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Metrics for Managing Research and Development

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Abstract

The paper proposes methods to measure the performance of research and development in new product development. We base the work in the context of evolving product families in the technology-based firm with the goal of more clearly understanding the dynamics and consequences of platform renewal and product generation for long term success.

We test the proposed methods with data gathered from a large measurement systems manufacturer. We find that the methods and the resulting measures provide management with a technique to identify both the technological and market leverage achieved from the firm's present and past product platforms. This provides a foundation for transforming single product, single period planning processes into a multi product, multi period form that embraces the product family and the renewal of product architecture. The research also shows the need to integrate data from engineering, manufacturing, and sales organizations to produce information for managing the growth of the firm's product families.

When should a firm renew the underlying technologies and designs of its products? How much will these efforts cost and how long may they be expected to take? What types of engineering and commercial benefits can the firm expect to gain from product redesign? How can a firm improve its approaches and strategies for product development? These are fundamental questions for sustained success in product development that we seek to address in this article. We will define the essential characteristics of products and propose measurement methods to guide the firm in its planning and management of new product creation. Systematic and continuous learning and improvement in the way in which a firm creates new products is the basis for more rapid and commercially successful product development. In turn, learning cannot be achieved without clear and purposeful measurement.

1. Measurement for Research and Development

What measures of performance can help firms better manage the development of new products ? What might be the purpose and goal of these measures ? The answer may lie in examining the desired outcomes of effective new product development. Productive, innovative firms are capable of generating a continuous stream of new products. If firms do not make new products, they lose competitive position and die. It has been shown that the elements of this stream of products, ie. the individual products, can be efficiently constructed on successive generations of underlying product architectures, commonly referred to as product *platforms*. (Sanderson and Uzumeri, 1991; Wheelwright and Clark, 1992; Meyer and Utterback, 1993). Modular platforms (Uhrich and Tung, 1991) with clear interfaces between embodied modules (Smith and Reinertsen, 1992) can allow a firm to rapidly and efficiently derive follow-on products based on its product platforms. Clear understanding of customers' needs that is then incorporated into platform and follow-on product designs can generate high levels of sales to engineering resource productivity. (Hauser and Clausing, 1988). As a product family evolves, platform architectures must be continuously renewed and new component technology integrated into these designs to keep the firm's offerings freshly competitive (Meyer and Utterback, 1993; Iansiti, 1993).

The purpose of measures of the effectiveness of research and development should be to demonstrate firm performance in this critical dimension of new product development, pointing the way towards improvement. How do firms measure R&D performance now ? The measures of R&D performance observed in Moser's (1985) industry survey were short-term in nature and focused on single products or projects. These measures either qualitatively assessed goal attainment or computed the variance between project plans and actual outcomes along the dimensions of cost and time. Moser found that the most commonly used R&D metric was "slip."

ie. the gap between expected and actual project time and budget. Slip rate measures the quality of management's schedule predictions. Some firms that use a stage-gate product generation process (Cooper 1990) compute slippage between the development phases for respective products, determining which phases encounter the greatest estimation difficulty. Gupta and Wilemon (1990) found that poor or unclear product definition was the primary cause of delayed projects. The measurement systems manufacturer whose data will be used later in this paper currently tracks successive phase slip for its projects. Management has found the initial stage of technical and market definition to be most problematic.

Accurate project estimation should not necessarily be construed as a predictor of successful technical and commercial outcomes in product development. Mansfield's (1972) study of a successful pharmaceutical company showed the firm experienced overruns on 80% of its new products efforts, with an average slip of 1.78 over planned costs, and 1.61. on planned schedules. (Mansfield, et al. 1971) Yet, the firm prospered from these "late" products. A study of an aluminum company's efforts to create industrial products outside its traditional smelting business revealed that "tight schedules" for novel products led to poor financial outcomes (Utterback et al. 1992) Slip rate is also commonly used to examine the experiences of individual projects (or products). This has little to do with what occurs in the aggregate across the stream of new products generated by the typical product-making company. From a product family perspective, the development of base architectures may take a long time to complete, but once finished, may serve as the foundation for rapid development of derivative products.

Numerous measures of R&D effectiveness have been proposed in the literature (some seventy-five in total based on our literature search of the topic). Appendix 1 places these measurements in a typology based on the *purpose* of measurement (Cordero 1990) and the *method* of measurement. The purposes of various measurement may be seen as seeking to understanding performance in the sequential stages of the product life cycle: measuring the effectiveness of product planning before actual development, controlling projects during development, measuring the technical outcomes of the completed development, measuring the commercial outcomes associated with completed products, and lastly, understanding overall performance across the span of a product's full life cycle. As shown in Appendix 1, the techniques of measurement that we found proposed in the literature to measure performance in these various stages included: (1) comparative assessments of new products in terms of success, (2) scoring models on product features relative to competitors' products, (3) benefits contribution methods based on the sales-related outcomes of products, (4) various forms of performance to schedule analyses (the most commonly used form today being total project slip or slip at different key phases of a project), and (5) analyses of individual and organization technical accomplishment, including the counting and comparison of patents awarded to members of a group or publications emerging from them.

The impact of these various measures is suspect, however. Schainblatt (1982) found that "there are no currently used systems for measuring R&D productivity that are not flawed." Of the firms that he studied, 59% did not measure the R&D function and only 20% compared R&D costs to commercial outcomes on a quantitative basis. Another survey of 700 manufacturing firms also found that 35% of the sample failed to systematically assess the performance of R&D (Rockwell and Particelli, 1982). A recent survey of 248 R&D executives by the Industrial Research Institute showed that "measuring and improving R&D productivity and effectiveness" was the "biggest problem" for respondents (Industrial Research Institute, 1993), a finding confirmed by Roberts (1994) in his survey of corporate executives.

We believe that the limited utility of existing measures of R&D performance is that by their design and implementation, these measures do not help management understand the longer term dynamics of evolving product lines, the renewal of their underlying architectures, and the leverage that these architectures provide in derivative products. Addressing this need is the purpose of this paper, and it is the key point of comparison between what we propose and the existing R&D performance literature. It should also be clearly noted that our primary focus is the R&D phase of product development as opposed to performance measurement for the manufacturing (Kaplan 1990), market introduction and distribution. A truly comprehensive picture would incorporate all these dimensions.

We will propose measures of R&D performance compatible with the management model of evolving product families. Data from a more than twenty year period within a large measurement systems manufacturer will then be used to test and explain these measures. We will first define the product family and then measures of R&D effectiveness suited for it. These metrics are then applied to a sample of industrial measurement systems and interpreted within the management, marketing, and technological factors influencing the evolution of these product families. We then conclude the paper with a discussion of the benefits, costs, and qualifications of the proposed methods and suggest areas for complementary research. The overriding goal of the paper is to make a contribution to management practice in the understanding of the effectiveness of R&D for product development that encompasses groups of individual products related by common architecture.

3. Meta-Metrics for the Product Family

3.1 Defining the Product Family

The effectiveness of the firm's new product generation activity lies in: (1) its ability to create a continuous stream of successful new products over an extended period of time; and (2) the attractiveness of these products to the firm's chosen markets.

Streams of new products generated by firms may be thought of as evolving product families. A product family is defined as a set of products that share common technology and address a related set of market applications. This commonality may be validated for a group of products by applying the technology and market newness criteria proposed by Meyer and Roberts (1986). Successive products within a product family can be assessed by virtue of newness of embodied core technology and market applications. An evolving product family will introduce new technologies into product designs and target new customer requirements. However, the scope of change will be bounded. New technologies and market applications of a product family will be "related" to older ones: new technologies will be combined with and enhance existing core technologies and the resulting products will target existing and related market applications. The commonality of technologies and markets leads to efficiency and effectiveness in manufacturing, distribution, and service, where the firm tailors each general resource or capability to the needs of specific market niches.

