely due to improvements in technology, efficiency and knowledge, rather than capital investment. Indeed, the remarkable story of YPF's privatization and resulting dramatic increase in efficiency deserves to be more widely known and studied. As expected, YPF's higher total factor productivity found expression in the higher profitability of its capital.

Merck Ltd.

Merck, an R&D-intensive pharmaceutical company, showed large gains in value added per worker, apparently primarily from increases in knowledge stemming from an aggressive R&D policy. It should be noted that conventional accounting does not treat R&D expenditures as part of a company's "intellectual capital", but rather treats them as current expenditures.

Table 7.8: Balance sheet data for Merck.

	1994	1993	% change
Value Added ($ b.)	$9.0	$8.0	12.5
Employees (L)	47,700	47,100	1.3
Capital (Assets, K)	$21.9	$19.9	10.1

Therefrom, we get a % Change in TFP = 11 % - (0.4)(8.7 %) = 7.5 %.

Probably, TFP calculations should be accompanied by a recalculation of capital investment, treating R&D spending as investment and amortizing it over 3-5 years to reflect the relative short life of this asset.

From the TFP data, one can deduce that the majority of Merck's labor productivity gain stems from its technological change - probably, its successful investment in R&D for new products.

7.5 Conclusion

Analysis of total factor productivity data for countries ultimately led to a new appreciation of the key role of knowledge and technological change as drivers of economic growth in per capita output. Extension of this tool to performance benchmarking for firms has taken a surprisingly long time (Wakelin 1998). By applying TFP to firm data, senior management and external analysts can find answers to the question: why is labor productivity growing (or not growing). Perhaps the key value of such TFP calculations is not that they provide definitive answers, but serve as a stimulus of further analytic questions that help both managers and investors better understand the firm's strengths and weaknesses.

TFP benchmarks for individual firms, or divisions within firms, are best seen as the beginning of an in-depth strategic analysis, rather than the end. A promising extension of TFP analysis for firms might be to apply the so-called "growth accounting" analysis of Denison (1967) – which partitioned TFP growth for countries among a large array of contributing factors – to TFP data for firms, to achieve a similar goal: the answer to the question, how and why did technical change grow (or fail to grow) in the firm?

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Appendix 7.1: Data for Top 20 Global Firms (Fortune 1000).

Company	% ch.share price	Assets 96	Employment 96	Assets 97	Employment 97	% change Rev	% change Profits
	5/29/98-5/30/97					1997 vs 1996	1997 vs. 1996
GM	32	222100.00	647.00	225888.00	608.00	5.80	35.00
Ford	107	262900.00	372.00	279097.00	363.00	4.50	55.60
Mitsui	-42	61144.00	42.00	55071.00	40.00	-1.60	-16.50
Mitsubishi	-49	77872.00	35.00	71408.00	36.00	8.00	-1.50
Itochu	-	59179.00	7.00	56308.00	6.70	-6.60	-
Royal Dutch Shell	18	124373.00	101.00	113781.00	105.00	0.00	-12.70
Marubeni	-	60865.00	65.00	55403.00	64.00	-10.40	-21.40
Exxon	19	95527.00	79.00	96064.00	80.00	2.50	12.60
Sumitomo	-32	43506.00	26.00	42866.00	29.50	-14.20	0.00
Toyota	-14	102417.00	150.00	103893.00	159.00	-12.50	8.00
WalMart	85	39501.00	675.00	45525.00	825.00	12.40	15.40
GE	38	272402.00	239.00	304012.00	276.00	14.70	12.70
Nissho Iwai	-	43647.00	17.50	40799.00	18.00	3.80	-81.90
NTT	-14	115864.00	230.00	113409.00	226.00	-1.70	77.50
IBM	36	81132.00	268.00	81499.00	269.00	3.40	12.20
Hitachi	-38	80328.00	330.00	75837.00	331.00	-9.40	-96.40
ATT	66	55552.00	130.00	58635.00	128.00	-28.50	-21.50
Nippon Life	-	322759.00	86.70	316530.00	75.90	-12.80	15.30
Mobil	12	46408.00	43.00	43559.00	42.70	-17.00	10.40
Daimler Benz	31	72331.00	290.00	76190.00	300.00	1.00	161.00

Source: Fortune Global 1000: August 4, 1997; August 3, 1998; Share price data is from Business Week: The Global 1000, July 13, 1998.
Capital K is measured by Assets; L Labor is no. of employees; % change in value added is proxied by % change in revenue.

8 Innovation Benchmarking in the Telecom Industry[1]

Main Ideas in this Chapter

This Chapter contains a new approach to innovation benchmarking, as applied to telecom and information technology. Management always should begin with measurement. This is especially true of the difficult and risky task of managing innovation. By quantifying aspects of the innovation process, hopefully management decisions can become fact-based and hence lead to superior performance. The Chapter first explains how technological benchmarking can be done for strategic positioning of firms in global telecom markets (telecom manufacturers); second, how overall positioning of firms in the information technology market is obversed; third, how knowledge production leads to innovation and growth; fourth, how specific positioning of firms in single-product quality within the area of telecom products is examined. Finally, the Chapter provides a typology of firms based on how well product quality, measured in the proposed way, correlates with market-based preferences.

8.1 Innovation benchmarking

According to Webster's dictionary, benchmarking is "A surveyor's mark (...) of previously determined *position* (...) and used as a reference point (...) standard by which something can be measured or judged." In business administration and management, the pioneering work of Kearns at Xerox Corporation built on the notion of measurement or judgement, when establishing the following definition: "Benchmarking is the continuous process of measuring products, services and practices against the toughest competitors or those companies recognized as industry leaders." (Kearns 1986).[2] Later on, a broader understanding in terms of action-oriented concepts led to such ways of thinking: "Benchmarking is the search for industry best practices that lead to superior performance." (Camp 1989, p. 12).

Although benchmarking is relatively new, it is quite well established. The main problem with benchmarking is that most people use rather crude scores to carry out benchmarking comparisons. The purpose of this paper is to go back to the original

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1 This Chapter was published in a preliminary version as a working paper WP#153-96 of the International Center for Research on the Management of Technology, Sloan School of Management, MIT, Cambridge, Mass., 1996.

2 The concept dates back to ca. 1979.

meaning and to propose a different type of benchmarking using *quantitative measures,* in order to position a product or service in terms of its technology. I.e., this paper concentrates on benchmarking of innovations, not of standard products or practises. This is not a critical remark toward common benchmarking - just another approach to the same goal. In general, whenever one can use quantitative data organized as a table, one is better off than when qualitative judgments are made - the conventional approach in benchmarking.

The *methodological tools* to be used for this quantitative benchmarking begin with patent statistics. But benchmarking is often not unidimensional, but rather multidimensional. So we may need to use new tools to express the multidimensional quality (strategic markets, strategic sub-technologies), such as multidimensional scaling (Section 8.2). Patent statistics are also useful to explore the knowledge production that leads to innovation and subsequent growth (Section 8.3). A technique known as technometric benchmarking is applied to give quantitative expression to the multidimensional nature of most products and services, i.e. to product quality (Section 8.4).

For most people, a patent is a legal document. What interests us in patent statistics is the *knowledge output quality* that finds expression in patents. If in a company two engineers work for a year on a defined project funded from internal sources (cash flow), and if they are successful and invent something new, then we eventually have a document emerging from this lab which tells us that two engineers worked for a while on a certain invention, described very precisely. We can read from the document, as we read from scientific publications, that this company has deliberately brought about a certain inventive step, now documented and codified. So patent documents point to those areas of activity in which a company has invested R&D labor and resources. When patent examiners (in most countries civil servants at patent offices) discover that the idea is not new - but is already known - it matters to patent attorneys but little to us, because the fact remains, the company invested, say, two man-years in the R&D.

The fact that our world is still divided into national territories, and that intellectual property rights are protected by national patent offices and in national borders, means that a patent protects an idea in *one* country and *one* market. Regional coverage of patent protection must be deliberately decided by a company. So when one invention, one patent application, is filed at home, it is a sign that a company intends to market it in the domestic market only. When patents are filed in seven or eight countries, it shows the company intends to either manufacture or market the product in many countries.

Patent analysis is difficult. We must treat the data with care. Some years ago, the OECD secretariat in Paris published a *manual*, a guideline, on what one should observe in working with patent documents (OECD 1994).[3] All the possible mistakes one can make in analyzing patents are listed, so that one can prevent them if one reads this document carefully.

8.2 Positioning of firms in global telecom markets - an exemplar of innovation benchmarking

Let us begin with companies in the area of telecom *manufacturing.* The companies in our analysis are listed in Table 8.1. Our objective is to examine the marketing information inherent in patent statistics.

Let us examine Siemens first. Figure 8.1 shows the number of patent documents originating with Siemens (they have a number of affiliated companies), somewhere in the world, and we first look at the domestic market. The number of patents filed is the largest in Germany. Many of them remain *only* in the domestic market. But a considerable share of all inventions originate in the United Kingdom. So out of all countries in the world, the U.K. is the *most preferred foreign market* for Siemens in terms of protection of their inventions. This is explained by Siemens' serious effort to enter the British market, in part through patenting, in the late 1980's. Other large European countries are nearly equally covered with patents. For smaller countries, the patent applications declines.

The number of intellectual property rights in the domestic market is less than double those abroad - so the company is quite international in its perspective. In the United States, though it is the single largest market in the world, the number of duplicated patents remains low despite the company Rolm which was acquired there producing some inventions. Siemens has neglected this country in comparison with Europe, and neglected Japan as well.

3 A rich bibliography on patent analysis is included in this source.

Table 8.1: Analyzed Telecoms Manufacturers and Network Operators.[4]

Company	No. of European patent applications in telecom technology invented 1987-89	Communications equipment (US $ m resp. international communi-cations revenue 1993)
Alcatel NV	423	14,823
AT&T	378	11,801
Bosch	226	3,530
Ericsson	82	7,767
Fujitsu	288	4,774
GEC	181	1,948
Hitachi	83	1,555
IBM	342	5,299
Matshushita	100	2,227
Motorola	403	10,096
NEC	419	9,480
Nokia	78	2,355
Northern Telecom	110	7,860
Oki	27	1,590
Philips	378	1,868
Siemens	552	12,205
Sony	100	1,181
STET/Italtel	43	1,520
Thomson	132	n.a.
Toshiba	222	1,710
Bellcore	82	0 (domestic)
British Telecom (BT)	121	3,193
France Télécom (FT)	89	3,693
GTE-Sprint	39	1,188
NTT	86	0 (domestic)

4 Data sources for patent statistics for (consolidated) company affiliations are Schmoch and Schnöring, 1994, and lengthier German data annexes cited therein (from 1992). Communications equipment revenues are from *Communications Week International*, pp. 16-17, November 1995.

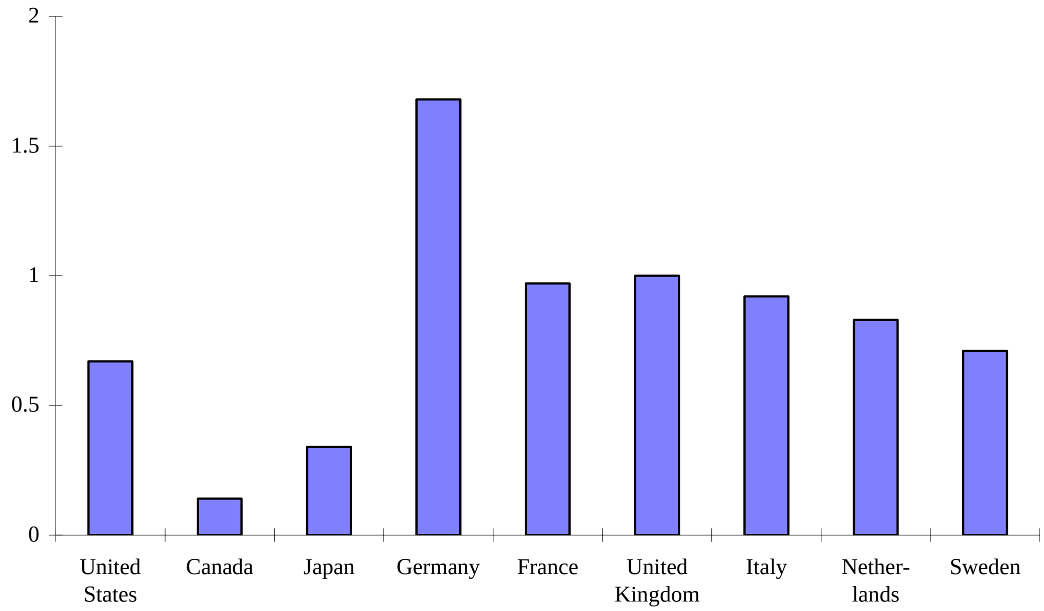

Figure 8.1: *Destination countries of telecommunications-related patent applications by Siemens (consolidated) 1987-1989.*[5]

We can carry out a similar analysis for other companies as well. Table 8.2 provides similar information for the other companies. In this table, the number of patents filed in the foreign country with the most patents applied for is taken as the benchmark value of 1.0.

It is evident from Table 8.2 that GEC is the mirror image of Siemens - a British firm filing heavily in Germany; GEC and Siemens run a joint subsidiary, originating from the Plessey group. Note the behavior of Japanese companies. This is a statistical artifact. The patent law in Japan is such that they cannot easily accumulate and combine several claims to be protected in one document. In practise, each claim requires its *own* document. Experienced patent lawyers provide a rule of thumb - divide the number of Japanese domestic patent applications by six or so to arrive at roughly comparable numbers. So we cannot surmise that the patenting activity in Japan is as fast and furious as the numbers indicate.

5 Source: Schmoch, 1996.

Table 8.2: Destination countries for telecommunications-related patent applications for selected companies 1987-1989.[6]

	Destination country								
Corporation (consolidated)	**USA**	**CND**	**JPN**	**DEU**	**FRA**	**GBR**	**ITA**	**NLD**	**SWE**
Alcatel NV	0.71	0.71	0.49	1.28	1.09	1	0.97	0.92	0.89
Bosch	0.40	0.11	0.39	1.98	1	0.95	0.92	0.69	0.58
Ericsson	0.88	0.37	0.71	0.92	0.85	1	0.69	0.76	1.02
GEC	0.66	0.37	0.73	1	0.99	1.3	0.91	0.81	0.81
STET/Italtel	0.63	0.34	0.50	1	1	1	0.89	1	0.97
Nokia	0.28	0.06	0.32	0.95	0.94	1	0.81	0.71	0.82
Philips	0.92	0.19	0.85	1.10	0.98	1	0.69	0.44	0.59

6 Source as in footnote to Figure 8.1. The European coverage is most frequently achieved via European patent application. Patenting in one European Union country does not automatically confer a patent in all other countries of the European Union, as is sometimes mistakenly believed, since the European Patent Office (EPO) has come into being in 1978. But it works as follows: you send in your invention to the EPO. You specify for which member countries you seek patent protection. They make a joint examination, which is costly (compared to a single national examination - say 5 times as much), but once done and when successful, it is handed over to the national patent offices, and without further investigation, it is accepted. If you choose this route, then count this document in a multiple way, for all designated countries. What you save, as a company or patent applicant, is simply the examination procedure, time and translators and attorneys' fees. But ultimately the *national countries* grant or decline the patent protection in their own country. This is a clear disctinction to the so-called International Patent which has to be transferred from the international to the national stage whereby costs accrue in each transferred system. Note that the EPO member states are not synonymous with the European Union. They include Switzerland, Liechtenstein and Norway - some 18 member states are involved presently, in contrast with 15 for the EU members.

Table 8.2 continued

Corporation (consolidated)	Destination country USA	CND	JPN	DEU	FRA	GBR	ITA	NLD	SWE
Siemens	0.67	0.14	0.34	1.68	0.97	1	0.92	0.83	0.71
Thomson	0.97	0.13	0.48	0.99	1.23	1	0.76	0.52	0.43
AT&T	1.96	0.84	0.98	0.93	0.93	1	0.65	0.54	0.51
IBM	1.11	0.10	0.85	1	1	1	0.32	0.10	0.08
Motorola	1.51	0.44	0.94	0.95	0.95	1	0.90	0.92	0.90
NorTel	1	0.48	0.38	0.36	0.36	0.38	0.20	0.35	0.34
Fujitsu	0.9	0.69	31.46	1	0.93	0.99	0.25	0.11	0.23
Hitachi	1	0.11	12.19	0.54	0.33	0.39	0.07	0.06	0.05
Matsushita	1	0.12	3.2	0.66	0.53	0.70	0.13	0.27	0.26
NEC	1	0.50	3.81	0.58	0.43	0.69	0.11	0.29	0.26
NTT	1	0.50	44.8	0.87	0.51	0.79	0.14	0.27	0.52
OKI	1	0.19	20.95	0.53	0.47	0.57	0.15	0.04	0.19
Sony	1	0.27	5.25	0.85	0.78	0.89	0.11	0.34	0.04
Toshiba	1	0.32	13.34	0.54	0.33	0.47	0.05	0.08	0.13

To this point, the strategic marketing aspect of innovation, as revealed in patent applications by protected national markets, has been analyzed. It was seen that potential strategic initiatives of companies in foreign markets can be tracked. In analyzing these data, one arrives at the conclusion, that in the telecom industry there are several, very different strategic positionings of companies at the end of the 1980's (see Table 8.3). There is a group of companies from various countries, which have an average share of broad patents. We have another group of companies, selective in patenting their inventions abroad among them some Japanese manufacturers. Then we may discern a group of companies with a special focus on the American market. Finally, there are companies with special focus on the Japanese market. And, another group of companies - among them newcomers in that market - that do little on the Japanese market.