The technological foundation of the product family we define as the product platform. A platform is the physical implementation of a technical design that serves as the base architecture for a series of derivative products. The efficiency of the platform in serving as a foundation for such derivatives is logically one key aspect of product family management.

The concept of platforms, product derivatives, and renewal is not new. Wheelwright and Clark (1992) differentiated between platforms, their derivative products, and platform "extensions" or renewals for vacuum cleaners; Meyer and Utterback (1993) did the same in their study of electronic imaging systems and peripherals, as did Sanderson and Uzumeri (1993) in the evolution of portable cassette players, and Lehnerd (1987) for power tools. These examples reflect more recent industrial experience and practice. Chrysler's newly achieved success with its LH series of automobiles, and more recently, its Neon automobiles, was based on a clear platform development strategy. Timely platform renewal has been essential to Intel's continuing success with its X8086 family of microprocessors. As soon as a particular microprocessor platform is completed, and derivative products start to be generated from it, resources are immediately allocated to obsoleting the current platform with new designs. Planning looks out into the future for several or more platform generations.

These cases can be generalized into an evolutionary model for the product family as shown in Figure 1. It represents a single product family that undergoes successive platform extensions, a new platform development, and the respective follow-on product developments of these platform versions. To achieve sustained success, a firm must seek to continuously renew its base product architectures. This approach generates a set of engineering activities focused on platform renewal that coexist with specific follow-on product developments based on existing product platforms.

Insert Figure 1 here

Excellence in platform design is centrally important to sustaining the quality and success of a product family. A platform design consists of a basic architecture, comprised of subsystems or modules and the interfaces between these modules. Smith and Reinertsen (1992) made the analogy of the subsystems being bricks, and the interfaces the mortar that binds them together. In an assembled product such as a camera, subsystems include the shutter mechanism, the lenses, the various operator controls and focus mechanisms, the flash, the power source, and the camera housing. The fittings and electronics by which these subsystems are integrated serve as the internal subsystem interfaces. The mechanisms for controlling shutter speed and the aperture, for rewinding and changing film, or for using a flash are the "user interfaces". The roll of film that one puts into the camera can also be viewed as having subsystems that include the spool around which the film is wrapped, the cover over the film, and the end caps. Even the film itself may be comprised of various layers (the subsystems) combined through chemistry in a continuous production process. The width of the spool, the length of the film leader, and the spacing of the edge perforations on the film are external interfaces that allow many types of films to be used in different cameras.

The notion of subsystems and interfaces leads to a typology of product family evolution that is shown in Figure 2 and which mirrors the approach of Wheelwright and Clark (1992) :

- The *initial platform* of a product family consists of the subsystems and subsystem interfaces of the basic product design. These subsystems are incrementally reengineered or refined to generate specific product offerings.

- A *platform extension* occurs when (a) particular subsystems within the existing platform design are substantially changed and enhanced, and/or (b) new subsystems are added to the design without disturbing the primary subsystems and interfaces in the existing design. For example, a computer manufacturer may replace a particular processor subsystem with a faster processor offered by a chip supplier. Both the initial platform and its extensions may be referred to as successive platform *versions*.

- A *platform renewal* occurs when the product design is rearchitected to incorporate major new subsystems and new subsystem interfaces. The new architecture may carry forward specific subsystems from older product platforms. It will also incorporate new subsystems as well as subsystem interfaces. The platform, if architected well, should provide new dimensions of value and cost competition to the firm.

Insert Figure 2 here

Specific derivative products can be based any these versions of platform architectures. We will refer to derivatives as the *follow-on products* of a platform. Appendix 2 shows how these key events may be formed as an identifying records for subsequent data gathering.

3.2 Defining Metrics for the Product Family

We propose the following measurements of R&D performance focused on platforms and their follow-on products within a product family: (a) platform *efficiency*, being the degree to which a platform allows economical generation of derivative products; and (b) platform *effectiveness*, being the degree to which the products based on a product platform produce revenue for the firm relative to the cost of developing those products.

R&D productivity is the degree to which an organization can translate relevant technological discoveries, made by itself or others, into functioning products that reap financial benefits for the firm. As argued above, platform efficiency indicates the degree to which a product platform serves as an economical base for generating follow-on products. Platform effectiveness is a measure of the commercial productivity of a series of related products, comparing the engineering resources used to create products with the commercial outcomes derived from those products (Baker and Freeland, 1975; Foster et al., 1985; Brown and Svenson, 1988; and Cordero, 1990). The inputs of firms into R&D are represented by the engineering budget amounts and project times associated with the development of new products. We believe that product sales is a better measure of commercial outcomes than profits due to the lack of consistency with which firms compute and maintain profits for specific products (Patterson, 1983). Profits from product sales are not consistently gathered at the product level by firms, and the definition of "profit" may vary among business units. In comparison, sales figures are absolute. We have also found them to be more accessible than profit figures in our field research.

These measures, when combined with visual interpretation of product family maps, can also help management understand the timing of platform renewal and the frequency of follow-on product generation from existing platforms. Further, these measures can be applied at three levels of the product family : (1) individual products within a platform version of product family, (2) at an aggregated level for the product family as a whole for successive platform versions, and (3) comparatively across different platform versions for different product families. We have come to refer to these measures as *meta-metrics* because their purpose is to help understand the dynamics of innovation across sets of products rather than individual ones.

3.2.1 Variables and Indices

This section presents the symbolic notation for the mathematical description of the meta-metrics. These notations are the building blocks for creating the measures of R&D performance to be presented thereafter.

Variables:

- S = Sales attributable to a platform or derivative product within a product family.
- C = Costs attributable to a platform or derivative product within a product family.
- D = The deflator factor relative to a base year. Used to correct for inflationary effects for very long product cycles.

Indices:

- N_p = Number of platforms in a product family *excluding* the initial platform version or architecture.
- N_v = Number of platform extensions, or generations created off the base platform architecture, *excluding* the initial platform version.
- N_f = Number of follow-on products in a platform, or platform extension, excluding the initial platform version.
- N_{TD} = The total number of follow-on products in a family excluding the initial platform version.
- T_D = The last time period number prior to entering the commercial cycle.
- T_C = The last time period for which sales were recorded in the commercial cycle.

$p =$ platform index; p = base, 1, 2, 3, ..., N_p

$v =$ platform version index; v = base, 1, 2, 3, ..., N_v

$f =$ follow-on product index; f = base, 1, 2, 3, ..., N_f

$t =$ time period index; t = 1, 2, 3, ..., T_D or T_C

For example, the sales in period t, of the second follow-on product, for the initial platform version would be given by:

$$(1) \qquad S_{1,base,2,t}$$

3.2.2 Aggregating the Sales and Costs of a Product Over Time

From these basic variables, sales and engineering costs attributable to products can be aggregated as part of performance measurement. Ideally, sales and costs are recorded at regular time intervals, t, throughout the entire product cycle. If so, the corresponding aggregated sales and costs are given by:

$$(2) \qquad S_{p,v,f} = \sum_{t=1}^{T_C} (S_{p,v,f})_t$$

and,

$$(3) \qquad C_{p,v,f} = \sum_{t=1}^{T_D} (C_{p,v,f})_t$$

where sales accumulate from introduction to the end of product life, and research costs accumulate from research initiation to the time of commercial entry of a product.

Over long product cycles, it is desirable to correct for inflationary effects in the economy. A deflator is computed for each time period relative to the desired base year. The deflators are applied to the formulas above to yield the adjusted aggregate sales and costs. Adjusted metrics are denoted with a superscript 'primed' symbol .

$$(4) \qquad S'_{p,v,f} = \sum_{t=1}^{T_C} (S_{p,v,f})_t D_t$$

$$(5) \qquad C'_{p,v,f} = \sum_{t=1}^{T_D} (C_{p,v,f})_t D_t$$

These formulas represent the aggregated sales and costs for individual *follow-on products* within the specific platform version within the same product family. To accumulate costs at the platform version level, the summations are extended. For example, the accumulated inflation adjusted sales for an entire platform, p, including all its platform extensions, would be given by:

$$(6) \qquad S'_p = \sum_{v=base}^{N_v} \sum_{f=base}^{N_f} S'_{p,v,f}$$

Similarly, the accumulated inflation adjusted costs for an entire platform would be computed using the cost variable, C. With these definitions, it is now possible to define the proposed meta-metrics.

3.2.3 Platform Efficiency

At the follow-on product level, average R&D leverage shall be defined as the costs incurred in developing a follow-on product, divided by the costs incurred in developing the version of the platform upon which the products are derived. It is generally defined as:

$$(7) \quad \textit{Platform Efficiency} = \frac{\textit{R\&D Costs for Follow-on Product}}{\textit{R\&D Costs for Platform Version}}$$

Mathematically, the notation for efficiency shall be E . The indices defined above shall apply accordingly. At the individual follow-on product level, the mathematical formulation for E, the efficiency of developing an individual follow-on product relative to its base platform, is given by:

$$(8) \qquad E_{p,v,f} = \frac{C'_{p,v,f}}{C'_{p,v,base}}$$

The question that this measure seeks to answer is: *"How much did the product cost to develop as a fraction of what was allocated to the base platform architecture?"*

The average platform efficiency is defined as:

$$(9) \qquad \overline{E}_{p,v} = \frac{\frac{1}{N_f}\sum_{f=1}^{N_f} C'_{p,v,f}}{C'_{p,v,base}}$$

The average platform efficiencies is therefore the average of the R&D costs associated with developing all the follow-on products of a platform version divided by the R&D costs of developing the platform itself. By grouping follow-on products within their base platform versions, the question being addressed is: *"How much did it cost on average to develop follow-on products relative to what was spent on developing the base platform versions within the product family?"*

One can also compare the platform efficiency of different platform versions across different product families . The question being asked is: *"How do the respective engineering groups within the corporation compare with one another in their abilities to build robust platforms which provide the basis for efficient product development?"* This might be useful for managers responsible for the development of several or more distinct product lines. An aggregate R&D cost leverage value can be computed for an entire product family by summing across follow-on products, platform versions, and between successive new platform architectures:

$$(10) \qquad \overline{E} = \frac{\frac{1}{N_{TF}} \sum_{f=base}^{N_f} \sum_{v=base}^{N_v} \sum_{f=1}^{N_f} C'_{p,v,f}}{\sum_{p=base}^{N_p} \sum_{v=base}^{N_v} C'_{p,v,base}}$$

What is a reasonable platform efficiency value? We strongly suspect that the answer is industry specific for particular types of products within assembled, nonassembled, information system and pure information product categories. Our application of this metric to the product families of the firm studied (described in the next major section of the paper) showed that strong product platforms yielded values for E as low as .10, meaning that efficient platforms allow the firm to produce streams of follow-on products at 10% per product of the cost of developing their respective base platform architectures.

If resources are being effectively used, and *learning is taking place*, we posit that platform efficiency should improve (that E should therefore decrease) with each successive platform version of a product family. E values of 0 or close to it may indicate that little or no new functionality has been added in the new product and that perhaps only that problems in earlier products had been corrected. Conversely, the closer E is to 1.0, the less efficient the base platform design proved for follow-on product generation. If the firm spends as much to make follow-on products as it does on a product platform, the platform is poorly designed. It should also be noted that technological breakthroughs achieved by the firm or its component suppliers could produce very low values of E. Interpretation of the metric should therefore be done in conjunction with assessments of product change and effectiveness. This combined analysis are provided later in the paper.

Platform efficiency can be used as an indicator of platform demise. An increase in E over successive follow-on products may indicate weakness in the underlying product architecture. This is consistent with the S-curve phenomenon where, after a certain point, little additional product generation performance is achieved from incremental investment. (Foster 1986) A decline in platform efficiency can also signify a change in management or key resources, human or otherwise. For example, the advantage gained by reusing a proven pool of resources can be lost through organizational change or by shifting the charter for developing a particular product family to another facility in a different geographical location. Key managers or engineers may also have been lost. All these factors must be considered as management interprets the *E* metric.

Market factors may greatly influence the efficiency with which existing platforms can be applied in the form of new products for market applications that the firm has not addressed before. Take the case of a firm venturing into a new business area by trying to create products that leverage existing technical competencies. The requirements of the new market may be so different that the firm encounters great difficulty satisfying the customers' needs, even with access to robust product platforms from its core business. The efficiency metric may in this case provide insight into the success of management's strategic decision to create a new product family.

Platform efficiency may also be considered from the standpoint of development time cycles. One can posit that a product platform, while taking relatively longer to create than follow-on products, is robust if it allows the firm to experience rapid generation of those follow-on products. Using the start and end of R&D for product platforms and follow-on products, an elapsed time cycle measure of platform efficiency can be expressed as:

$$(11)\quad E^{CycleTime}{}_{p,v,base} = \frac{T_{p,v,f}}{T_{p,v,base}}$$

and replicated to the aggregated levels of all products within a platform version, and across platforms versions within distinct product families.

It stands to reason that if indeed platform development efforts take longer to complete than follow-on product efforts, R&D aimed at platform renewal should be pursued concurrent within product developments on existing platforms. This will insure a continuous stream of products that embody competitive technology.

3.2.4 Platform Effectiveness

Computing R&D returns as accumulated profits divided by development costs on a product by product basis was proposed by Foster, et al.(1985) to assess the productivity for products over the full R&D and commercial life cycle. As stated above, we used product sales instead for reasons of reliability and accessibility. We propose that the effectiveness of a platform may be assessed by comparing the product sales to product development costs, either at the individual product level, or for groups of products within distinct platform versions. This measure of effectiveness may be considered one of understanding the commercial leverage provided by technologies applied by the firm in its products. *Platform effectiveness* is synonymous with *platform leverage*, referred to as L in the equations below.

The platform leverage measure, L, seeks to address the following questions:

What have been the returns realized on the firm's R&D investments comparing sales from products to the costs of developing them ?

How has a particular product family trended over time through its successive platform versions? Have returns on investments improved or declined?

Are certain development groups more effective in creating leverage from their respective platform development efforts than other groups within the firm?

Platform effectiveness at the follow-on product level is given by:

$$(12) \qquad L_{p,v,f} = \frac{S'_{p,v,f}}{C'_{p,v,f}}$$

and, aggregated at the platform version level by:

$$(13) \qquad L_{p,v} = \frac{\sum_{f=base}^{N_f} S'_{p,v,f}}{\sum_{f=base}^{N_f} C'_{p,v,f}}$$

which is the sum of the sales of products within a platform version divided by the sum of the R&D costs for creating those products.

Platform leverage may be further aggregated across all platform versions within a product family, and then used to compare the platform effectiveness between distinct product families as follows:

$$(14) \qquad L_p = \frac{\sum_{v=base}^{N_v} \sum_{f=base}^{N_f} S'_{p,v,f}}{\sum_{v=base}^{N_v} \sum_{f=base}^{N_f} C'_{p,v,f}}$$

The L metric provides information on product performance, individually and in aggregate, across the entire product life cycle inclusive of R&D and commercial activities. As the costs of follow-on product developments decline relative to that of their underlying platforms, the values for platform effectiveness for the product stream should increase.

There are many factors that can lead to declining platform leverage within a product family. First, the platform architecture itself may have outlived its utility as a basis for creating specific products that are competitive in the market in features and cost. This would lead to declining sales. As for the denominator, R&D costs may be rising due to problems in platform efficiency as defined above, ie. the economical generation of follow-on products. If this is the case, then one could posit an inverse relationship between the two respective measures of *platform effectiveness* and *platform efficiency*. A decline in platform efficiency may well indicate the need to create a new platform architecture. The causes for that decline may be many. For example, changes in the organization may impede the ability of the technical staff to perform well. Or new external technologies may emerge that competitors use in their products and which the firm fails to understand and integrate into its own products.