What do we know about how these companies position themselves in the overall information technology arena, with their telecom activities? Are they broad, or narrow, in technological terms? This is a typical multidimensional problem. Here we offer a brief introduction to a statistical technique known as multidimensional scaling.

Table 8.3: Typical patent strategies of selected companies on foreign markets.[7]

Feature	Examples
Average share of foreign patents, broad coverage	Alcatel, AT&T, Philips, Siemens
Generally, little foreign patenting, but broad coverage	Ericsson, GEC, Motorola, many network operators
Selective strategy	Hitachi, Oki, Matsushita, NorTel
Special focus on the American market	Matsushita, Hitachi, NEC, Thomson, Philips
Special focus on the Japanese market	AT&T, IBM, Motorola, NorTel, Philips
Low presence on the Japanese market	Bosch, Nokia, Siemens, STET, Thomson

Suppose you were given a typical triangle of road distances between pairs of major European cities. For, say, 8 cities, there are 8 • 7 / 2 = 28 such distances. Now, suppose you were asked to place these cities on a two dimensional map, such that the distance between each pair of cities precisely matches the distance noted in the table. The task: Write a computer algorithm that will do so. There are such algorithms, and they position each "city" (which in some cases is a variable, technology, or a company), state whether the "map" is accurate or not (in terms of a coefficient of goodness of fit), and provide other types of useful information. This is

7 Source: Schmoch and Schnöring, 1994.

multidimensional scaling (MDS), a version of which is also known as smallest space analysis (SSA). Note that there is an exact solution only in the (28-1) dimensional space, as our starting point is road distances not air distances taken from the two-dimensional surface of our globe as usual.

Let us conduct an MDS analysis of IT. We take the telecom manufacturers (including for comparison the network operator in Japan, NTT),[8] use their patent profiles over technological entities (a fine classification exists, including more than 70,000 individual items, the International Patent Classification), and define six major fields in information technology, telecom (TELCOM), electronic elements (ELTRN), multimedia technology (or audio-visual or consumer electronics, AVEL), optical technology (OPTICS), storage (STOR) and data processing (DAT). We then compare the profiles of any two companies to see whether they are similar or not. (We calculate the correlation coefficient of each pair of company technology profiles). Two companies which each put 16.6 % of patenting activity in each of six fields will have a correlation of one. Two companies each of which puts 100 % of its patenting activity into a different field, will have a low correlation ($R^2 = 0.2$ in the example). They are thus considered dissimilar.

Figure 8.2 shows a multidimensional scaling map of companies, where distances in the diagram represent similarity - Euclidean proximity. To understand the MDS map fully, as with any map we need a convention or wind rose, a "north" and "south" in IT. An artificial "North" and "South" is created as follows. We invent an *artificial* company, one that doesn't exist and that is active in one subfield - say, multimedia or consumer electronics. For this field, we assign *all* this imaginary company's patenting activity, 100 %. Then this company becomes a "pole" - one can compare all other companies to this virtual company that is the strongest possible in this field. We thus create fictitious companies to represent the "pole" in optics, in electronics components, and so on.

This map of technological profiles, in terms of several poles, represents real findings and not artificial ones. Looking at single companies validates this method - and we have. This is the simplest way to benchmark individual companies relative to other firms - each company can recognize their closest competitors as those that have the most similar profiles.

8 This is justified as the NTT labs develop IT technology in collaboration with Japanese manufacturers which is patent-protected by NTT; see Grupp, 1993.

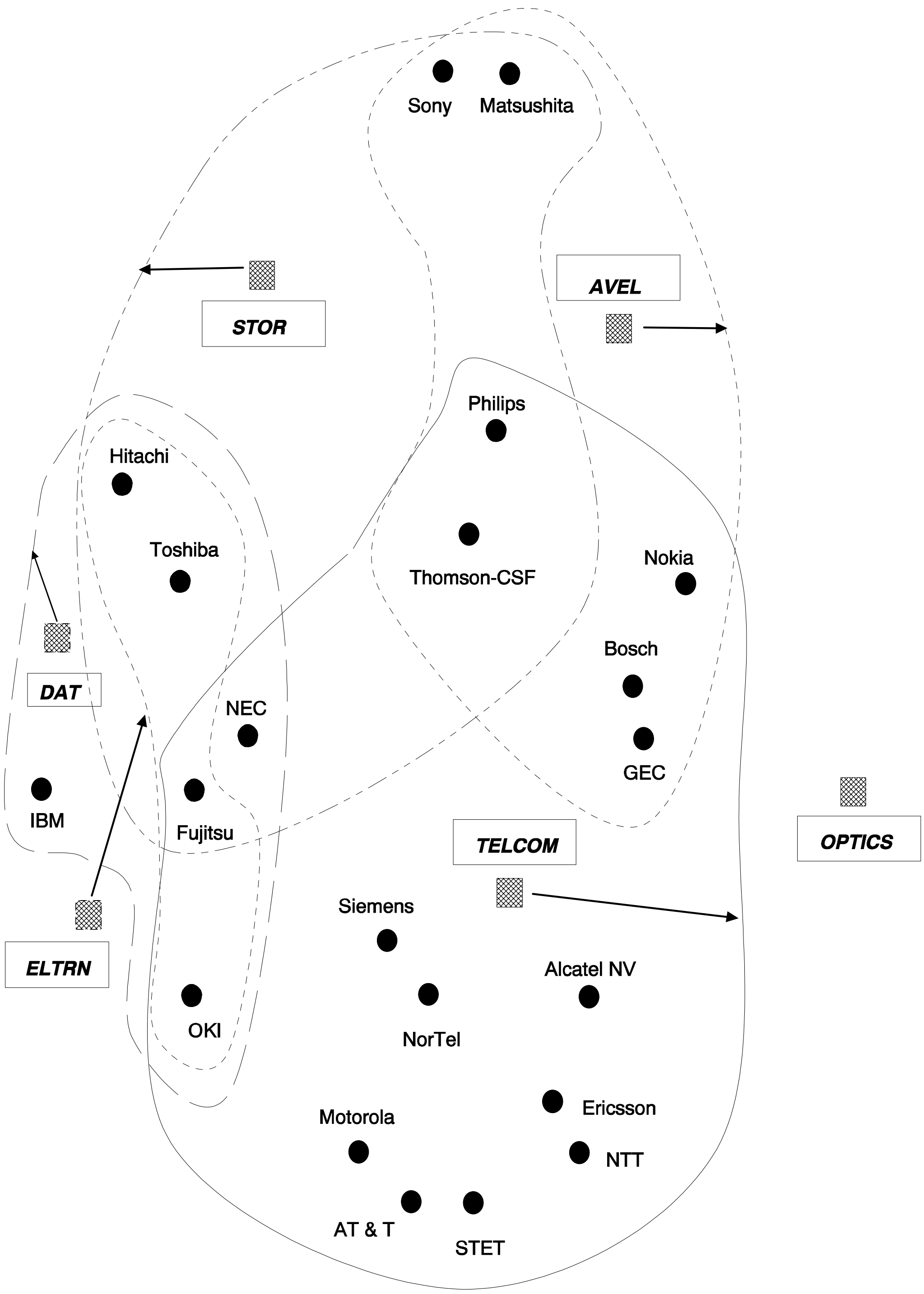

Figure 8.2: MDS map of information technology for selected companies in the period 1987 to 1989.[9]

Now, let us zoom down to a more limited market - only telecoms. We introduce an MDS map based on a breakdown of patenting in subfields (Figure 8.3). We get in principal the same thing, but just a window of the larger map. We see groupings of

9 Source: Schmoch, 1995.

companies who are strong in optical telecommunications (OPT T), switching (SWIT), mobile radio telecoms (RATIO T) and electrical transmission (ELKT T - remote measuring and sensing), and terminals technology (TRML). The map provides us with an interesting picture: we now know who are the strong innovators in optics, in

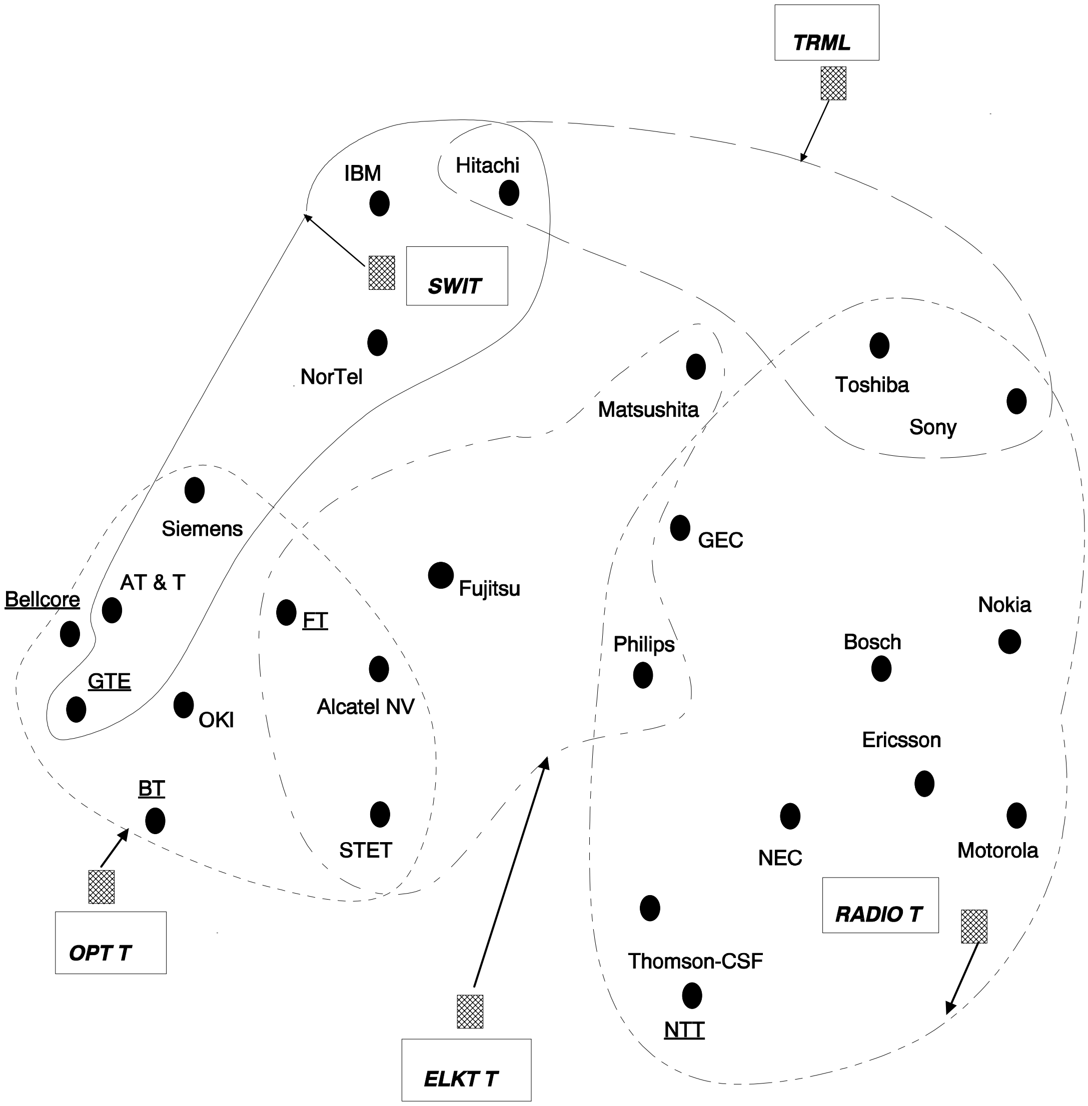

Figure 8.3: MDS map of communications technology for selected companies in the period 1987-1989.[10]

transmission - Toshiba is a newcomer, so we get new information on new entrants in this field where we may not have subject information before. The network operating companies - with the exception of NTT - support the national innovation systems

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10 Source as in footnote of Figure 8.2. Network operators underlined.

mainly with optical technology, an important ingredient to modern telecoms networks.

Whereas at the end of the 1980's, everyone was competing with everyone, at the beginning of the decade, there were islands of specialization, a nice partitioning of the markets. After the opening of the telecom markets through deregulation, there was fierce competition in nearly all markets. This is what a similar MDS map would show, for the beginning of the 1980's. From several snapshots of the MDS strategic positions, you can make a movie, combining them, to get a dynamic picture.

8.3 Knowledge production and growth - the innovation module

Timeliness of technical results and newness of the company's technology portfolio strongly affects its innovation performance and - more specifically - new product revenues (Roberts 1995). The lessons for clarifying the role global technology knowledge plays for the technology levels to be achieved are two-fold. First of all, in general terms, the more patents with international significance a company takes out the more sophisticated its product innovations seem to be. On the other hand, some companies offer very sophisticated products on world markets with no comparable patent production (Grupp 1998, Chapter 10).

There are three possible explanations for the latter observation. First, companies may have a very good tacit in-house knowledge base in the relevant technology, or rely on secrecy or very short market introduction times and do not care for comprehensive, international protection. Another possibility would be that companies have a strong domestic patent base but do not take out foreign duplications of their inventions, accepting all the associated international market risks. This case can be checked by an analysis of patent flows (Table 8.2) and can be ruled out. The third possibility is that the companies produce excellent products from global knowledge external to the company. By acquiring leading-edge companies, licencing, networking and other forms of technology cooperation they may produce innovative products from creative technologies of other firms (including public laboratories). This is an important element in telecommunications.[11]

From this analysis it is concluded that there are various ways to innovation. Some companies acquire technological knowledge from other, e.g. global sources instead of using intramural technology generation and patent protection. But not all companies can do so in telecoms, so that for a number of companies a knowledge production

[11] Compare the national R&D infrastructures in Grupp (1993, loc. cit.).

relationship between in-house technology generation and innovations achieved should appear to be established. Furthermore, technology generation anticipates innovation performance levels for some years. Patent stock data for previous years should fit better to the technology levels than the most recent activities as cumulative technology acquisition by firms is so important.

The "knowledge production function" for innovation as measured by the growth levels of innovative products can be modelled as follows (this is a further development of the knowledge production function model of Griliches):[12] It is a one dimensional approach taking some scalar output measures as is shown below. If we, however, want to use qualitative, non-pecuniary proxy measures, i.e. for product quality, we cannot use the conventional production models. A version of linear programming exists, however, that was explicitly built to measure the efficiency of decision-making units (which can be individual firms) and that does allow qualitative inputs. This approach is known as Data Envelopment Analysis (DEA). Essentially, it examines which decision-making units (DMUs) are on their production possibilities frontier, or isoquant, in the knowledge economy and which are not.[13] Here we try out how far the scalar approach holds.

The knowledge production function approach can be represented in the following way:

$$Y = A(t)K^{\beta}U$$

where Y is some measure of output of the firm, K is a measure of cumulated knowledge or research "capital", a(t) represents other determinants which affect output and vary over time including standard economic inputs such as capital investment, labor and so forth while u reflects all other random fluctuations in output. Certainly, this is just a first approximation to a considerably more complex relationship (Griliches, loc. cit., p. 55).

From the logarithmic form we arrive at the growth equation

$$d \log Y / dt = (1/Y)\, dy / dt = a + \rho\, (R/Y) + du/dt$$

where the term β (d log K)/dt is replaced by using the definitions $\rho = dY/dK = \beta\ (Y/K)$ and $R = dK/dt$ for the net investment in knowledge capital.

12 Summarized in Griliches 1995.

13 See, e.g., Grupp (1996, loc. cit.) or Grupp et al. 1992.

We now calculate the deflated growth in communications equipment revenues 1993 in comparison to 1986[14] and approximate R by the number of patent applications following the base year 1986, i.e. inventions in the priority years 1987-89. This is a "skeletal" model of depreciation and obsolescence of (patented) knowledge, but more realistic data are difficult to obtain. It means, that inventions from 1986 or earlier years do no more matter for the revenues in 1993, and inventions from 1990 and later do not yet. Patent application number always measure the increase (dK/dt) in knowledge as they add up to the already existing (and eventually patented) knowledge. The assumed lag of about four years until novel knowledge affects markets is taken from earlier empirical investigations (Grupp 1991).