4. Applying and Interpreting Meta-Metrics

4.1 The Sample

The data used to test the metrics were gathered from a measurement systems manufacturer. The company's sales in 1993 exceeded $1 billion. The firm's core capability has been the application of measurement technologies to industrial applications. Management considers these products as "front-end" devices that gather data in real-time and assess them, identifying problems and sending these data to "back-end" information systems.

Studying the historical record of these product families required many discussions with engineering and marketing managers working in the business unit responsible for each product family. The first goal was to construct product family maps, using the typology described in the prior section to distinguish between (a) the initial new platform development efforts, (b) extensions to existing platforms, (c) the creation of wholly new platforms or product architectures to replace those in existence, and (d) the specific products associated with each platform generation. Drawings of product architectures at the subsystem and interface level were used to help identify platform enhancements and the development of new platforms within each product family. The firm's internal product naming conventions proved particularly useful for initial grouping of product streams within successive platform generations.[1] The product family maps were presented to the engineering teams working on the respective product lines for feedback and to create consensus on their validity. In total, the data set used in this paper contains information for five product families, which collectively, provided a rich database of platforms, platform extensions, and follow-on products to test our methods.

Figure 3 shows the product family map for Family A comprised of centralized information display and control stations that gather and manipulate data from front-end data collection devices for the purposes of event handling and data trending. The life cycles of Family A's two platforms are denoted by a thick line, representing the start of R&D for each architecture until the end of active marketing of products based on the platforms. These two platforms contained two very different product architectures, as described by engineers at the subsystem and interface level. The first platform was based on analog signal processing, and the second, on digital signal processing. Products based on the two platforms also "looked" very different to the outside observer. The first platform had two versions; the second platform, only one. The specific follow-on products based on each platform version are described in the text enclosed in the right-angled lines. The starting date of the earliest R&D project associated with each product is represented as the thinnest of the lines on the map. This line is an aggregate representation of numerous individual projects folded into a particular product. For several hundred products in the total sample, individual R&D projects number in the thousands. Allocation of these individual projects to specific platform and follow-on product development was performed by engineers who had worked on the development efforts.

Insert Figure 3 here

While R&D managers within the firm identified product families and their components, we applied the technology and market applications newness method of Meyer and Roberts (1986) to validate the relatedness of the product families. Appendix 3 shows the application of the method to Family A. The reader can note that relatedness of the products within that family in terms of embodied core technologies and market applications. The assessments of newness in technology generally correlate with the engineering costs associated with each successive product shown for Family A.

The determination of platform and follow-on product spending within each product family was based on the following assumption: the costs associated with individual projects whose results

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[1] Tornatsky and Klein (1982) have argued that knowledgeable observers of a particular industry will make consistent interpretation of those individual products that belong to specific product families.

were embodied in the first product spinning off from a particular version of a given platform were deemed to be platform development efforts for that version. In other words, the spending for the first product of a platform version and the spending for that platform version were treated as one in the same. Note that often the firm had R&D efforts longer term in nature. Such efforts would be pursued concurrently with work on a current platform version but not completed until later and rolled into a subsequent platform version or an entirely new platform. This illustrates the idea of concurrent platform development that we deem essential to product renewal and sustain success within the product family.

Maps similar to Figure 3 were created for all the product families incorporated in the study. For each product within a family we sought to construct from corporate record the following data: (a) the start of R&D (for the projects associated with the product), (b) the end of R&D, (c) the start of marketing, (d) the end of active marketing of a product, (e) the development costs, (f) the manufacturing engineering costs, (g) the product introduction costs, and (h) the sales in U.S. dollar equivalents. All financial amounts were recomputed to their value in 1993 dollars. We used the Consumer Price Index to inflate dollars from prior years to their 1993 dollar equivalents. These yearly adjustment factors are provided in Appendix 5. Because historical data for engineering costs and sales revenue were not maintained on a yearly basis for individual products, we first aggregated these amounts to a product and then applied the CPI index to these totals, using the index value for the last year of the R&D cycle and commercial cycle respectively. Ideally, one would want to maintain these data on a yearly basis so that the CPI index might be applied more precisely to the numbers.

The combination of the product family maps and their associated data comprised the complete basis for computing the measures of platform efficiency and effectiveness (leverage), and for observing timing factors in development. While these data might seem reasonable for any firm to maintain, they proved difficult to gather. On one hand, the company maintained very detailed information on cost allocations for individual R&D projects, either in paper form as project data sheets sitting on the shelves of R&D managers, or for more recent years, in computer files. These data provided man-months of direct labor, an internal "cost" for that labor, and materials charges. We were unable to gather manufacturing engineering costs and market introduction costs on a consistent basis, and therefore excluded these from the development cost for the product families in the sample. For several product families in the sample, only man-year allocations were available. We multiplied these amounts by a cost per man year amounts for the given years in development that were supplied by management.

Project data had to be aggregated during interviews where individual projects were assigned to the products by R&D managers who had been associated with the projects. Sales data were maintained in the accounting department in various forms, and for the majority of product families, were already allocated to individual products and merely had to be totaled for those years in which a product was actively marketed. It is of further importance to note that the integration of engineering data with sales data had not been systematically performed in the firm to provide management information. This reflects the fact that while concurrent engineering is a regular practice in the firm (particularly for the development of wholly new platforms or new platform versions), *concurrent management* between functional areas has proven more difficult to achieve.

In the next three sections of the paper we will now apply and interpret these metrics at three levels of analysis: within a single generation of a product family, comparatively between generations of a product family, and comparatively between different product families.

4.2 Metrics Applied at the Follow-on Product Level

Two product families, Family A and Family B, demonstrate the application and interpretation of the measures of platform efficiency and effectiveness at the specific follow-on product level. Family A , described above, is comprised of central information systems products. It had two successive platform architectures, with the first platform having two basic versions (the second being a major enhancement of the technology embodied in the first). A total of twelve products were based on these platforms. The data gathered for these products and the computed measures of platform efficiency are provided in Appendix 4 (which contains the computed metrics for all product families used in the paper). The first products released from a product platform are considered the denominator of the efficiency equation. All data were normalized to their 1993 dollar equivalents.

Insert Figure 4 here

Figure 4 shows both platform efficiency metric and its running average for the products within each respective platform version. The running average of platform efficiency smoothes wide fluctuations that may be observed for individual products, helping to show more clearly the overall trend. Product CIS 1A-F1 (Central Information System, Platform 1, Platform Version A, Follow-on Product 1) was developed on approximately 15 cents on the platform dollar, and CIS 1A-F2. for 18 cents on the platform dollar. While this follow-on product was being developed, management initiated a concurrent effort to substantially improve the underlying architecture with new component technologies and software development tools. It understood that its current architecture could not support the efficient development of the stream of products planned over the next five years. The results of this decision, and the new platform extension, were dramatic. While the first follow-on product of CIS 1B came in a cost of 16 cents on the platform dollar, subsequent products were developed rapidly at very incremental cost of under 5 cents on the CIS 1B platform dollar. Management initiated yet another platform enhancement effort even while products were being created from the CIS 1B architecture. In this case, the needs of customers and the availability of new hardware and software components mandated an entirely new architecture. Upon its completion, derivative products were created for approximately 10 cents on the CIS 2A platform dollar. Across our sample, platform efficiency values of 10 cents or below on the related platform development dollar represent very good values in terms of leveraging platform architectures in specific follow-on products. This level of efficiency can only be maintained over time with a policy of continuous platform renewal. Otherwise, as an architecture ages, it presents increasingly greater obstacles to engineers to achieve customer requirements.

We turn to another product family to illustrate the platform effectiveness measure, and how both metrics may used to indicate the need for platform renewal. Family B is comprised of measurement "boxes" that gather industrial process information in real-time, identifying emergency events and sending data to information systems such as those of Family A. The map for Family B is shown in Figure 5. The period from the start of R&D of the product platform to the end of the commercial cycle for products derived from it exceeds ten years. The base architecture contained a microprocessor, communications, and display electronics, a data acquisition and filtering subsystem, and a data management subsystem. This product platform took 3.5 years to develop, and from it, five follow-on products were created. The first three follow-on products were developed in approximately 30% of the elapsed time allocated to platform development, and the last two, spiking up to almost half that time. In total, the platform start of R&D to end of commercial cycle spanned more than a ten year period. Figure 5 also contains the engineering cost and sales figures for Family B's products. Time wise, these data existed only in aggregate form, meaning that they reflect end of R&D and commercial cycle totals respectively.

Insert Figure 5 here

Using the equations defined above, values for platform efficiency and effectiveness were computed for Family B. These data and the computed metrics for Family B are provided in Appendix 4 and are plotted in Figure 6. To facilitate comparison between the efficiency and effectiveness measures, the efficiency scale is plotted in reverse value order (ie. a value of .05, showing strong efficiency, is plotted at the top of the axis and weaker values of efficiency at the bottom).

The platform efficiency measure shows high levels of efficiency for the first three follow-on products based on the platform, where each was developed for on average 11 cents on the original platform dollar. Then, for the fourth follow-on product, the metric spikes down to a value of 42 cents on the platform dollar. The fifth product experienced a similar lack of platform efficiency, costing about 36 cents on the platform dollar.

Insert Figure 6 here

The platform effectiveness measures for Family B are also highly revealing. Platform effectiveness indicates the commercial leverage of products (or sets of products) as a ratio of total product sales to product development costs. By definition, we compute this measure on a product by product basis (rather than comparing any given product to its base platform as in assessing platform efficiency). For Family B, commercial leverage grew strongly from the initial product (MS1-Initial) to that of the third follow-on product (MS1-3). In particular, MS1-3 was an outstanding commercial success, returning $259 for every dollar spent on its development. The fourth and fifth follow-on products (MS1-4 and MS1-5) experienced a decline in sales relative to development costs.

Taken together, these measures of platform efficiency and effectiveness were interpreted by management to indicate that underlying product platform for Family B needed renewal. In the words of one R&D manager, the product platform began "running out of gas" after the third follow-on product in its ability to a) facilitate rapid and cost effective development of derivative products, and b) deliver the features required by customers at a price point that would lead to continued strong sales. This deduction would not have been obvious by looking at annual R&D budgets or product sales, nor by simply looking at the product family map (Figure 5). We can also rule out several factors that might have otherwise caused changes in costs and sales. During this time the market was relatively stable. There were no significant new market entrants and the rate of market growth was fairly constant at about 5% per year. The sales force, pricing, and practices associated with Family B also remained fairly stable.

Organizational issues strongly affected the evolution of Family B. Earlier generations of this particular measurement device prior to Family B had been developed in an American R&D laboratory. Senior management moved the charter for developing the new product architecture represented by Family B to a European R&D laboratory, a group that had demonstrated competence in creating low-cost, modular products in related product areas. The R&D charter for

Family B was then shifted back to the American group starting with the fourth follow-on product (MS1-4) as part of a larger initiative to rationalize R&D foci among the firm's various R&D groups. The American group defined follow-on products and jointly implemented these definitions with its European partner. As expected, some degree of organizational turbulence ensued and helped lead to higher costs and longer development times. The charter wars experienced within the product family contributed to the firm's failure to embark on a platform renewal effort in a timely manner and has placed a stellar product line under substantial market risk in the future.

Today, management has embarked on a crash effort to create a new product architecture. This effort would have been better started earlier during the peak of the platform's success in its terms of efficiency and effectiveness during product MS1-3 shown in Figure 6 and certainly after the declining efficiency of MS1-4. Seeking to avoid this problem, the group's new platform development plan is being extended to include initiation of the "next generation" several years hence. Additionally, senior management has reorganized R&D to place American and European laboratories within a single business unit to ameliorate the destructive charter wars of the past.

4.3 Meta Metrics Applied at the Platform Version Level

The measures of platform efficiency and commercial effectiveness may also be computed at an aggregate level for the product family, ie. in aggregate for successive platform versions within a product family. To illustrate this, we turn to Family C, comprised of highly complex imaging products used for measurement applications. Current products in the family contain more than 30,000 different components (making platform version tracking at subsystem and interface level necessary for this type of analysis). The family's map is shown in Figure 7. It spans more than 15 years.

Family C has had two underlying product architectures, IM1 and IM2. IM1 had three successive platform versions, IM1A, IM1B, and IM1C. The two platform extensions of IM1 introduced new imaging modalities that provided users with substantially improved diagnostic capabilities. The second product platform, IM2 (replacing IM1) featured an entirely new architecture that was a combination of more powerful image gathering and processing subsystems and new software subsystems for the user interface and data management. It effectively offered twice the "horsepower" to users. IM2 itself had four platform versions, noted as IM2A, IM2B, IM2C, and IM2D. IM2B was an extension of the platform to a new market application. IM2C incorporated a new imaging modality. IM2D both incorporated a new modality and applied it to a new market application.

Insert Figure 7 here

These various platform efforts were each three to five years in the making. From the customer's perspective, however, the firm was introducing new products every year, and more recently, every six months. The ability to generate this stream of products was based on a strategy of concurrent platform renewal, which itself was based on the pursuit of even longer term research into new measurement techniques and associated technologies. Appendix 4 contains the engineering and sales data aggregated on a platform version basis for Family C and the resulting metrics for platform efficiency and effectiveness. These measures plotted in Figure 8, with the efficiency measure plotted in reverse value order.

Insert Figure 8 here

The metrics help reveal two very different types experiences for the two platforms in this product family. Family C's product family map (Figure 7) shows the careful, patient development of the initial platform, IM1A. The development of that platform's two successive versions, IM1B and IM1C, was approached in a concurrent manner. Strong levels of platform efficiency resulted. For all three versions of the first platform, follow-on products were generated at less than 10 cents on their respective platform version dollar. The quality of the product line, and the accumulating cost efficiency in introducing new products, came to a propitious peak during the third version of the first product platform (IM1C). Just as the firm was putting its best foot forward in terms of engineering, two major competitors, themselves large, diversified businesses, exited this market due to highly publicized scandals that elicited government intervention. The firm exploited the opportunity. Family C's products during this time yielded over 80 dollars in sales for each dollar of engineering cost to develop them (as seen under IM1C) in Figure 8.

The second platform of Family C (noted in Figures 7 and 8 as IM2A, IM2B, IM2C, and IM2D) experienced a different fate. The team sought to double the imaging power of the system. Management decided to produce the image processing subsystem boards with a newly installed process technology (surface mount manufacturing). Given the major change in both product design and manufacturing process, the platform renewal was started too late. Further, several years earlier, one of the company's lead engineers had left to start his own firm and created a product line that was directly competitive. He had initiated a platform renewal "on the outside." Meanwhile, management seemed to be resting on the laurels of the first platform. When it received word of the new startup's efforts, a crash effort initiated to create a new platform. Then, the new competitor announced its new products to industry acclaim. Management had to respond: products based on IM2A were brought to market quickly thereafter even though the new technology had not yet sufficiently ripened.