Cross-section linear regression analysis of the 19 manufacturing companies in Table 8.1 gives the results as displayed in Table 8.4. Knowledge production explains parts of the variance significantly although all the other potential inputs (labor, physical capital, tacit knowledge) are included in the residuals only. A visual impression of the relation is provided in Figure 8.4.

Table 8.4: Regression results for the knowledge production function of telecom manufacturers (revenue growth 1993 compared to 1986).

Measure / Variable	Value
ρ	0.0053 ± 0.0018
Constant	0.6312 ± 0.3700
R^2 adjusted	0.298
F	8.652
t	2.941
Significance	0.91 %
DW	2.296

14 Using OECD's implicit GDP price indices.

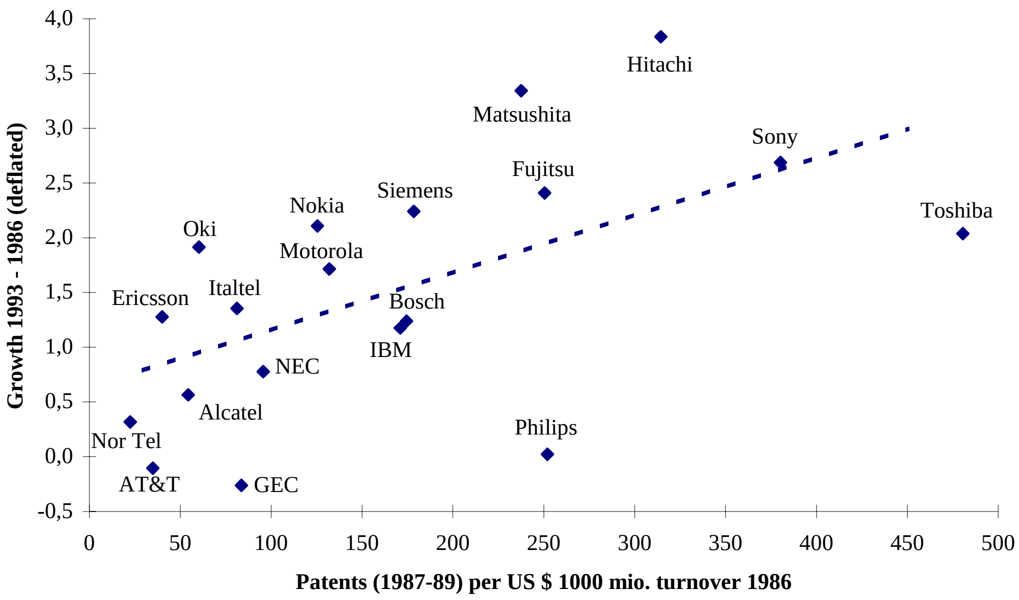

Figure 8.4: Delated growth of corporate revenues and knowledge production of telecom manufacturers.

From the econometric point of view this analysis is very crude and simplistic. For benchmarking it is however sophisticated and useful. It tells us what a corporations gets for its technological activitites. Philips or GEC, for instance, invested in (patented) knowledge and are traditionally strong R&D performers. They failed to convert this into innovations that led to average growth of revenues in this particular market for telecoms goods. This is not to talk managers into a reduction in R&D activities, rather, to adjust the innovation "module" in a more effective way to reach better yields of knowledge investments. Newcomers in the telecoms market such as Matsushita or Nokia grew so quickly with modest own knowledge sources[15] that one is tempted to express a word of warning: Long-term sustainable growth may be vulnerable if you depend too much on external or tacit knowledge sources.

8.4 Technometric benchmarking for individual products: The case of optical communications lasers

After examining broader industry trends, it is possible to "zoom down" to the product level, using a different approach. Here, patent statistics cannot help. In an invention, it

15 The growing importance of acquiring technology from outside sources is undeniable; see, e.g., the benchmarking study by Roberts 1994.

is not specified what the product characteristics will be like. We need another instrument of analysis of product innovation quality - one known as technometrics.

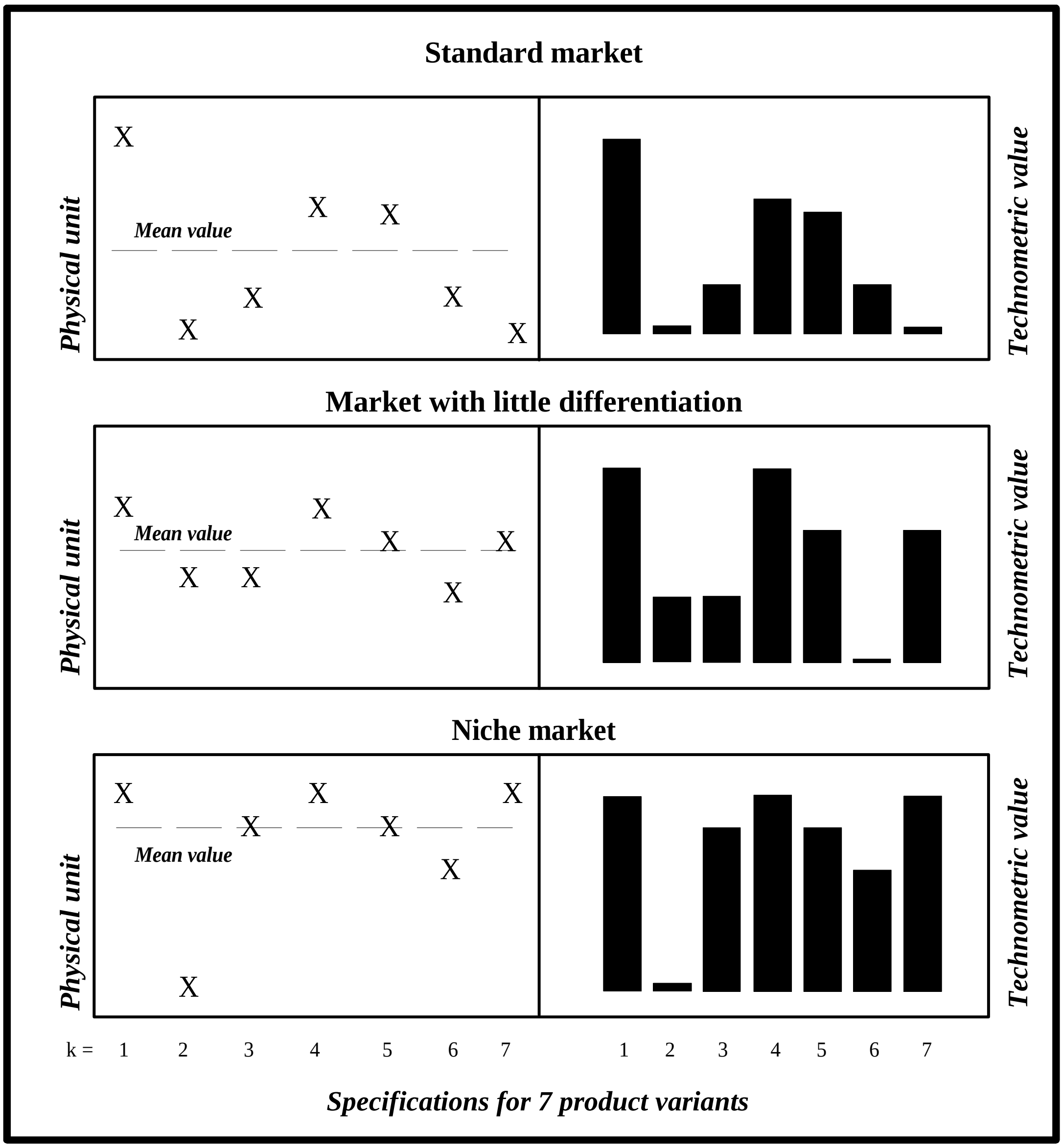

Figure 8.5: Sketch of technometric benchmarking concept.

We have the following starting point. A product is described by its characteristics. Consumers do not buy "products", rather they purchase a combination of characteristics or attributes, that satisfy their wants and needs. For example, a laser is descibed by wave length, power, stability, and so on. In general, experts know which are the important characteristics. But the problem is, each characteristic has a different unit of measurement. So it is not a vector - you cannot derive a comparable measure. The technometric concept converts it into a metric scale, a dimensionless one, all features between zero and one - which enables us to build a profile that can be compared one to another, one attribute to another, one product to another.[16]

Figure 8.5 provides a graphical illustration of technometric profiles for seven different products, and three different possible patterns. Technometric benchmarking makes it possible to construct a detailed profile of the product, comparing one characteristic only across products. One can also look at the entire profile of a single product, across *all* characteristics, without weights - simply draw all the 0,1 values. Only if you want a one-dimensional scalar number, to aggregate the technometric scores, does one need weights for each product attribute. The weights are, of course, representative of the preferences of customers. They can be determined by market surveys, focus groups, or, at times, by eliciting the opinions of those engaged in direct marketing of the product.

Figure 8.6 provides a profile of product quality for laser diodes, of mm range, for telecom applications in optical fibres, presented in the following way: The world state-of-the-art level is set to one. This changes over the course of time, but is equal to one at a given point in time. For Japan, all Japanese manufacturers are aggregated, as if they were a single firm ("Japan Incorporated"). In some attributes, they are world-class, in others, well below it. In laser power, at least one Japanese manufacturer offers world-class quality. In others, no Japanese manufacturer attains world-class sophistication. This holds for all Japanese companies taken together.

The broken line portrays a specific company, Company A. It has products, laser diodes, on a world level, in part, and below world level, in part. One can see precisely strengths and weaknesses at one glance. So this, of course, is the adequate "zoom" for benchmarking Company A against Japanese competitors. This is a typical application of technometrics for benchmarking the products of company A for the domestic Japanese competition. Of course, in such a case, Company A can search for a remedy for this situation, if it indicates weaknesses - by looking abroad, for those who have a technological solution. In other cases, one can search for a strategic partner in Japan.

16 Earlier concepts of technometrics, such as Grupp 1995 or Frenkel et al. 1994, were not turned to benchmarking. The technometric procedure in benchmarking is best described in Grupp 1998, Chapter 11.

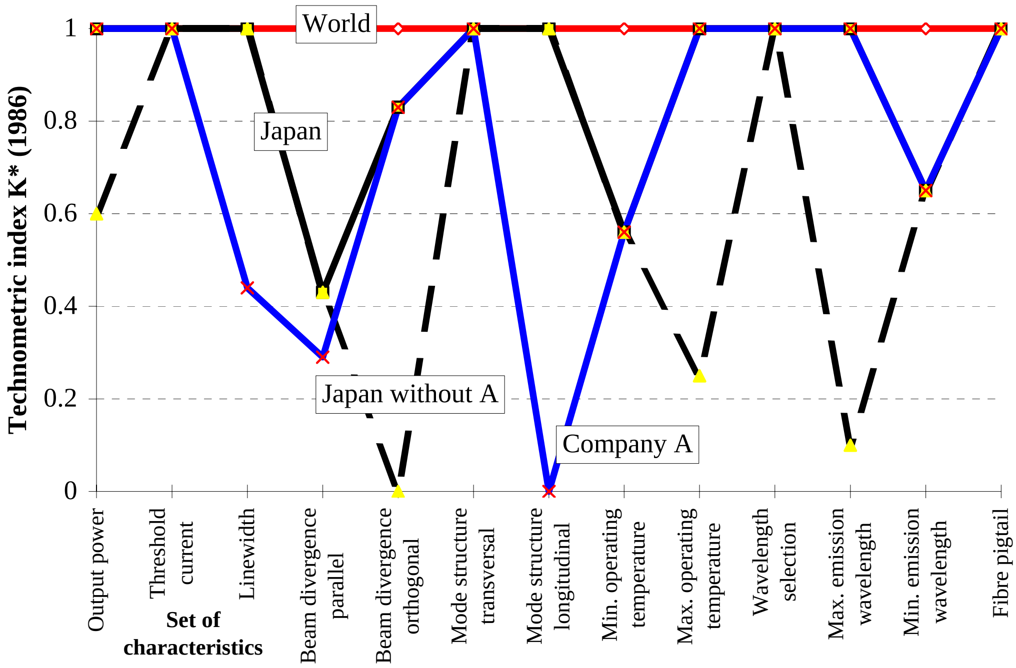

Figure 8.6: *Example for product quality measurement for single products and domestic market aggregation: Laser diode in the μm range for optical communications.*

At times, we want to have an international comparison. Figure 8.7 shows a technometric comparison of laser diodes in the micrometer range, not suitable for optical communication. There is Company A, German, and a line for Germany without Company A, and the world class - the present profile of all Japanese and all US companies. Company A will learn from this, whether there are German competitors better than itself, and whether there is expectation that one can find a partner for a strategic alliance in Germany - and if not, to which other country might one look. This is exceedingly useful for strategic innovation.

For an overall measure of product quality index, one dimensional, we can do this only if we have preferences of customers, showing what weights they give each single characteristics. There are several methods. You can ask people, a sample of them, how they would value single characteristics. You can devise this from prices - the method of hedonic price indexes - by seeing the statistical link between product prices and their attributes, with coefficients of attributes indicating the importance of those attributes. Such information is presently not available for laser diodes in optical communications.

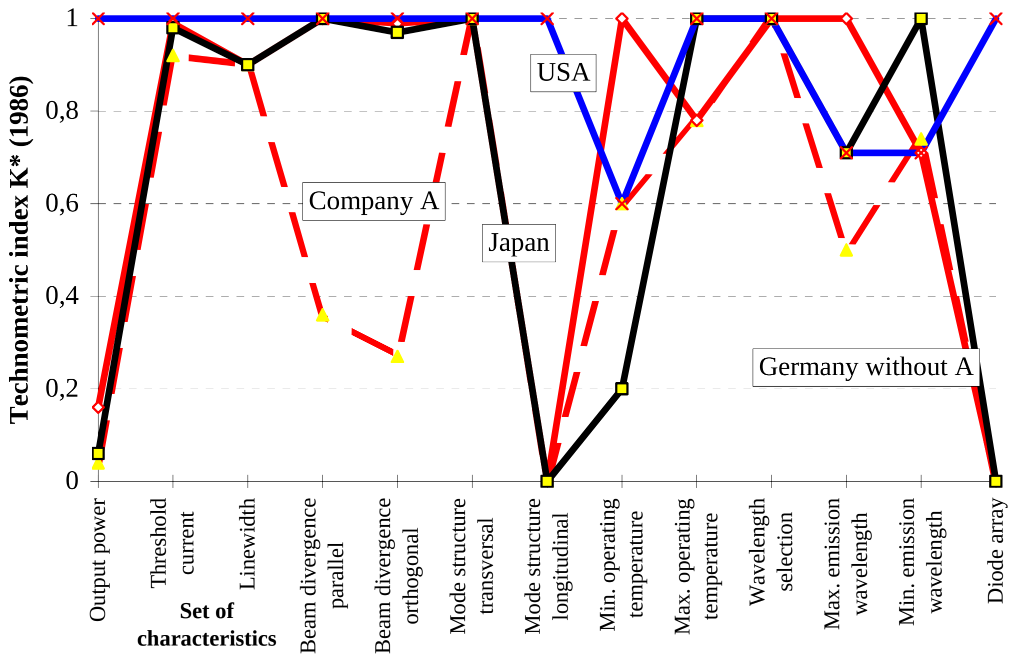

Figure 8.7: *Example of product quality measurement for single company products and international comparison: Laser diodes in the μm range.*

8.5 A typology of strategic focus

One can construct a kind of typology of companies and their technological strengths or weaknesses, building on the technometric profiles. There are four basic types of firms (see Figure 8.8):

- uncompetitive,
- unfocused,
- focused, and
- dominant.

One sees this by mapping firms' products in two-dimensional space, with the X axis indicating, for each attribute of a product, its technometric score (from zero to one), and the Y axis indicating, for each attribute, the weight or importance of that product in the eyes of its consumers. In other words, a product with 10 key attributes will be characterized by 10 pairs of numbers. The first number in each pair, the X value, represents the attribute's objective, technometric score, and the second number, the Y value, indicates the subjective consumer preference weight.