The initial product under IM2A experienced problems in the field. The follow-on products during this time offered little new functionality to customers (being new output peripherals, for example). The team was consumed with fixing problems in the underlying architecture. This yielded the extremely high platform efficiency measure for products under IM2A (in Figure 8). In IM2B, the next version of the second IM platform, a new market application was targeted. The products generated from IM2B were very successful commercially. However, the efficiency decreased with the metric for IM2B rising to over 30 cents on the platform dollar. Then, in IM2C, the team introduced a new measurement technique. Significant technical obstacles in the underlying architecture had to be surmounted. The efficiency metric deteriorated to almost 2.5 dollars relative to the platform dollar to produce follow-on products during that time (referring to IM2C in Figure 8). The fourth version of the platform (IM2D) extended the product line to a new measurement application. The platform technology had stabilized by this point, and the derivative products were introduced at a more acceptable cost of 30 cents on the IM2D platform dollar. It was a level of efficiency, however, that was still three times poorer than that experienced throughout the products of Family C's first platform.

The effectiveness measure of commercial leverage computed for the successive versions IM2 platform shows the results of this failure to move smoothly between platform architectures. Sales of the product line plummeted during IM2A. The new market application targeted by IM2B reversed the downslide. However, the difficulty of creating new products within the platform led to declining leverage in IM2C, and further decline in IM2D. It should be noted that during this fifteen year period, overall market growth remained strong in excess of 15% per year.

If equal costs had been incurred in the creations of platforms IM1 and IM2, our measures of efficiency for these two platforms could be clearly compared. In this case, however, the development of IM2 was nearly twice as costly as IM1 (which, as shown in Figure 8, was due in part to the late start and hasty development of IM2). But even without correction the explosion of costs for derivative products from IM2 is obvious. An advantage of product family maps is that such differences in both raw data and efficiency measures between successive generations within a product family can be clearly seen and compared.

Our interpretation of these metrics and the events that caused them was reinforced when management provided staffing information. Staffing data comprised the number of engineers who had worked on underlying platform projects versus those for follow-on products on a year by year basis. Figure 9 shows these allocations as percentages, together with the increase in total staffing over time. Note the sharp shift in this allocation when management sensed the urgent need to replace the first product platform, IM1, with IM2. The percentage allocation to platform-related activity swung from 10% of the engineering staff to 70% in a single year! Once IM2 stabilized, resources were shifted largely to follow-on product development.

Insert Figure 9 here

Management learned from this experience. The team initiated an entirely new platform development effort (which we may call IM3) to replace IM2 with better imaging and user interface capabilities. We visited the company during the week when IM3 had passed all the internal quality control tests. To our delight, the R&D manager was convening a meeting of his best engineers. Their purpose: to begin the design of the next product platform (IM4). The shift in engineering allocations between platform work and that for follow-on products has become less dramatic, indicating a policy of continuous platform renewal.

4.4 Comparisons between Product Families

The platform metrics can also be used by senior management to comparatively assess R&D performance for a set of product families and facilitate learning from that endeavor. To show this, we will use the platform efficiency experiences of two different product families, referred to as Family D and E . Both product families are comprised of measurement devices, each targeted a different but related market application. Family D had a single product platform, with three versions of that platform and 11 follow-on products. Family E had two product platforms, each with several or more platform versions, and also 11 follow-on products. We gathered data, made maps, and computed platform efficiencies as described above (see Appendix 4 for specific data).

The two product families were developed during equivalent time periods by two different R&D groups. The performance of these two groups in terms of platform efficiency is shown in Figure 10. The first two versions of the Family D's platform were highly productive in terms of economical generation of follow-on products. The third platform version, however, suffered in this regard. Discussions with managers involved in development at that time confirmed our suspicion that the platform had reached its limit in terms of efficiently delivering the new capabilities required by customers. A new architecture for Family D (as opposed to the platform extension labeled D1 C in Figure 10) would have best been started in the early 1980's. Instead, the renewal of Family D was initiated in the late 1980's, resulting in a new platform (labeled D2 A in Figure 10) from which products were released starting in 1990. While the efficiency of this platform for creating derivative products (.27) was better than that of its immediate predecessor (.42), that value was still below the strong platforms in terms of technical leverage within the company.

Insert Figure 10 here

In contrast, the platform efficiency values for Family E indicate consistently strong performance. The values for the successive platforms versions are all in the 10 cents on the platform dollar range, including the today's present platform (E2 B in Figure 10). Note further the overlap between the development of the second platform (E2 A) and the creation of follow-on products from its precursor (E1 C). Family E indicates a rhythm in platform enhancement and renewal that we deem highly desirable.

This comparative analysis facilitates internal benchmarking of R&D activities. In order to learn, an organization must remember past experience. In the context of new product development, this corporate memory includes the evolution of product families and their architectures, the composition of teams and skills, and customer perceptions and participation in the creation of products. Measurement of these factors and analysis of their results in areas such as platform efficiency and effectiveness provides information for experimentation and learning. Once management has identified product families with high levels of platform efficiency and effectiveness relative to other product families, management may then explore underlying approaches and techniques for product planning, design, and integration.

5. Discussion

In our field work, we encountered a number of frequently asked questions:

> *When should we renew our platforms? How much will platform efforts cost, and how long can we expect them to take? What types of engineering and commercial benefits can we expect to gain from these efforts once complete? How can we improve our approaches and strategies for product development?*

The work presented in this paper does not explicitly tell management precisely when to create a new product platform. However, our concepts and metrics provide managers with a rich context to determine when product platforms should be obsoleted with new platform designs and what to expect from these new designs once new products are developed from them. In short, the work comprises a framework for learning, specifically targeting the R&D dimension of product development. (Maidique and Zirger, 1985) The axiom "hind-sight is 20-20" is well remembered. Without descriptions of factors influencing events, such as those provided for the product families in this paper, observed measures of R&D performance may be prone to misinterpretation.

The cost-effectiveness of implementing these measures within a company will vary. The place to start is to ask management if it recorded the evolution of the firm's product families and can provide information on platform and product engineering costs and as well as product sales. Researchers may be surprised at how few firms have a grasp on these fundamental data. While we expect that most firms have not taken the initiative to combine engineering and sales information, if product development costs and sales are maintained at least in paper form, the cost of creating the R&D measurement system will not be excessive in light of the value returned.

The collection and synthesis of these data are essential to support what we referred to earlier as concurrent management within product developing firms. As we were concluding our study in this company towards the end of 1993, it was confronted with a major market discontinuity. The company's traditional skill had been to make "high end", technically pioneering products for customers that had the money to buy new features at ever higher prices. Certain regulatory and market forces had recently reversed this condition: customers now desired low-end, value rich products. At the time of this writing, the culture, people, and processes within the firm had yet to facilitate a change in engineering approaches and philosophy. Marketing and engineering remain distinct "islands" of work that had to become one.

Achieving high levels of platform effectiveness, or leverage, is easier to achieve if the market is growing strongly. If the target market proceeds to flatten, a successive platform version that may be better designed and enable greater functionality in follow-on products, may exhibit a decline in leverage. While we have included market growth in our interpretation of the metrics in the discussion above, a more formal incorporation of this information is desirable for the measure of leverage. Unfortunately, we were unable to gather reasonably complete market growth rates at the product family level within the sample firm. Our discussions with management indicated, however, that market growth rates, suppliers, the structure and scope of distribution channels, and even the individuals key positions of management (business, marketing, and R&D) were all remarkably stable during the time periods studied. Other factors such as manufacturing capacity and the sourcing of components showed continuous growth and no changes of a disruptive nature. There is little doubt, however, that management should seek to augment measures of an internal nature with external information that might have significant bearing on the phenomena under investigation.

Another measurement issue concerns a more holistic definition of product development costs. The ideal data set gathered for product development costs would include manufacturing engineering and market introduction costs with those for product engineering. One might also wish to track the costs of installing products, training users, and repairing initial product defects as part of assessing platform efficiency and effectiveness. We were unable to gather these data. We believe that the lack of integration between information systems in engineering, manufacturing, and marketing which we encountered is not atypical in industry.