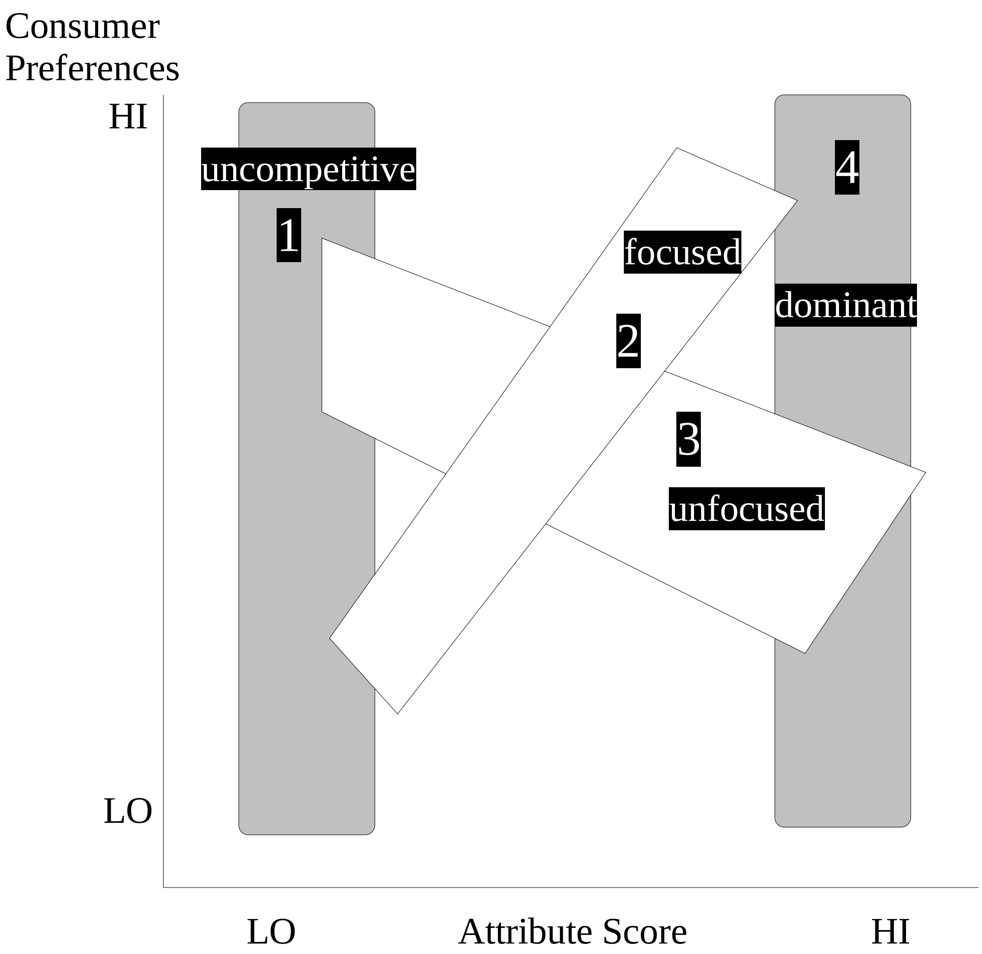

Figure 8.8: *Typology of Firms.*

The way those 10 points cluster establishes a firm's competitive position. If the firm's product is consistently weak relative to its competitors, it is "uncompetitive". This is shown by an essentially vertical line rising from "LO" product quality. Its market success is highly dubious. If the firm's products are technometrically strong for attributes consumers rate as unimportant, and vice-versa - technometrically weak for attributes consumers rate as important, then the firm's product is unfocused, or rather misfocused. Its market share is unlikely to be high or growing.

If the firm's products are strong for attributes consumers rate highly, but weak for attributes consumers think unimportant - the product is focused, and market share will be strong. Finally, if the product is technometrically superior for all its attributes - then the product is defined as "dominant".

The first type of firm, "uncompetitive", has uniformly low product quality, for attributes consumer value highly as well as for those they value less highly. These firms are uncompetitive, unless their products compete on the basis of very low price (and hence, are produced at low cost). The second type of firm is "focused". These firms are strong precisely in attributes that the market values highly. Their R&D tends to be well directed and strategically planned in line with market preferences. The third type of firm is "unfocused" - their product quality is strong precisely for attributes the market as relatively unimportant, perhaps as a result of poor R&D investment. Finally, there are dominant firms. These firms have consistently high product quality across all attributes, both relatively important and relatively unimportant ones. They tend to dominate their markets.

We anticipate a positive link between the performance of companies and their products, and their placement in the above typology. Uncompetitive or unfocused products should fare more poorly than those that are focused and dominant. As more elaborate data are missing for telecommunications, we presently cannot provide examples. Such analysis remains on the research agenda; the feasibility of this strategic analysis has already been shown for sensor technology (Grupp and Maital 1998; see also Chapter 4 in this volume).

References to Chapter 8

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9 Relation between Scientific and Technological Excellence and Export Performance: Evidence for EU Countries[1]

Main Ideas in this Chapter

A two-stage model of innovation is presented, in which: I. economic inputs (such as R&D spending) generate science and technology outputs (such as publications, citations, and patents), and II. these science and technology outputs in turn serve as inputs, that generate knowledge-based exports. An integrated system of science and technology indicators, built on a "stages" model of the innovation process is used as the basis for testing the model for twelve European Community countries, through statistical regression. It is shown that a systematic empirical relationship exists between inputs and outputs, for both Stage 1 and Stage 2. The structure of our Chapter is as follows. The first Section presents a "stages" model of innovation, together with an operational, integrated network of indicators that serve to quantify each stage. In the next Section, we construct a two-stage model of comparative advantage, in which two types of types of efficiency are defined: Stage 1, *efficiency in translating R&D resources into technological and scientific output*, and Stage II *efficiency in translating scientific output into export sales of R&D-intensive products.* In Section 9.3, we define and describe our data set. Section 9.4 presents our regression results, and in Section 9.5, we conclude and summarize, and list some policy implications of our findings.

9.1 A "stages" model of innovation

The purpose of this Chapter is to utilize quantitative indicators of scientific and technology performance to examine empirically the link between scientific and technological excellence and export performance, for twelve European Community countries. Specifically, we propose to analyze (a) whether, among these countries, investment of resources in applied and basic research – as measured by spending on Research and Development (R&D) – is related empirically to technological and scientific "output", and (b) whether scientific "output" is empirically related to generation of exports. But how to specify input and output indicators?

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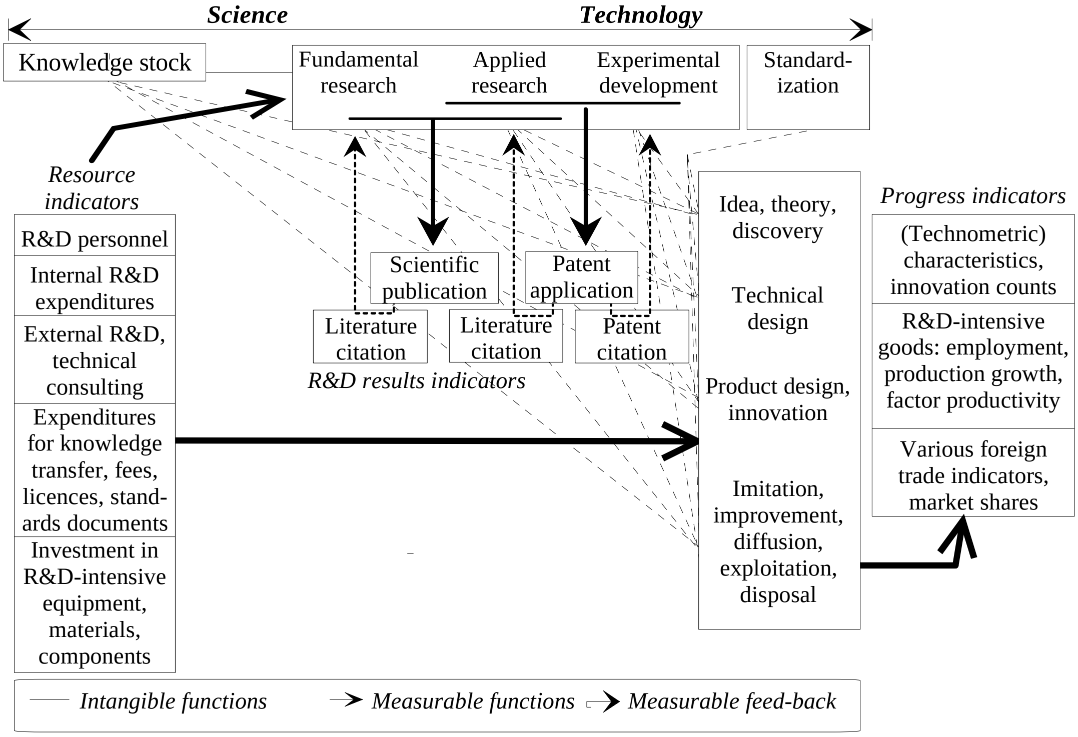
1 An earlier version of this Chapter, co-authored with A. Frenkel and K. Koschatzky, was published in *Science and Public Policy* 21(3), pp. 138-146, 1994.

Figure 9.1: Stages of research, development and innovation, and corresponding science and technology indicators.



Grupp et al. (1992a)[2] have constructed a "stages" model of the innovation process, in which six different phases or functions are defined: theory and model development, technical realization, industrial development, innovation and imitation, diffusion, and finally utilization. The model is accompanied by a comprehensive, operational set of indicators that quantify each stage and enable researchers to examine its relation with succeeding and preceding stages (see Figure 9.1 which corresponds to Figure 6.1 in Chapter 6). While, as is noted there, "... the well-known approach by indicators ... grasps only parts of the complex and cyclical (feedback) innovation-oriented processes", nonetheless, such indicators "offer an opportunity to speak a common language in science and innovation research."

The model takes a somewhat "economic" perspective, in the sense that each of the stages is characterized by "inputs" and "outputs". The model is highly recursive, or "feedback", in nature, because the outputs of one stage become the inputs of succeeding stages.

2 Reprinted in Chapter 10 in this volume.

The initial stage, theory and model development uses R&D spending as its inputs or resources, and generates scientific outputs: publications, and citations of publications. The field of scientometrics – the quantitative measurement of scientific output – is by now well developed, and comprehensive databases of publications and citations, by subfield, are now widely accessible. The second and third stages of the innovation process build on scientific expertise, as expressed in publications and citations, to generate patent applications and stocks of patents. Here, too, data are widely available for a wide range of products, services and processes.[3] At the innovation and imitation stage, technology – as expressed in patents – is used to generate products, processes and services, whose quality or level of sophistication can be measured by the "technometric" approach (Grupp 1990). In the technological diffusion stage, product and process quality is transformed into export sales and global market share.

Detailed data are available on exports, according to standard industrial product classifications, by country of origin and by country of destination. It should be emphasized that this model is not necessarily linear or rigidly sequential; for some products and processes, some stages may be skipped, while for others, the precise sequence may differ from that in Figure 9.1 (for instance, patents may precede publications and citations).[4]

Since each stage of the innovation process is characterized by empirical indicators, the "integrated network model" is an operational one; using it, it is possible to test hypotheses and to conduct cross-country comparisons.

The focus of this Chapter is on the extent to which inputs are used efficiently to generate outputs. In order to examine this important issue, it is first necessary to model the process through which nations acquire comparative advantage in high-

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3 A large literature exists on the theme of productivity and efficiency in R&D activities, addressing the question, how well are R&D inputs converted into R&D outputs? Many of these studies are "micro" in nature; see for instance Brown and Svenson (1988), Mandakovic and Souder (1987), Roll and Rosenblatt (1983), Sardana and Vrat (1989), Stahl and Steger (1977), Schainblatt (1982), Szakonyi (1985), and Thor (1991). Our approach is aggregative and "macro" in nature, with nation-states as our individual units.

4 "... scientific, technological and economic progress are certainly not linked in a sequential manner... linear. models are not at all applicable. To cope with this more general situation in science and innovation the authors... developed cyclic or coupled models of science and innovation phases." (Grupp et al. 1992, p. 8). These authors go on to discuss why science, technology and innovation are often highly non-linear "In reality improving and diffusing products and processes is seldom if ever a simple task or a replication by unimaginative imitators. From utilisation of diffused innovations, that is their consumption and disposal, incentives for new research and more innovation may be triggered off at leas in terms of the cyclic model suggested here. The push on science and technology from environmental problems may serve as a good example". (ibid, p. 9).

technology products, and then utilize that comparative advantage in achieving high levels of exports and export market share. This is the task of the next Section.

9.2 A two-stage model of comparative advantage

A nation's export value-added can be partitioned according to the sources of that value added: Research and Development – value added accruing from R&D spending, leading to goods and services that perform well in global markets; production of those goods and services, at minimum cost and maximum quality; and marketing and distribution. This is the so-called "value-added chain", used effectively by Porter (1980).

It is possible to model the innovation process as a two-stage one. In the first stage, economic resources – physical and financial capital, and skilled manpower – expressed as Research and Development spending are invested, in order to generate scientific and technological outputs (publications, citations, patents, etc.). In the second stage, the scientific and technological outputs become inputs, that generate new products and processes, of which some are exported.

Presumably, comparative advantage in high-technology products (where science and technology play important roles) can arise either from excellence in generating scientific outputs (stage one), or from excellence in utilizing scientific outputs, or both.

Stage 1

Let X be a vector of variables x_l, x_2, ..., 1 x_n, measuring the magnitude of resources invested in R&D, and let Y be a vector of variables y_l, y_2, ..., y_n, measuring the resulting scientific and technological outputs (citations, publications, patents, etc.). Then there exists a "production function" F( ), that maps from R&D inputs X to scientific output Y:

$$Y = F(X) \tag{9.1}$$

This production function can be subjected to the same types of economic analyses as conventional production functions, that map from, say, labor and capital, into value-added. In particular, the efficiency of translating R&D resources into scientific outputs can be measured. Grupp, Maital, Koschatzky, and Frenkel, 1992, for example, adopt a linear programming approach to measuring efficiency in transforming scientific excellence into exports. Or, alternately, using regression analysis, the empirical relation of Y and X can be examined, and individual countries' performance compared with the trend line – an approach that we take here.

Equation (9.1) is a measure of Stage I efficiency – the degree to which resources invested in research are efficiently utilized to achieve scientific excellence.

Stage 2

The second stage in the export process involves the translation of scientific excellence into R&D-intensive, goods and services that capture export sales. This stage encompasses the production, marketing and distribution components of the value-added chain.

Let Z be a measure of export performance, and Y be, as above, the measure of scientific excellence. Then a production function G( ) exists that maps from scientific excellence to export performance:

$$Z = G(Y) \tag{9.2}$$

As with F( ), G( ) can also be analyzed empirically, and used for comparing various countries with one another.

Availability of adequate data for X, Y and Z makes it possible to study Stage 1 and Stage 2 efficiency for a sample of countries. Such analysis makes it possible to partition causes of superior or inferior export performance between Stages 1 and 2, and as a result, to construct policies for stimulating exports that attack the root of the problem.

We propose to test this hypothesis, using data for X, Y and Z for twelve EC countries. Before presenting our empirical results, we first describe the extensive data set itself.

9.3 Scientometric and economic indicators

The variables used in this study are listed below, together with a description of their nature and their sources. For our purposes, "high-technology" products are defined as those with R&D spending equal to or greater than 3.5 per cent of sales. A complete list of product groups that meet this criterion, according to the three-digit SITC code, is given in Appendix 9.2.

"X" variables

For our measure of R&D inputs, we simply used gross spending on Research and Development, expressed as a fraction of GDP Data were all converted to U.S. dollars using purchasing power parity indexes, that measure the buying power of currencies rather than existing market exchange rates.

GERD: gross R&D Spending, annual average for 1981-85; converted to U.S. dollars using Purchasing Power Parity index of O.E.C.D.; $ billion. Source: O.E.C.D., S&T indicators.

GDP 81/85: gross Domestic Product, average for 1981-85, $ billion, converted to U.S. $ using Purchasing Power Parity index as for variable 1.

GERD/GDP: ratio of GERD to GDP, as per cent.

"Y" variables

For our measures of scientific excellence, we used indicators in three different areas: patents, citations, and publications.

Patent indicators

For patents, we measured the number of patents granted, for the twelve EC countries, at the United States Patent and Trademark Office (USPTO), as a measure of a country's aggressiveness in seeking global protection for its intellectual property. We computed the sum total of patents invented in 1977-86, as an expression of cumulative patent activity, at the USPTO, and expressed them as a fraction of GDP for each country?[5]

These indicators are based on the number of patents registered by the twelve European countries, in the U.S. Patent and Trademark Office (USPTO). They express the willingness and desire of each country to defend their intellectual property, in proportion to GDP.

PAT: number of patents, matched to product groups, USPTO, 1984-86.

PAT/GDP: PAT, as a ratio to GDP.

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5 This variable measures not only patent activity in the U.S., but also the degree of willingness of firms and inventors to apply for patents at the United States Patent Office. For many reasons, the eagerness to patent inventions in the U.S. is not identical across all countries. Hence, this variable reflects not only some measure of R&D output, but also the extent to which firms and inventors are prepared to create a "footprint" of this output in the form of patents.

PATPOT: cumulative no. of patents, USPTO, 1977-86.

PATPOT/GDP: PATPOT as a fraction of GDP.

Publications and citations

These indicators measure, for each country, the number of scientific publications by scholars who cite that country as their primary address in their publications, as listed by the databases of the Institute for Scientific Information (I.S.I.), in Philadelphia, Pa. The publications are for articles in scientific and engineering journals. Citations are similarly drawn from the I.S.I. databases.

For publications, we used the listings of the Science Citation Index, for engineering and science journals separately, and then added the two. We also expressed this indicator as a fraction of GDP.

For citations, we used similar listings from the Science Citation index, also divided between engineering and scientific periodicals and then summed, and also expressed as a fraction of GDP.

PUBSCIENG: number of publications in both scientific and engineering publications. (not including Life Science publications), 1981-85.

PUBSCIENG/GDP: PUBSCIENG as a fraction of GDP.

CITSCIENG: number of citations in both scientific and engineering periodicals, 1981-85.

CITSCIENG/GDP: CITSCIENG as a fraction of GDP.

"Z" variable

RCA: revealed comparative advantage, for product groups; 1988, defined as:

$$RCA = 100 \{ (ES^2 - 1)/(ES^2 + 1) \},$$

where Export Share $$ES = \frac{EX / IM}{EXTOT / IMTOT}$$

EX is a country's total Exports of high-tech products, IM is that country's Imports of such products, **EXTOT** is the country's total exports of manufactures, and **IMTOT** is the country's total imports of manufactures.[6]

The data based on trade figures were derived from Legler et al. (1992). It is important to note that high-tech exports are compared to total exports (and imports) of *manufactured goods* only. The trade variables therefore serve as a measure of the extent to which trade in *manufactured products* is high-tech. (See Grupp 1990, and Legler et al. 1992.) The data themselves are given in Appendix 9.1.

9.4 Empirical results

Regression equation estimates for the Stage 1 and Stage 2 Models are shown in Table 9.1. For purposes of this analysis, we chose to combine the "leading-edge" (goods for which R&D spending equals 8 per cent or more of sales) and "high-level" products (between 3.5 per cent and 8 per cent). Disaggregation does not substantively alter our conclusions. In general, the level of government intervention in leading-edge products is much greater, and hence exports of such products are less influenced by pure market forces.[7]

Stage 1: Translating R&D into scientific excellence

Figures 9.2, 9.3, 9.4 and 9.5 show the relation between four measures of scientific output - publications, citations, patents, and cumulated patents – expressed as a fraction of GDP, and Gross R&D spending, also as a fraction of GDP, for twelve

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6 The RCA (Revealed Comparative Advantage) answers two questions simultaneously, a) Do the domestic suppliers of high technology products have a solid footing in the international market compared with foreign competitors and suppliers of other domestic sectors? And b) Do they succeed in substituting domestic production for high technology imports, compared with suppliers in other sectors?

7 "...there are two hemispheres in the world of R&D intensity. One (the high-level consumer products with expectations of a relatively good turnover per R&D investment), in which technical performance by patents does play a role and is a decisive factor for international ~ competitiveness alongside with R&D activities by industry. Scientific achievements are not so important here. The other hemisphere (the leading-edge technologies with moderate expectations in turnover per R&D investment) in which factors other than technology guarantee international success, is characterized by stronger government intervention both on the side of R&D and also in terms of procurement and regulation. Here, scientific excellence is indispensable." Grupp (1995). Grupp adds: "Business-financed R&D governs the high-level commodities and thus all high technologies, whereas international success in leading edge products must be nurtured from somewhere else. ... the financial means of governments poured into the business R&D system largely explains where the position of a country in leading-edge products is. ... Governments in EC countries are the drafthorses in very R&D intensive fields and provide financial means for the pioneering of possibly less effective new leading-edge technologies."

European countries. The European countries chosen are: Germany, France, UK, Netherlands, Belgium/Luxembourg, Denmark, Ireland, Spain, Italy, Greece, Portugal. For each Figure, the regression line for the "Y" (dependent) variable regressed on the "X" (independent) variable is shown.

Table 9.1: Scientific and technological output indicators as a function of gross R&D spending/GDP (independent variable: gross R&D spending as percentage of GDP). Regression equations for "Stage 1" model: twelve European countries.

Dependent Variable	Intercept	Coefficient of Independent Variable (GERD/GDP)	R^2 adj	P	N
PUBSCIENG/GDP	21.15 (5.18)	29.02	0.75	.0003	11
CITSCIENG/GDP	16.42 (21.82)	115.34	0.73	.0005	11
PATH/GDP	-1.68 (0.85)	5.066	0.78	.0002	11
PATPOT/GDP	-7.28 (2.97)	18.59	0.79	.0001	11

* (standard error of slope coefficient in brackets)

The United Kingdom lies above the twelve-country trend line both for publications and for citations, suggesting considerable Stage 1 efficiency in that country in generating scientific outputs from R&D resources, while Germany lies somewhat below the trend line (see Figures 9.2 and 9.3). It is possible that the ISI database used for publications and citations, which comprises mainly English-language periodicals, biases the results in favour of English-speaking nations (like the U.K.). However other studies suggest that irregardless of this bias, the U.K. does achieve a very high level of publications and citations, relative to other countries.

The slope of the two regression lines can be interpreted as:

$$\frac{d(PUBSCIENG / GDP)}{d(GERD / GDP)} \quad \text{and} \quad \frac{d(CITSCIENG / GDP)}{d(GERD / GDP)}$$

meaning, the increase in publications and citations, respectively, normalized by GDP, for a one per cent increase in R&D spending (as a percentage of GDP). The respective slopes are, approx., 30 and 115.

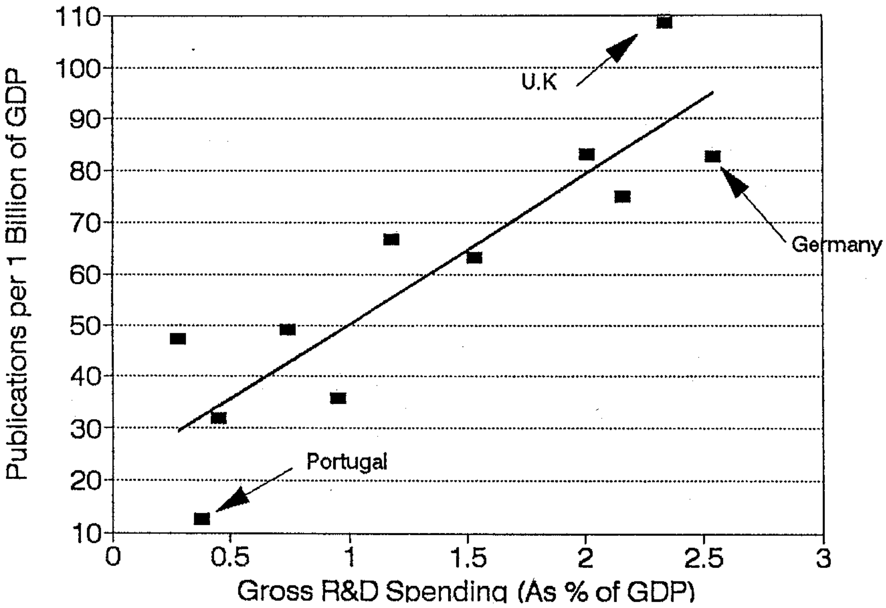

Figure 9.2: *Publications in Science & Engineering per GDP as a function of gross R&D spending (as % of GDP 1981-85) in twelve EC countries.*

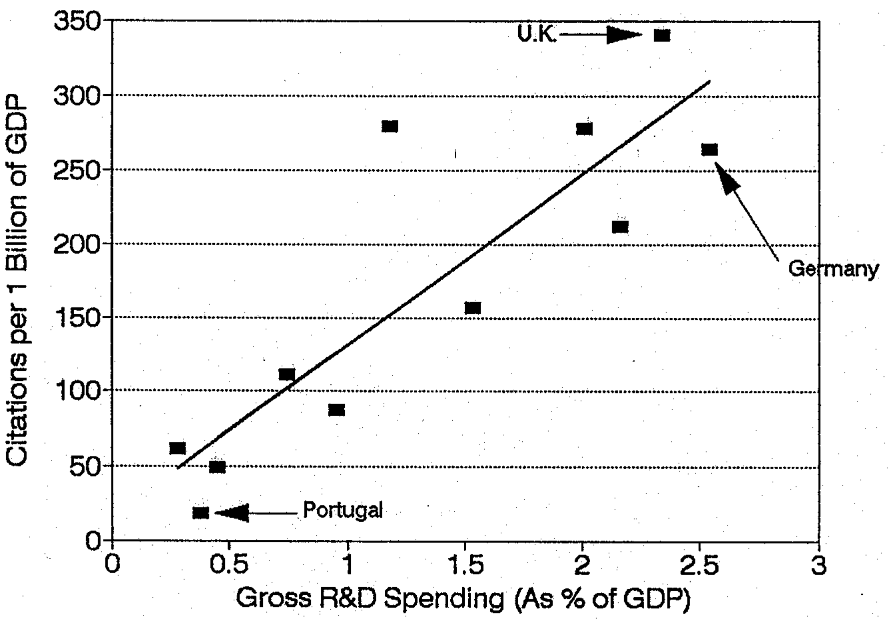

Figure 9.3: *Citations in Science & Engineering per GDP, as a function of gross R&D spending (as % of GDP 1981-85) in twelve EC countries.*

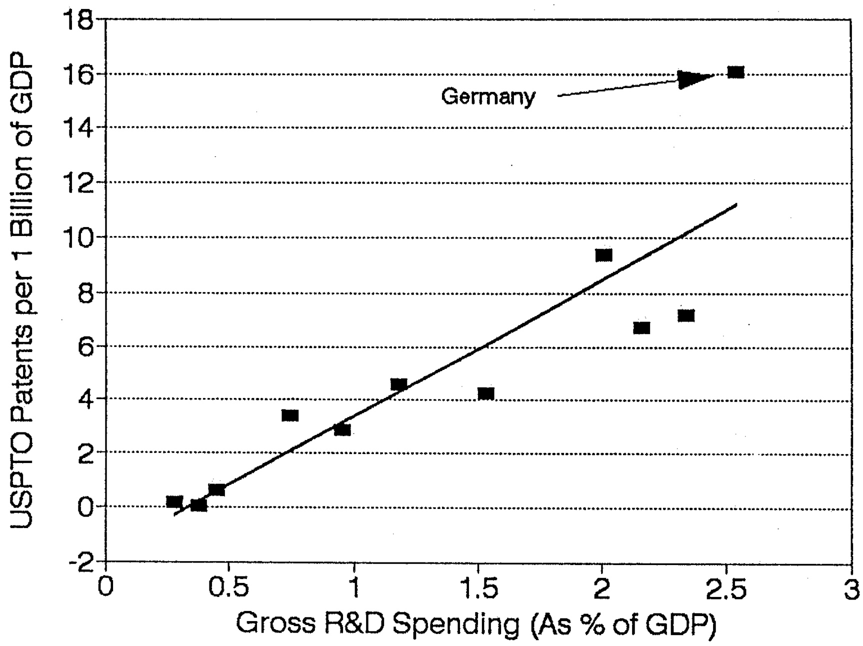

Figure 9.4: *Patents per GDP (at USPTO 1984-86) as a function of gross R&D spending (as % of GDP 1981-85), in twelve EC countries.*

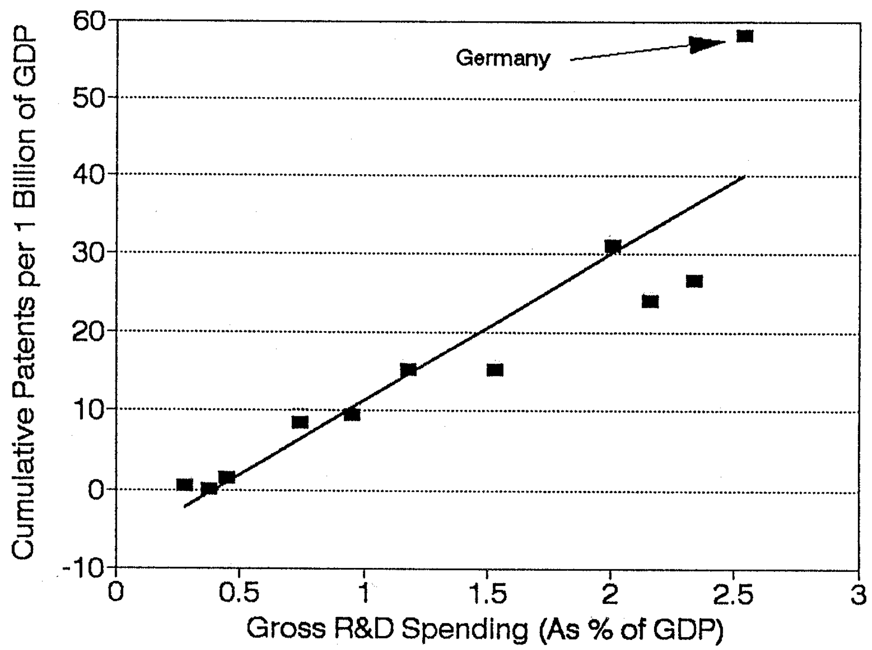

Figure 9.5: *Cumulative patents per GDP (at USPTO 1977-86) as a function of gross R&D spending (as % of GDP 1981-85), in twelve EC countries.*

A different picture emerges for patents. Here, Germany lies well above the trend line, both for Patents per GDP and for Cumulative Patents per GDP (see Figures 9.4 and 9.5). This suggests that German firms in large part follow an aggressive patenting policy at the United States Patent Office, to a greater extent than that practiced by firms in other European countries.

Apart from the German "outlier", the regression-line fit between R&D spending (as a percent of GDP) and patents/GDP is a relatively close fit for the twelve EC countries. Here again, the slope of the regression line is a measure of the incremental rise in patents/GDP for a one percentage point increase in R&D spending/GDP.

Stage Ib: Translating Publications into Patents: Our empirical analysis suggested to us that Stage I – transforming R&D resources into scientific and technological "intellectual property" – is really comprised of two substages: Ia) use of R&D resources to generate research results, expressed as publications and citations; and Ib) use of scientific and technological knowledge (which find expression in publications and citations) in order to generate patentable inventions.

To test this hypothesis, we computed two additional statistical regression lines, in which Patents/GDP was the dependent variable, and Citations/GDP and Publications/GDP each served as the independent variables, respectively. The results are shown below in Table 9.2, and in Figures 9.6 and 9.7.

The results clearly indicate a) that there is a strong trend line between patents/GDP and citations and publications; and that the two major outliers in the data are Germany, which lies well above the trend line in terms of its energetic patenting activity, and the U.K., which lies well below the trend line in its patenting activity. The U.K.'s weak patenting performance may explain in part the relative weakness of the U.K.'s performance in knowledge-based exports, relative to its comparatively strong scientific and technological achievements.

Table 9.2: Regression equations for stage "Ib" PAT/GDP as a function of CITSCIENG/GDP and PUBSCIENG/GDP in twelve European countries.

Dependent Variable	Intercept	Slope	R^2 adj	P	N
CITSCIENG/GDP	0.76223	0.21577	0.534	0.0064	11
PUBSCIENG/GDP	0.74245	0.22330	0.501	0.0089	11

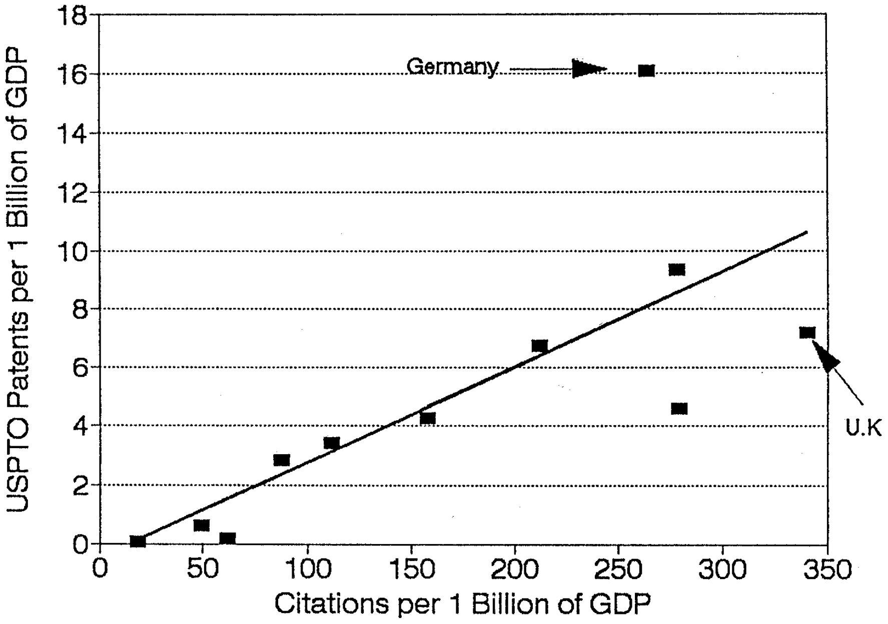

Figure 9.6: *Patents per GDP (at USPTO 1984-86) as a function of citations in Science & Engineering per GDP 1981-85, in twelve EC countries.*

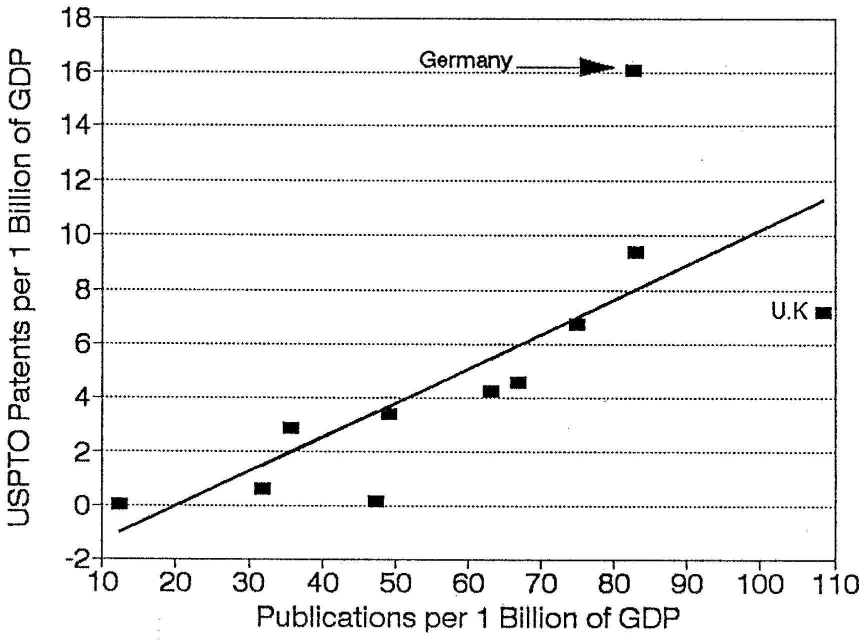

Figure 9.7: *Patents per GDP (at USPTO 1984-86) as a function of publications in Science & Engineering per GDP 1981-85, in twelve EC countries.*

Stage 2

Translating scientific excellence into export sales, Figures 9.8 and 9.9 and Table 9.3 show the statistical regression lines for the Stage II equation, which expresses Relative Comparative Advantage (RCA) as a function of patents and cumulative patents. Here too, the statistical fit is relatively good, confirming the close empirical link between knowledge-based export performance, in terms of an index of world market share, and patent performance.