Product quality also needs to be continuously assessed. How well does a stream products meet target customer needs? What competitive benchmarks in terms of overall value and features does the firm have to guide its platform development efforts ? Platform efficiency may be viewed as related to the design quality of platforms. The platform effectiveness measure should also reflect the fact that higher quality platforms and derivative products fare better in the marketplace than those of lesser quality. Nonetheless, we would not wish to use these measures in isolation from measures product functionality versus price, service record (such as critical hardware or software failures), and for many firms, the cost of integration of its products with those of other companies at the customer's site.

The development of an entirely new platform is riskier than the development of follow-on products based on it. This is because platforms involve a greater innovation effort -- and hence greater technical uncertainty -- than derivative products. The anomaly is that while incremental innovations may have less technical risk to the firm than architectural innovations, it is precisely such architectural innovations (often from new entrants) that have historical made firms' competencies and products obsolete over the long term (Utterback, 1993). The failure to develop new platform architectures on a continuous basis subjects the firm to substantial market risk. We have found that engineering managers generally understand this. Business managers often do not, leading to inappropriate expectations regarding project time and cost (ie. new platforms are different than platform enhancements, and both are different than specific product developments). In turn, these expectations can result in misallocation of resources.

We remember the words of one senior engineer:

> *How can we get management to understand the differences between platform efforts and those for specific products? Our new product planning processes focus on single products and the emphasis is to create them faster and at lesser cost. We can't achieve this without newer and better platforms. Too often, our efforts to renew aging platforms are pursued "undercover" and we start them too late. We need our planning processes and reward systems to facilitate and encourage appropriate behavior with respect to platform development and renewal.*

The last statement is particularly intriguing. The approach presented here provides firms with a foundation for reconsidering their new product planning processes and reward systems. We have observed the stage-gate new product development processes of many firms to be strictly single product and single period in application, making little if any explicit differentiation between more fundamental platform efforts and the development of derivative products. A planning process that embraces the product family and the renewal of architecture is a possible multi product, multi period basis for further research and application.

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Figure 1
Product Family Evolution
Platform Renewal and New Product Generation

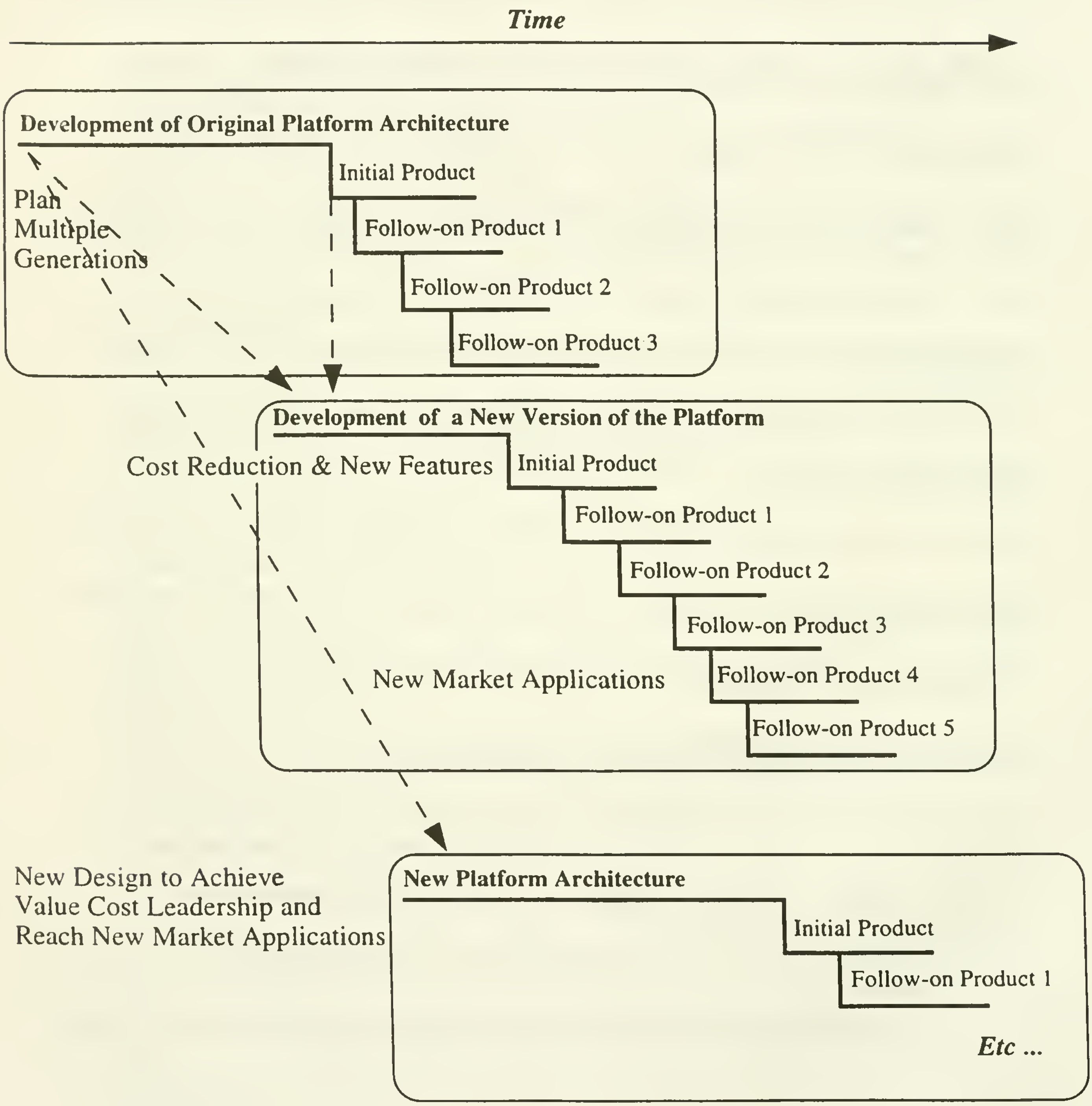
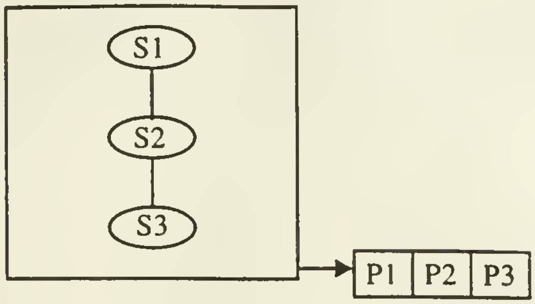


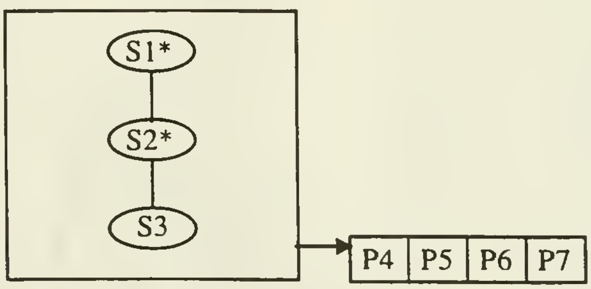
Figure 2
Platform Change

Initial Platform Architecture: Common Subsystems and Interfaces for Multiple Products



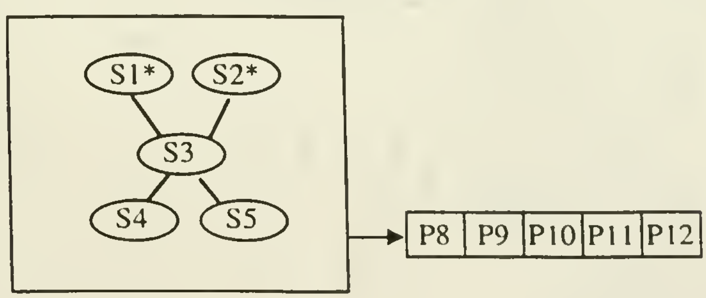
Derivative Products

Platform Extensions: A new generation where number and types of subsystems and interfaces remain contant, but where subsystems and interfaces are enhanced.