The goodness of the regression fit is diminished because of the inclusion of Portugal and Greece. These two countries have very little patenting activity at the USPTO and are not yet really players in the global knowledge-based export market. Excluding these countries would substantially increase the value of the multiple correlation coefficient.

For Germany, success in translation of patenting activity into exporting success is not impressive. While the distance between the point signifying Germany, and the twelve-country trend line, is not significantly different from zero, nonetheless Figures 9.8 and 9.9 do indicate that resources invested in Germany in activities related to patenting may not be used with full efficiency.

Table 9.3: Regression equation for Stage II: Revealed Comparative Advantage as a function of scientific inputs (dependent variable: RCA).

Dependent Variable	Intercept	Slope*	R^2 adj	P	N
PAT/GDP	-43.72 (1.75)	5.43	0.46	0.0126	11
PATPOT/GDP	-41.58 (0.49)	1.45	0.43	0.0166	11

* *(standard error of slope coefficients in brackets)*

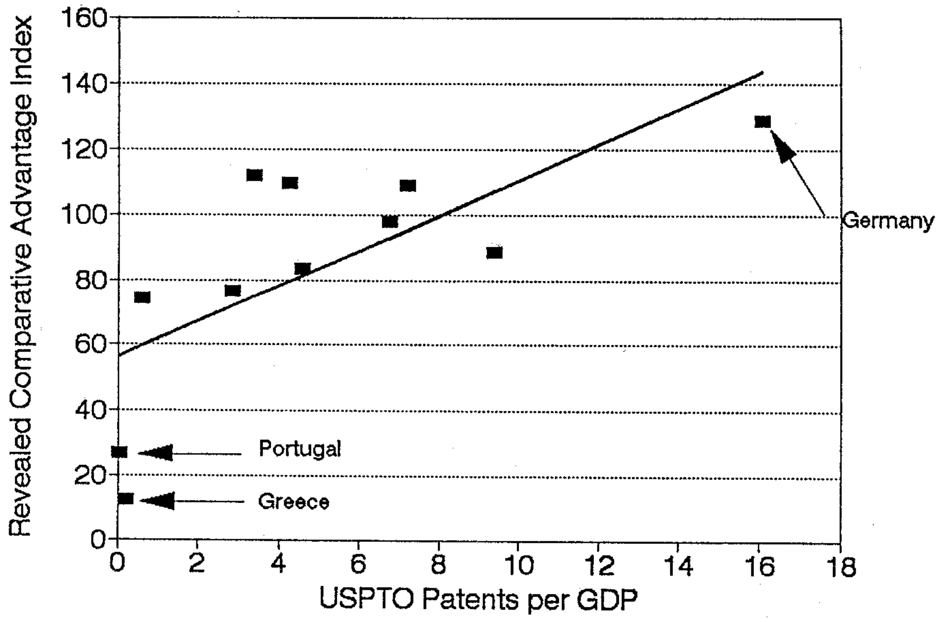

Figure 9.8: *Revealed Comparative Advantage index 1988, as a function of patents per GDP (at USPTO 1984-86), in twelve EC countries.*

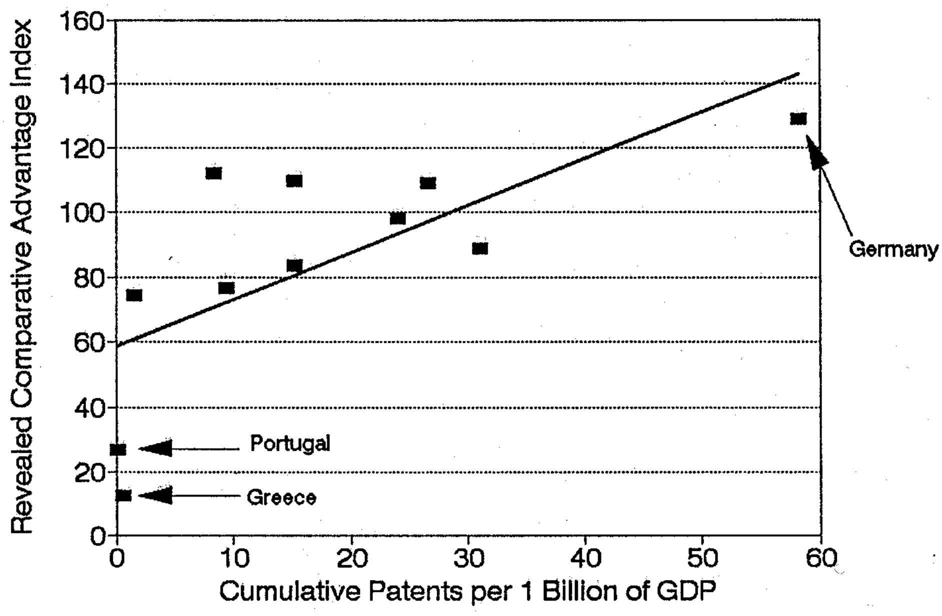

Figure 9.9: *Revealed Comparative Advantage index 1988, as a function of cumulative patents per GDP (at USPTO 1977-86), in twelve EC countries.*

9.5 Conclusion and implications

Our empirical results have confirmed the posited link between inputs and outputs, in both stages of our two-stage innovation model: a) between R&D resources and scientific outputs, and b) between scientific outputs and export performance, among twelve EC countries. The Stage I link between R&D resources and scientific and technological outputs (publications and citations) is much stronger, in terms of the least-squares fit, than the Stage II link between scientific and technological output and export performance. The model's performance is somewhat improved by introducing an intermediate stage, in which patents are expressed as a function of citations and publications.

In general, the results confirm our basic hypothesis presented at the start of this Chapter, that international commercial success in high-technology products exports is basically supported by R&D spending as a fraction of GDP, and by the resulting outputs of scientific and technical knowledge and patents.

One straightforward policy implication is this: There is no free lunch. Achieving larger export shares in knowledge-based products requires investment of substantial resources in Research and Development. At the same time, there is still considerable variation among countries in the efficiency with which they exploit scientific and technological excellence. Great Britain is a case in point – that country's sizeable output of publications and citations is rather inefficiently converted into high-tech exports and market share, compared to other EC countries. While the reasons for this are not clear, they may be related to passive patenting policy abroad and insufficient skill and investment in marketing.

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Appendix 9.1: Data.

STATE	GERD 81-85	GDP 81-85	GERD/ GDP %	PUB-SCIENG 81-85	PUB-SCIENG/ GDP	CIT-SCIENG 81-85	CIT-SCIENG/ GDP	PAT 84-86	PAT7 GDP 84-86	PATPOT-77-86	PATPOT/ GDP	RCA 1988
Germany	16.66	655.91	2.54	54169	82.59	173437	264.42	12461	16.07	38205	58.25	28.76
France	12.48	576.7	2.16	43190	74.89	122344	212.14	4370	6.74	13871	24.05	-2.10
U.K.	12.69	542.17	2.34	58774	108.41	184502	340.30	4472	7.21	14443	26.64	9.07
The Netherlands	2.98	147.97	2.01	12276	82.98	41167	278.21	1527	9.37	4595	31.05	-11.22
Belgium/Luxemb.	1.49	97.48	1.53	6151	63.10	15363	157.60	461	4.25	1480	15.18	9.47
Denmark	0.65	55.23	1.18	3690	66.81	15418	279.16	288	4.58	838	15.17	-16.55
Ireland	0.16	21.57	0.74	1060	49.14	2401	111.31	83	3.40	181	8.39	11.84
Spain	1.15	257.83	0.45	8215	31.86	12748	49.44	181	0.61	413	1.60	-25.80
Italy	5.28	555.79	0.95	19845	35.71	48420	87.12	1777	2.85	5235	9.42	-23.46
Greece	0.15	53.93	0.28	2550	47.28	3345	62.02	11	0.18	33	0.61	-87.57
Portugal	0.19	49.64	0.38	622	12.53	923	18.59	2	0.04	7	0.14	-73.06

Appendix 9.2: List of R&D intensive products.

No	SITC III	Product group (non-official terms)	R&D Intensity
1	516	Advanced organic chemicals	
2	525	Radio-active materials	
3	541	Pharmaceutical products	
4	575	Advanced plastics	
5	591	Agricultural chemicals	
6	714	Turbines and reaction engines	
7	718	Nuclear, water, wind power generators	
8	752	Automatic data processing machines	Leading-edge goods
9	764	Telecommunications equipment	
10	774	Medical electronics	
11	776	Semi-conductor devices	
12	778	Advanced electrical machinery	
13	792	Aircraft and spacecraft	
14	871	Advanced optical instruments	
15	874	Advanced measuring instruments	
16	891	Arms and ammunition	
17	266	Synthetic fibres	
18	277	Advanced industrial abrasives	
19	515	Heterocyclic chemistry	
20	522	Rare inorganic chemicals	
21	524	Other precious chemicals	
22	531	Synthetic colouring matter	
23	533	Pigments, paints, varnishes	
24	542	Medicaments	
25	551	Essential oils, parfume, flavour	
26	574	Polyethers and resins	
27	598	Advanced chemical products	High-level products
28	663	Mineral manufactures, fine ceramics	
29	689	Precious non-ferrous base metals	
30	724	Textile and leather machinery	
31	725	Paper and pulp machinery	
32	726	Printing and bookbinding machinery	
33	727	Industrial food-processing machines	
34	728	Advanced machine-tools	
35	731	Machine-tools working by removing	
36	733	Machine-tools without removing	
37	735	Parts for machine-tools	
38	737	Advanced metalworking equipment	

39	741	Industrial heating and cooling goods	
40	744	Mechanical handling equipment	
41	745	Other non-electrical machinery	
42	746	Ball and roller bearings	
43	751	Office machines, word-processing	
44	759	Advanced parts: for computers	
45	761	Television and video equipment	
46	762	Radio-broadcast, radiotelephony goods	
47	763	Sound and video recorders	
48	772	Traditional electronics	High-level products
49	773	Optical fibre and other cables	
so	781	Motor vehicles for persons	
51	782	Motor vehicles for good transport	
52	791	Railway vehicles	
53	872	Medical instruments and appliances	
54	873	Traditional measuring equipment	
55	881	Photographic apparatus and equipment	
56	882	Photo- and cinematographic supplies	
57	883	Optical fibres, contact, other lenses	

Conclusion: How to Build a Successful Business Model

Main Ideas in this Chapter

This concluding Chapter focuses on the importance of building a complete, integrated and well-conceived business design around a new product or process idea: including production, marketing, finance, design, advertising, sales, distribution, human resource management, etc. Success at innovation is comprised of a large number of necessary conditions – which together are jointly sufficient for market success, but failing even one component, generate a high probability of failure. The "direct business model" is used as a unifying example. We also cite examples drawn from knowledge-based startups whom we interviewed and studied during our research. We indicate how the microeconomic tools described in this book can help build a successful business model, and alter it when and where necessary. We start with a definition of a business model and then present the direct business model of Dell. After introducing the elements of business design and transition problems we explain the writing of a winning business plan.

What is a business model?

Conceiving a new product or process and then bringing it to the marketplace is comparable to the 3,000-meter steeplechase event in Olympic track competition – a medium-distance race interspersed with hurdles. In new product development and innovation many things must come together: the idea; R&D and prototyping; raising financial resources; hiring staff; organizing production; developing marketing, sales and advertising plans; building distribution channels; and setting up and managing supply chains. In new product development, as in the steeplechase, each hurdle must be successfully surmounted in turn, in order to reach the finish line victorious, and win the gold medal. In both activities, though in theory you can stumble once and still win – each time this happens, the odds of succeeding are greatly reduced. To win, you need to have the short-term stamina to leap over each hurdle – and also the long-term endurance to last the full course, while running at near-top speed.

So, consider for a moment a set of eleven obstacles or hurdles, each of which must be successfully surmounted, in order to complete the innovation course successfully. Imagine yourself as a hurdler. Suppose the odds of leaping each obstacle are very high – 80 per cent. What are your chances of finishing the entire obstacle course, by surmounting every single one of the 11 hurdles?

The answer: 0.8 multiplied by itself eleven times, or only 8.6 per cent. Even when the odds are very high for succeeding at each stage, overall the chances for a successful new product launch – even when the initial idea is very well conceived – are about one in twelve. The reason: Every aspect of the new product's business design must be successful, from start to finish. The overall probability of success is multiplicative, meaning that failure at any stage brings the entire innovation process crashing down. A great many entrepreneurs, especially those with little business experience, fail to grasp this fundamental point, believing that the brilliance of their initial conception is sufficient to generate momentum that will create a winning product in the marketplace. By shortchanging the business design, and failing to devote to it sufficient resources and thought, many great new product ideas are doomed to failure.

The reader may wonder why precisely eleven obstacles or hurdles were chosen. The reason: The business design checklist includes eleven stages or aspects – see the Section on the elements of a business design below.

This Chapter examines in depth the detailed aspects of a complete business design. In addition to the technology underlying the creative process, there must be considerable management skill to build a winning business design. It must be clearly understood: *the amount of creativity invested in the design of the business model that brings the product to market must be no less than the creativity that spawns the new product itself.* Often, a creative business design applied to a humdrum product generates enormous business success, while a faulty business design applied to a phenomenal creative idea leads to massive failure.

Definition

A *business model is a comprehensive integrated plan covering every aspect of conceiving, developing, prototyping, producing, selling, marketing, advertising and financing a new product, process or service.* Business design is the process that creates the business model. Good business design is as essential for achieving competitive advantage as strong product innovation.

Example #1: First Alert

The second author, his wife and two of his children awoke one morning, all with splitting headaches. The cause turned out to be a gas heater, whose chimney had been blocked by wind-blown debris, causing incomplete combustion and generating dangerously-high levels of carbon monoxide. Death could not have been very far away.
A technological breakthrough has now created a small platinum-based CO sensor, now comfortingly on the Maital household's wall. One might think that this innovation would lead to instant marketplace success. Yet despite the clear need,

the lifesaving value of the product, and its reasonable cost (about $40), a faulty business model could easily lead to rapid bankruptcy. Rather than build costly independent retail sales and distribution systems, the First Alert product was cleverly sold through gas utilities, who have a very strong interest in preventing disasters and near-disasters of the sort described above. Some US states, and countries, now mandate such detectors wherever gas heaters are used. The combination of legislation, and gas utilities, brought this product to far more households than would have been the case, had the company built a conventional retail-type model. In this case, creativity was as evident in the business model as in the product's core technology.

Example #2: "Kind of Blue"

One of the most famous jazz albums of all time, "Kind of Blue", was based on music sketched out by trumpeter Miles Davis only hours before the recording session. Jimmy Cobb (drums), Miles Davis (trumpet), Bill Evans (piano), John Coltrane (tenor sax), and Cannonball Adderly were among the performers. None of the musicians had seen the music before, or rehearsed it. This album innovated modal improvisation – jazz inventions based on changing scales, rather than changing chords. Over a period of two days, what many regard as the greatest, most innovative jazz album ever recorded was completed. It remains one of the perennial top-selling jazz albums.

This album illustrates a key point in new product development. The spontaneity, serendipity and creative spark are all vital elements; often, they emerge out of controlled chaos, like that prevailing in the "Kind of Blue" recording session. Once that chaos has created an innovative product, order takes over. The album has to be produced, advertised, marketed and distributed, in a rapid, orderly fashion. *It is this combination of chaos and order, so difficult to create and even more difficult to manage, that is the basic requirement for a successful business design for innovation.*

A metaphor

A second metaphor is useful for understanding the link between new product development and business design – that of the human cell. The nucleus of the cell contains key genetic material, and is the cell's most important part, just as the product or service is at the center of the business design. But the nucleus cannot survive without the cell wall, cytoplasm, etc. – all of which support it and enable the cell to thrive and to reproduce, just as the various components of the business design – logistics, supply chain, marketing, production, assembly, advertising, human resources, finance – enable the core product idea to reach the right people, at the right time, at the right cost and price. Roberts has shown clearly that "companies that historically show product strategic focus perform substantially better over extended periods than companies that implement multiple technologies and/or seek market diversity" (1991, p. 306; see also Meyer and Roberts, 1986, 1988). With innovative products at the core of the business design, and with the design focused on creating marketplace success for the product, performance and success are substantially enhanced.

Direct business model of Dell

Perhaps the most dramatic example of a winning business design is Dell's "direct business model" – sale of computers direct to consumers and businesses – an example that will serve as a unifying theme in this Chapter. We will also make reference to a number of high-tech startups whom we studied and interviewed, while researching the implementation of our technometric approach in innovative companies.

Consider now perhaps the most successful business model of the past two decades: Dell's direct sale of computers, through Internet, phone and fax, to consumers and businesses. Michael Dell, founder and principal owner of Dell Computers, is only 34 years old and his personal worth is more than $16 billion dollars.[1] Measured by sales, Dell was the 78th largest firm in the U.S. in 1998, up from 125th in 1997; its 1998 revenue was $18.2 billion, with profits of $1.46 billion. Dell's stock was worth $111.3 billion on March 15, 1999; and its rate of return on shareholders equity (operating profit as a % of shareholders equity) was a startling 63 %, implying that Dell earned its shareholders a billion dollars in economic rent in 1998 (profits over and above the opportunity cost of its capital).[2] Clearly, the "direct business" model pioneered by Michael Dell is worth close study. Here is an account of the nature and origin of Dell's business design, with his own words in italics.[3]

As a young student at the University of Texas, Dell found computers more interesting than biology. His parents wanted him to be a Doctor. But when he went off to college as a freshman, he had three computers in his trunk and was making supplemental income by reselling used PC's. His parents actually made him stop selling computers because they noticed he was not concentrating on this school

1 According to Forbes magazine (1999), he is the sixth wealthiest billionaire in the world, behind Bill Gates, Warren Buffett, Paul Allen, Steve Ballmer and Philip Anschutz, and the youngest (by one year, over Amazon.com founder Jeff Bezos, 35).

2 Fortune Magazine, 1999a, pp. F1-F20. Also: Business Week, 1999, p. 64.

3 Michael Dell Speech at MIT, in Wong Auditorium, 11/19/98 5:30pm; and Magretta 1998, pp. 73-84.

work. He quit selling them, but only for a month and then realized computing was what he really wanted to do. He saw this as his major opportunity. In 1982-3, he realized that IBM was selling PC's for $3,000, when the components cost only $1,000. The difference was accounted for by retailers' margins, cost of inventory, shipping, distribution, etc. Dell realized that he could buy those same components, assemble PC's and sell them directly to customers, saving the high costs of retailing. This was his basic business model. The key advantage of the direct model, apart from cost savings: It facilitates direct contact with the consumer, enabling Dell to learn about changes in market demand and consumer preferences, and bring to market winning new models long before competitors learn of such changes through indirect channels.

The success of this business model is remarkable. Dell is growing at an incredible rate. There are only 82 companies in the world that have had revenue growth for the last 10 years of at least 10 % per year. There are only 11 companies that have had revenue growth for the last 3 years of 30 % per year. Dell is one of them. And – there is only one company (Dell) that has had revenue growth for the last 3 years of greater than 50 % per year (they actually had 55 % growth). They have no distribution channel conflicts because they have no distribution channels! Dell designs, manufactures and distributes their own computers and the combination of all these factors into one firm has created tremendous value for the customer and his company. Though they didn't get into the consumer market until several years ago, their consumer business is operating in 35 countries via direct distribution without problems. Dell built 2 million PC's in the third quarter of 1998 alone, and *they only maintain 7 days of inventory stock.*

A significant differentiation that they provide is customer software image preloads, of the 7 million machines they will sell this year, 2.5 million of them have custom software from the end-user preloaded. The fact that they only have 7 days of inventory on hand provides a direct financial payback because PC supplies typically depreciate at a rate of 1 % per week.

Integrating marketing and R&D

They also mentioned that unlike other PC manufacturers and distributers who are forced to "guess" what customer demand will be and "guess" what the right product mix is to send to their distributors, Dell is intimately involved with their customers and knows exactly what their customers want and the guessing is removed, they build exactly what the customers are ordering/buying and this is a competitive advantage.

The Dell theme is lower overall cost for sales and support. They first started out in direct personal selling, then added phone, and now internet sales. They are now booking over 10 million dollars a day in internet sales (20 % of their sales are currently online) and they are looking for that to grow to at least 50 % online in the "near" future. Two million visitors go to their websites a week.

"*Because we're direct and can see who is buying what, we noticed...the industry's average selling price was going down, but ours was going up. Consumers who wanted the most powerful machines were coming to us...and without focusing on it in a significant way, we had a billion-dollar consumer business that was profitable!*"

Dell introduced the concept of Premier pages where they dedicate a specific set of web pages to a particular company that has pre-selected configurations, prices, etc which a company can direct their employees to choose their work PC from these pages. They have over 8,500 of these Premier web pages. 80 % of their on-line business is to large business and institutional customers.

Supply chain management

80 % of Dell's components are purchased from only 20 suppliers, with this they have a very tight link with their suppliers. They are convinced *you can replace physical assets in the distribution channel with information assets* and this strategy has worked all over the world. They started with desktops, then added laptops, now servers and they will continue to add more offerings as it makes sense.

Dell currently owns only 9 % of the worlds PC market and he sees a huge opportunity to own much more of it. Dell went from 2 % to 20 % marketshare in two-and-one-half years in the U.S., surpassing HP and IBM without any specialized service and support infrastructure of their own. They contract out service and support with companies like Unisys, Wang, EDS, etc to do this job. PC Standards have really allowed the Dell model to work and as standards settled in, cost became a greater factor and they have capitalized on this.

Dell predicts the next phase of expanding their business will depend on improving the quality of the total product including service and support – the total customer experience. Dell thinks the overall PC industry is currently very bad with quality and overall support and sees this as an opportunity for him to differentiate himself and his company.

What can be learned?

What other industries will this Dell model work? Dell mentioned the automotive industry as having potential. There are a tremendous amount of assets in car production, start to finish. The only reason it's this way is because history dictated this. The problems IBM and some of his other competitors are having is exactly this history, or legacy, of distribution channels that is weighing them down (see the Section on "Transition Problems" below).

"We concluded we'd be better off leveraging the investments others have made and focusing on delivering solutions and systems to customers....We said... shouldn't we be more selective and put our capital into activities where we can add value for our customers (by not creating every piece of the value chain, and by using outsourcers and suppliers)?. ... It's fair to think of our companies as being virtually integrated. That allows us to focus on where we add value..."

Elements of business design

Business Design is a process that can be perceived as running down a list of key questions that need concrete answers (Slywotzky, 1996) right from the moment that a new product, process or service is conceived (see Table 1). It was this process that Dell followed, whether explicitly or intuitively.

Basic assumptions

The essence of every business model is a clear brief statement about how the product or service creates value for customers, beyond what is currently (or in the near future) available. For example: here is the value statement of the U.S. Coast Guard, as provided by a Coast Guard officer and MBA student: "The Coast Guard is a multimission force that seeks to: a) eliminate death, injury and property damage, and eliminate environmental damage and natural resource degradation, in the maritime environment; b) protect maritime borders from all intrusions, c) facilitate maritime commerce, and d) defend the nation as one of the five armed forces."

Value statements must be constantly evaluated, in response to changes in basic assumptions:

- How are customers changing? How do their life styles, preferences, values, goals, family life, etc. change? And how must our products change in response?
- What are customers' priorities? For instance: the baby-boomer generation appeared to some focused on acquisition of wealth and goods; the baby-bust generation seems more interested in quality of life. Product innovation must reflect this.
- What are the profit drivers? New products should be profitable. What factors drive profitability? And how can this profitability be sustained, in the face of inevitable competition and imitation? Success, if it comes, will almost certainly

draw imitators. A good business design considers long in advance how this competition will be met.

Table 1: Business design - a checklist.

1. Basic Assumptions
* How are customers changing?
* What are customers' priorities?
* What are the profit drivers?

2. Customer Selection
* Which customers do we want to serve?
* Which customers will drive value growth?

3. Scope
* Which products do we want to sell?
* Which support activities should be in-house?
* Which ones should we subcontract or outsource?

4. Differentiation
* What is my basis for differentiation?
* What is my unique value proposition?
* Why should the customer want to buy from me?
* Who are my key competitors?
* Who will be my key competitors in 1 to 5 years?
* How convincing is my differentiation relative to that of my competitors?

5. Value Recapture
* How does the customer pay for the value we create?
* How are my shareholders compensated for the value we create?

6. Purchasing System
* How do we buy, transactional or long term, antagonistic or partner?

7. Manufacturing and Operations
* How much do we manufacture vs. subcontract?
* Are my manufacturing/service delivery economies based primarily on fixed or on variable costs?
* Do we need state of the art or 90th percentile technology?

8. Capital Intensity
* Do we use capital-intensive (high fixed cost) systems or flexible less-capital-intensive systems?

9. R&D and New Product Development
* Internal or outsourced, focused on process, or on product?
* Focused on astute project selection or on speed of development?

10. Organizational Configuration
* Centralized or decentralized?
* Pyramid or network?
* Functional or business or matrix?
* Internal promotion or external hiring?

11. Go to Market Mechanism
* Direct sales force?
* Low cost distribution?
* Sales representatives (multi brand)?
* Account management? licensing?
* Direct business model?
* Hybrid system?

Source: adapted from Slywotzky, 1996.

Some of the greatest new innovations arise from the direct needs of inventors. For instance:

Example #3: Surgery?

An Israeli engineer was found to have a brain tumor. He was dissatisfied with the accuracy of existing imaging techniques, and was unwilling to undergo the surgeon's knife facing such inaccuracy. Using his engineering skills, he found an innovation that achieved what was to him the required imaging precision – and underwent the surgery. The innovation became a fast-growing startup. Few value statements – or "needs assessments" -- are more meaningful than one involving personal need or distress experienced by the entrepreneurs themselves.

Example #4: "Please sign here"

In 1990, many entrepreneurs worked on pen-based computing. Most of the uses of this new technology focused on drawing, highlighting, or correcting text – all done reasonably well with keyboards.

A basic assumption was that individual signatures would, for legal and other reasons, remain handwritten. A British entrepreneur named Jeremy Newman refused to accept this assumption, and created software designed to get a legally binding signature without paper, by signing on a pressure-sensitive pad. His company, PenOp, based in New York, shipped 30,000 copies in a short time. His product creates value for field agents of insurance companies, police officers and financial services firms.[4]

Customer selection

Business design begins with an analysis of the nature and size of the potential market, including the "demographics" – basic data on income, education and age of potential buyers. These data help provide answers to these questions:

- Which customers do we want to serve?
- Which customers will drive value growth?

Good business models have a sharply-defined image of who potential customers are – their needs, preferences, and goals. They include a brief statement about who these customers are. For example: We plan to sell our line of upscale T-shirts to males aged 30-40 with above-average incomes and college education. Demographic analysis should also consider the rate at which targeted customers are growing in numbers, and in resources. For instance: the fastest-growing demographic group in the U.S. in the next two decades will be those over age 65.

Example #5: "Now Johnny – eat your fork like a good boy"

A startup company we studied invented remarkable technology for producing edible straws – straws stiff enough to drink through, yet made of tasty food-like matter that could be eaten. The technology was patented. The same material could produce edible plates and utensils. The company's senior management tended to waiver between focusing on "edible utensils" (stressing the functionality of the utensil) and on "tasty snacks" (stressing the value of the material as a crunchy food).

The "utensil" product had the following key features: functionality, hardness, elasticity, weight, price, appearance, storability, shelf life. The "snack" product had the following features: taste, texture, color, sweetness, appearance, aftertaste, natural food content. The company had difficulty defining whether it would sell the product as a utensil or as a snack. Its business model never did solve the basic problem of production: Existing food companies were unwilling to rent production capacity, yet the startup itself could not afford to build its own production line. The product has yet to reach the market.

4 Fry, 1998, p. B7.

Scope

There is perpetual tension between the desire to reach the largest possible market – a key factor that attracts venture capital is market size – and the need to focus sharply on high-likelihood customers. This requires hard decisions about:

- Which products do we want to sell?
- Which support activities should be in-house?
- Which ones should we subcontract or outsource?

Pioneering new business models sometimes eschew actual production of products, preferring to subcontract or outsource such production to plants in, say, Southeast Asia, while investing scarce capital in R&D and in marketing – a model followed with huge success by Nike. It should not be assumed from the outset that to bring a new product to market, it is necessary to produce it. In today's global deflation, widespread excess productive capacity often means that subcontractors can be found, who are happy to produce to order and who already have the factory capacity in place. This can save large amounts of capital – though it runs the risk of facing shortages in booming markets, when excess capacity suddenly changes into production delays and excess demand.

A winning business design often perceives innovation as creation of product platforms – a whole series of new products – rather than single new products. For example: Intel's n86 series of microprocessors. Like other aspects of business design, platforms must be planned from the outset (Clark and Wheelwright, 1993; Tabrizi and Walleigh, 1997).

Example #6. "Six workers, three products"

We spoke with a startup company, a wholly-owned subsidiary of a large American medical-products firm, that was engaged in R&D on three wonderful products: a) a medical laser printer, b) a precise calorimeter for measuring caloric intake, and c) software for creating images from ultrasound data. The company had three employees with Ph.D.'s and three technicians. Each product was among the best of its kind, or even unique – but each lacked a winning business design. In the cost-cutting environment of American health care, the company's high-priced products met stiff market resistance; inferior products with cheaper price tags sold much better. The company seemed to us to lack product focus. Its printer was best in size and weight, but scored low in interface flexibility, contrast and resolution – key features for its specific market. The founder eventually joined another medical startup, as its ceo.

Differentiation

Business design always follows a popular version of Einstein's Relativity Theory: value creation is always relative to some alternative, and new products require strong "differentiators", showing how they differ from what can already be bought. "Me-too" is not a winning innovation philosophy. Product differentiation requires answers to these questions:

- What is my basis for differentiation?
- What is my unique value proposition?
- Why should the customer want to buy from me?
- Who are my key competitors?
- Who will be my key competitors in 1 to 5 years?
- How convincing is my differentiation relative to that of my competitors?

Dell's business model "differentiator" is the ability to offer customers computers precisely tailored and customized to their needs, based on their choice of a wide range of options, rather than forcing them to buy computers "off-the-shelf". Dell's defense against imitators is the huge difficulty of making the transition from conventional retailing to the direct model. This example shows why building the appropriate business model from the outset is so crucial. It is extremely difficult to transition from one business model to another, once the design is set in concrete (see below the Section on "Transition Problems").

Example #7: "Pen to computer"

A string of companies tried to launch pens that recognized handwriting and stored handwritten material, for transfer to computers later. They included GO; IBM's Thinkpad-plus pen (cancelled); EO; and Apple's Newton. None succeeded. All were based on OCR (optical character recognition) software. An Israeli entrepreneur chose a different approach. His computer-pen, instead of recognizing charactes pixel by pixel, had motion sensors that recognized the *motion* of handwriting, and recognized, for example, the letter "a" according to the kinetics of how the writer wrote it. The pen achieved a 5 % error rate – good or better than the prevailing optical technology. The product was superb – but faced the obstacle that virtually no Israeli company had successfully pioneered and sold a mass-market product in America and Europe. The enormous marketing and advertising resources needed to launch a revolutionary product were not forthcoming. Again, a great core idea stumbled when the surrounding business design fell short.

Value Recapture

Business designs consider carefully how value-creation can, through pricing policies, be turned into profit. Value creation is a sufficient, but not necessary, condition for profit, and the issue of how to capture value is a vital one. The key questions:

- How does the customer pay for the value we create?
- How are my shareholders compensated for the value we create?

Internet businesses provide an example. The Internet grew extremely rapidly, in part through its open nature and in part because it offered information and services without charge. Internet users became accustomed to this. When Internet businesses sprang up, they faced the key dilemma: how can value be captured by charging non-zero prices, for things users had been accustomed to getting for nothing. This required innovative pricing policies.

In an age when shareholders are increasingly militant, return to shareholders is crucial. A business model must carefully conserve shareholders' capital, in order to ensure the highest possible return on capital investment. For example: a leading spreadsheet software firm invested excessively in a splendid new headquarters building, rather than in R&D for its new-generation product, and soon found itself acquired and out of business.

Example #8: "Expensive means good"

We met with a company that had developed a radically new method for cleaning silicon wafers electronically (the existing process was chemical-based, and hence, costly, and environmentally unfriendly). This product matched the market leader in every product feature but two: price (it was very expensive) and reliability (it had significantly greater downtime).

The company's business design called for maintaining the high price, since the product created high value for its users, and investing heavily to resolve the reliability problem. The company's initial public offering was successful; investors saw high profit potential in the product, and hence placed a high market value of the company's stock.

Purchasing system

Managing relationships with suppliers has become increasingly important, as growing numbers of firms choose to outsource. The issues that must be addressed are:

- How do we buy: transactional or long term; antagonistic or partner?
- What part of our operation do we outsource: components, service and maintenance, information technology, data processing, R&D?

- How can we integrate our suppliers seamlessly into our own operations? (A good model for supplier management is Dell Computers).
- How can effective use be made of enterprise resource planning (ERP) software, to manage our purchasing operations?

Manufacturing and operations

Here, a key issue is: Do we need to build our own production facility? A business model growing in popularity is one where production is subcontracted to producers elsewhere; in the Dell model, computers are assembled, customized to each customer's preferences, using components made by other firms.

- How much do we manufacture vs. subcontract?
- Are my manufacturing/service delivery economies based primarily on fixed or on variable costs?
- Do we need state of the art or 90th percentile technology?

Capital intensity

Production and assembly may be either labor-intensive or capital-intensive. In low-wage countries, it makes sense to use labor-intensive methods. The issues here are:

- Do we use capital-intensive (high fixed cost) systems or flexible less-capital-intensive systems?
- Is replacement of labor with capital, using robotic systems, a wise short-term and long-term investment?

R&D and new product development

Management of Research and Development is a vital part of every business design. The issues that arise here are:

- Should R&D be internal or outsourced, focused on process, or on product? How much of our R&D resources should be devoted to research, and how much to focused development?
- How can R&D personnel best learn about marketplace needs?
- How can R&D teams work effectively with marketing, production, advertising and sales functions, to accelerate time-to-market?
- What mechanisms ensure that R&D projects will be completed on schedule? This is especially important – missing a "window of opportunity" by even a month or two can be damaging or even fatal to a company, at a time when the pace of innovation is rapid and competition is fierce.

A key principle widely embraced in knowledge-based businesses is: Outsource capacity (i.e. production, assembly, etc.), not knowledge. Competitive advantage generally resides in a company's proprietary knowledge; outsourcing knowledge creation gives up this advantage from the outset.

Organizational configuration

The organizational structure of a company has much to do with whether the company achieves its goals. Just as in architecture, where form follows function, so in innovation does structure follow the organization's objectives. A company focused on being innovative, and on creating new products and bringing them rapidly to market, needs a flat, flexible organization in which individual workers and managers are empowered and are able and willing to accept responsibility and make decisions. The issues are:

- Should the organization be centralized or decentralized, hierarchical or flat, inverted tree or pyramid, or network, functional or business or matrix?
- Should managers be developed through internal promotion or external hiring?
- How can learning within the organization be facilitated? How can the organizational structure be so organized, as to smooth internal communication and transfer of knowledge and experience from one part of the organization to another?

Go to market mechanism

From the outset, the way in which the product is delivered to the customer must be carefully thought through. Too often, product innovators adopt an implicit "Field of Dreams" approach – if we build it, then, they will come. The issues are:

- Use a direct sales force or low cost distribution, employing non-salaried sales representatives (multi brand)?
- How will account management be handled? Licensing of the product?
- Is the direct business model applicable? If so: in what form?
- How will the Internet be used as a sales channel?

Example #9: "Value to consumers"

A business consultant worked with a chip manufacturer, who had developed a chip for digital cameras. The product did not sell well. His recommendation: enhance the value of digital cameras, by enhancing the ability of users to print out digital photographs with home printers. The result was a new chip, designed for PC printers, that made digital photography more worthwhile. The result: more direct sales, and more sales to digital-camera producers, because their product was made more worthwhile to consumers.

All these questions, and many more, must be carefully considered, even at the stage of inception, when the product is only an idea. The reason: The business design will be as an important a part of the product's marketplace success as the quality and features of the product itself. Moreover, it is vital to design a winning business model from the outset. Changing an existing business model leads to "transition" problems that can be exceptionally difficult; a business model creates agents who have a vested interest in preserving it, even when it is inimicable to the company's continued success.

Transition problems: Getting to the right business model from the wrong one

Two innovative new business models now dominate their industries.

- Dell's "direct business model" for selling computers directly to businesses and individuals through telephone, fax and Web sites;
- ETrade's "Internet Web-based stock trading", where customers pay $14.95 per trade implemented through ETrade's web site.

Some 30 per cent of all computers are now sold through the direct business model, and Dell expects this to rise to above 50 per cent within two years. Some 15 per cent of all stock trades are now done through on-line trading, and this percentage too is rising rapidly.

Now, consider the management problem facing, say, IBM and Merrill-Lynch, leading companies in their industries. IBM's ceo clearly recognizes the power of the direct business model. Why not embrace it immediately? Surely IBM has organizational skills at least close to those of Dell. Merrill Lynch's chairman also cannot fail to have noticed the tidal wave of on-line trading. Why, then, can you do nearly everything with Merrill Lynch on-line – except buy and sell stocks?

The problem is one of transition. If IBM, or Compaq, were to announce tomorrow that their sales would henceforth be "direct" – or largely, direct – how would their resellers react? How would Sears, Circuit City and other retailers respond? They would instantly regard IBM as a competitor, rather than supplier, and stop selling IBM products. During the transition period from resellers to the direct model, IBM or Compaq sales would suffer grievously.

What constituency keeps Merrill Lynch from moving rapidly to on-line trading? Their own stockbrokers, of course, who profit handsomely from commissions and related bonuses. Those stakeholders are at least as powerful as the shareholders.

Often, the power of a new business model – and the ability of an innovator to sustain it – is in the difficulty established incumbents have in abandoning their existing business model. Large organizations, when faced with a new business model, have to grapple with the issue: How do we get there from here? For Merrill Lynch, IBM, Compaq, and many other established incumbents – there seems to be no trustworthy road map.

Writing a winning business plan[5]

Business design is similar to architectural design. Conceptions must be turned into blueprints, that show builders what must be erected and how. The blueprint of a business model is known as a business plan. Strong business plans are essential for success at innovation. The business plan provides a common language for all those involved with the new product, gives them a clear focus and objective, and sets goals. It also conveys to insiders – senior management within the company, or members of other divisions – and to outsiders – venture capitalists or other investors, suppliers, and strategic allies – what the innovators' intentions are.

Good business plans deal with four elements, and how they interact: People (human resources; those starting the venture, plus those outside the company who will assist); Context (the industry, marketplace, and economy; factors beyond the entrepreneurs' control); Risk-Reward (profitability and the risk entailed in gaining it; what can go wrong, what can go right, and how to respond); and Opportunity (the value-creation formula and how and whether it can be sustained; what will be sold, to whom, when, how, and why).

A common misconception is that the most important element of a business plan is the spreadsheet showing projections of costs and revenues. This is not the case. It is precisely the ease of creating such spreadsheets that makes them suspect. As Sahlman (1997, p. 98) notes: "Most [business plans] waste too much ink on numbers and devote too little information that really matters to the intelligent investors.... numbers should appear mainly in the form of a business model that shows the entrepreneurial team has thought *through the key drivers of the venture's success or failure*" (our italics).

Every innovation project, whether involving a new business startup or an R&D project within an established firm, needs a detailed business design, blueprinted in a business plan. One purpose of a business plan is to convey the project's intentions to others (investors, suppliers, customers, etc.). Another purpose, no less important, is

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5 This Section is based in part on: Sahlman 1997, pp. 98-108.

to define to the entrepreneurs or project managers *themselves* what the ends and means for achieving them are. A good business plan is like a clear, easy-to-read road map – you can navigate without it, but navigating with it is far easier and improves the chances of reaching your destination speedily.

Utilizing the toolbox in building a business model

In this concluding Section, we conclude and summarize our book, by indicating how our microeconomic tools can help build a business model.

Incremental improvements

The introduction to this book began with a rudimentary business model built around improving a single feature: taking a pharmaceutical product (Fosamax) weekly, rather than daily. Significantly improving one key feature can often create winning new products.

Philosopher Isaiah Berlin spoke of thinkers who were either "foxes", who knew many little things, or "hedgehogs", who knew one big thing. Consider, for instance, the Palm Pilot. Previous PDA's (personal digital assistants) like Apple's Newton tried hard to do too much. Palm Pilot, like the hedgehog, knew one basic thing – keeping track of our meetings, addresses and phone numbers – and did it very well. Identifying a key feature, or features, and improving them, can generate successful products. Chapter 1's tool, for optimizing incremental innovation, can help guide this process, using basic economic cost-benefit logic.

Feature improvement must be market-driven. Chapter 15 shows how key information from the marketing department can be used to match "psychology" – the benefits buyers derive from features – with "technology" – the relative cost and feasibility of feature-based innovations. Ways to integrate value knowledge residing in Marketing and Research & Development departments, when those groups are often separated by geographical distance and always by cultural distance, is an issue that business models must address.

Radical innovation

Akio Morita's Walkman had a radically new feature: its size, and earphones, enabled Walkman owners to hear music wherever they happened to be. The cellular phone, invented only 16 years ago, offered the same radically-new feature – the ability to communicate from almost anywhere. Both these radical innovations encountered stiff internal resistance, within the companies developing them. Why would anyone *want* to hear music while walking around – or talk to their wives or friends or colleagues on the phone?

Alfred North Whitehead once said that we live in the concrete, but think in the abstract. We tend to disagree. Most of us *think* in the concrete as well. Radically new innovations demand a leap of insight, and a courageous managerial decision to take that leap, precisely because people think in the concrete, and, lacking concrete examples, find it hard to image a radically new feature and the benefits it conveys. This is why market research can often be radical innovations' nemesis. Chapter 2 offers a quantitative tool for analyzing and optimizing radical innovation, while at the same time recognizing that many of the inputs and data needed for this model are highly uncertain. Often, the need to quantify something inherently resistant to quantification helps clarify our thinking, even if the method itself is too demanding of data to be fully workable.

Frequently, R&D investment in new, pioneering technologies proves fruitless. This was the case with the first companies to produce commercial lasers. Conventional approaches to quantifying the economic returns on such investments – discounted cash flow, or net present value – often cause bottom-line-conscious managers to avoid such projects. A new approach to valuing risky R&D investment in radical innovations, explained in Chapter 3, takes into account the "option value" of such investments – the fact that while first-generation lasers were clumsy and flawed, second- and third-generation ones created an enormous market, benefiting humankind greatly; and obviously, the success of second-generation products build on the (often expensive) learning process experienced in the failure of first-generation ones. The metaphor of R&D investment as a "real option" can sometimes turn what appears to be an unprofitable innovation into a profitable one – and point to a correct decision.

Creating value

The essence of every business model is the creation of value for customers. Value creation is often a rather mysterious process, with customers themselves finding it difficult to articulate precisely what they need, or why, or why they value a particular product or service. In Chapter 4, we offer a tool for using market-based information to help answer the question*: Which product features drive value, and hence price?* By helping innovators determine which features "explain" (in a statistical sense) market price, the "hedonic price" tool can often identify the nature and direction of innovation activity. In our experience, generally a small number of key features explain most of the variance in market price. Innovative products that fail to excel in those key features will not likely succeed.

One way products create value is by reducing uncertainty and offering assurance of quality and consistency – features inherent in globally-known brand names.

Chapter 5 offers a new feature-based approach to measuring the market value of brand names, by measuring separately the contribution of brands to market price, and the contribution of product features. This approach can help business-model builders quantify the potential value of the large (and often vital) investments required for brand-building.

How important is innovation?

Adam Smith, in The Wealth of Nations (1776), asked why some countries grow wealthy, while others remain poor. His answer focused on the availability of land and resources relative to population. Seven years earlier, in 1769, fellow Scot James Watt had invented the steam engine, which made physical and financial capital, rather than resources, the key growth-generating resource and led to the First Industrial Revolution (caused by steam power) and the Second, powered by electricity. Today, the world is experiencing a new Industrial Revolution, the Third (see Moss, 1996). This revolution is powered by global markets and knowledge-based products and services generated by innovative companies and nations. The posited link between science, technology, innovation and economic performance is examined in depth in Part II of this volume. Chapter 6 focuses on the microeconomic link between firm-level profitability and innovation in Israel, while Chapters 9 and 10 look at the link between scientific excellence and export performance at the country level, for the European Union and Israel. Chapter 7 proposes applying a tool widely-used for measuring technical change at the country level (total factor productivity) to individual firms, and shows how; while Chapter 8 offers some benchmarking tools for one of the world's most innovative and fastest growing industries, telecommunications.

Tracking product quality

Good business models try to create sustainable competitive advantage. They are inevitably based on careful assessments of competing products. Part III offered a series of product and industry studies, showing how our feature-based technometric approach can be used to benchmark and compare product quality at a given point in time (for biodiagnosic kits, in Chapter 11, and for industrial sensors, in Chapter 12), and to measure changes in product quality across two points in time (Chapter 13), also for sensors. Chapter 14 studies a variety of knowledge-based products, and discovers that new and old technologies tend to co-exist, offering a range of potentially-successful business models from "create the radically new" to "perfect the old and reliable".

Epilogue

Joseph Schumpeter characterized innovation as "creative destruction". Lester Thurow has observed that a better characterization of the innovative process might be "destructive creation". The process of innovation destroys markets for old products, in the course of bringing new and better ones to consumers. In this process, there are winners and losers, as in nearly all dynamic change. Those who lose belong to products and industries that are on their way out. Those who win are linked with innovative products and industries.

We began this book with an observation about innovation being a delicate balance between chaos and order. It is our hope that achieving this balance, with the aid of some or all of the microeconomic tools we describe, can place managers and workers together in the ranks of the winners. Recently, a leading American toymaker announced that at the height of the Christmas toy-buying peak, it was laying off thousands of workers – its senior managers had failed to anticipate the shift away from conventional toys and into video games and electronic toys, a shift evident years earlier. A systematic effort to quantify innovation and benchmark it might have prevented a bleak Christmas for laid-off workers.

Ultimately, innovation is about improving people's lives. We hope this book makes a small but noticeable contribution.

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Managing New Product Development and Innovation

A Microeconomic Toolbox

Hariolf Grupp and Shlomo Maital

Comprising over a decade of research, the fifteen chapters in this book offer a selection of practical microeconomic tools for managing new product development and innovation. An overall theme unites these tools: feature-based innovation. By quantifying product features and evaluating the costs and market value of improving each, a simple yet powerful conceptual framework is created. Using this framework, creative business models can be built, along with innovative products, services and processes that achieve marketplace success. The book addresses the five key questions facing all managers of knowledge-based companies:

- Which new features should be added to existing products?
- Which radically new features should be innovated?
- How can marketing and R&D be integrated?
- How can the value of brand names be estimated and optimized?
- How can the sophistication of product technology be measured, both at a given point in time and between two points in time?

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Shlomo Maital has been an associate of the Samuel Neaman Institute for Advanced Studies in Science and Technology since 1985. **The Samuel Neaman Institute for Advanced Studies in Science and Technology** is an independent policy-research institute, established in 1978 to assist in the search for solutions to national problems in science and technology, education, and economic, health and social development. An interdisciplinary think-tank, the Institute draws on faculty and staff of Technion, other institutions in Israel and specialists abroad. The Institute serves as a bridge between academia and decision makers through research, workshops and publications.

Hariolf Grupp is Deputy Director of Fraunhofer-ISI. **Fraunhofer Institute for Systems and Innovation Research (ISI),** located in Karlsruhe, Germany, performs interdisciplinary research at the interface of technology, economy and science. By analysis of promising technologies, development of research priorities and monitoring of technology policy programmes, ISI assists decision-making processes in the public and private sectors. The institute promotes technical and organisational innovation processes in industry, service sectors, state facilities and private households. Technology forecasting and assessment, regional analyses and innovation services are offered in the fields of production, biotechnology, energy, environment and communication. Interdisciplinary methods of analysis, assessment and forecasting such as Delphi surveys, in-depth interviews, techno-economic indicators, quantitative models and qualitative procedures are utilised in this.

TECHNION - ISRAEL INSTITUTE OF TECHNOLOGY
Technion City, Haifa 32000, Israel Tel: 972 4 829 2329, 823 7145 Fax: 972 4 823 1889 info@neaman.org.il
www.neaman.org.il