Derivative Products

Platform Renewal: A New Architecture, where subsystems and interfaces from prior generations may be carried forward and combined with new subsystems and interfaces in the new design.



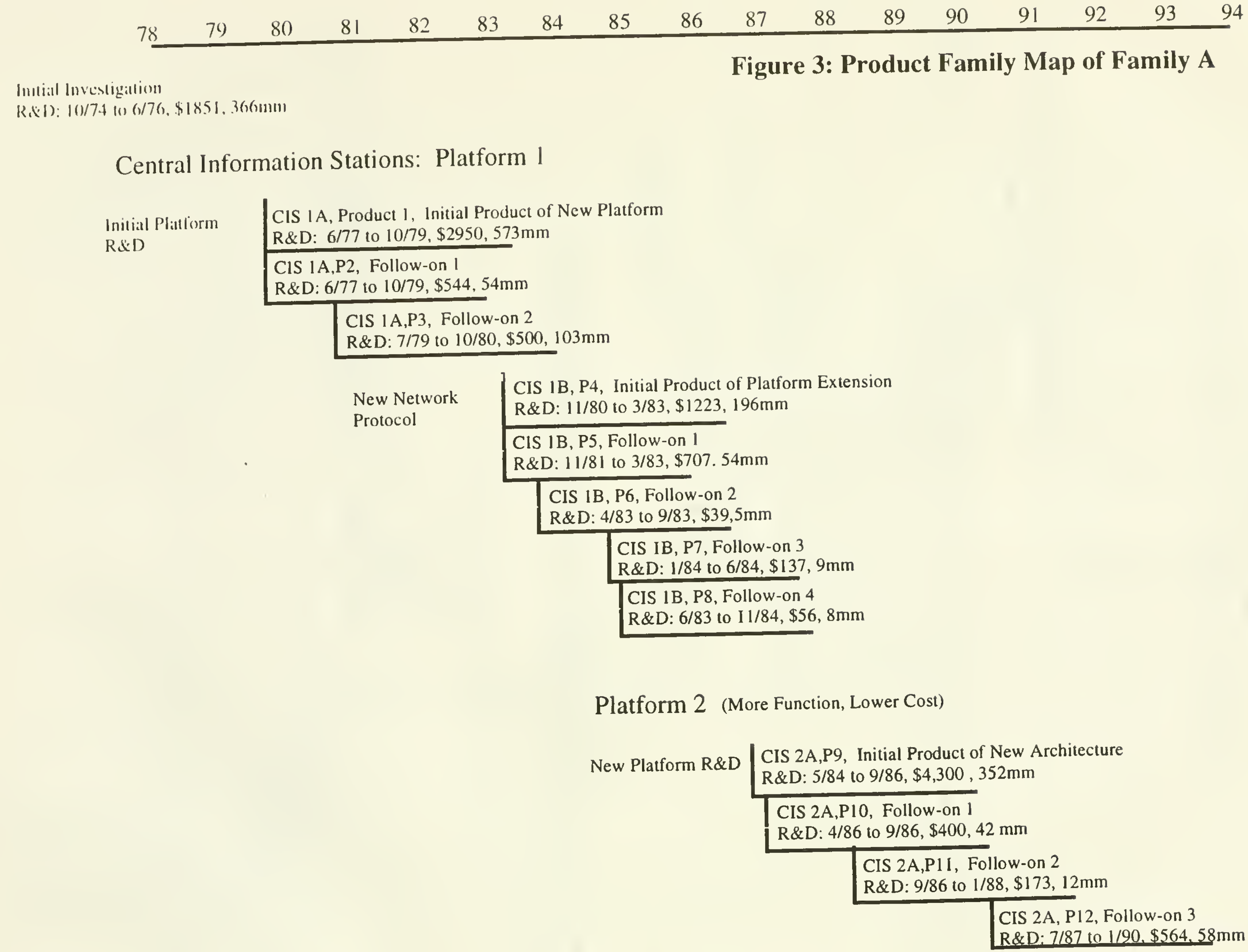


Figure 3: Product Family Map of Family A

Figure 4
Family A: Platform Efficiency

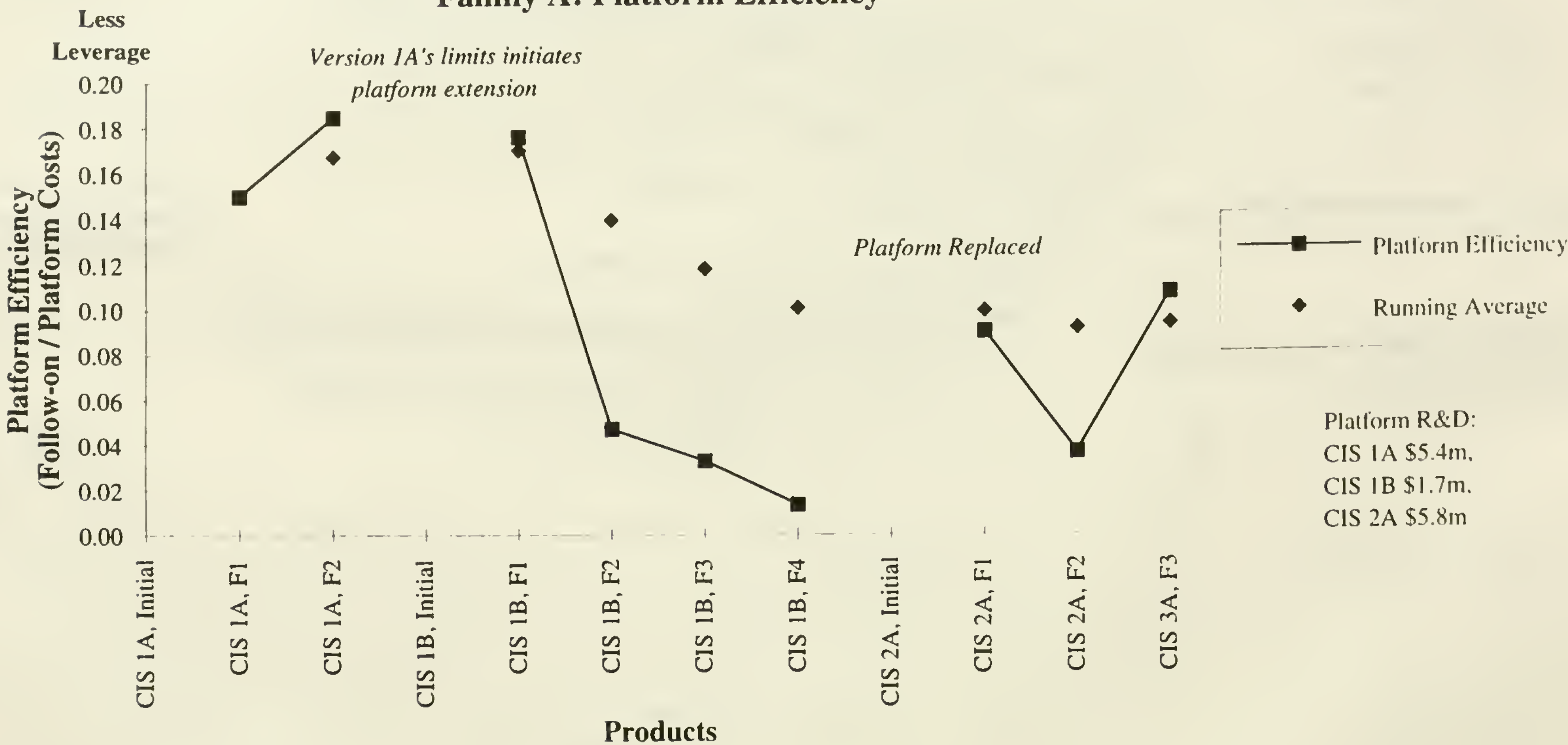


Figure 5: Product Family Map of Family B

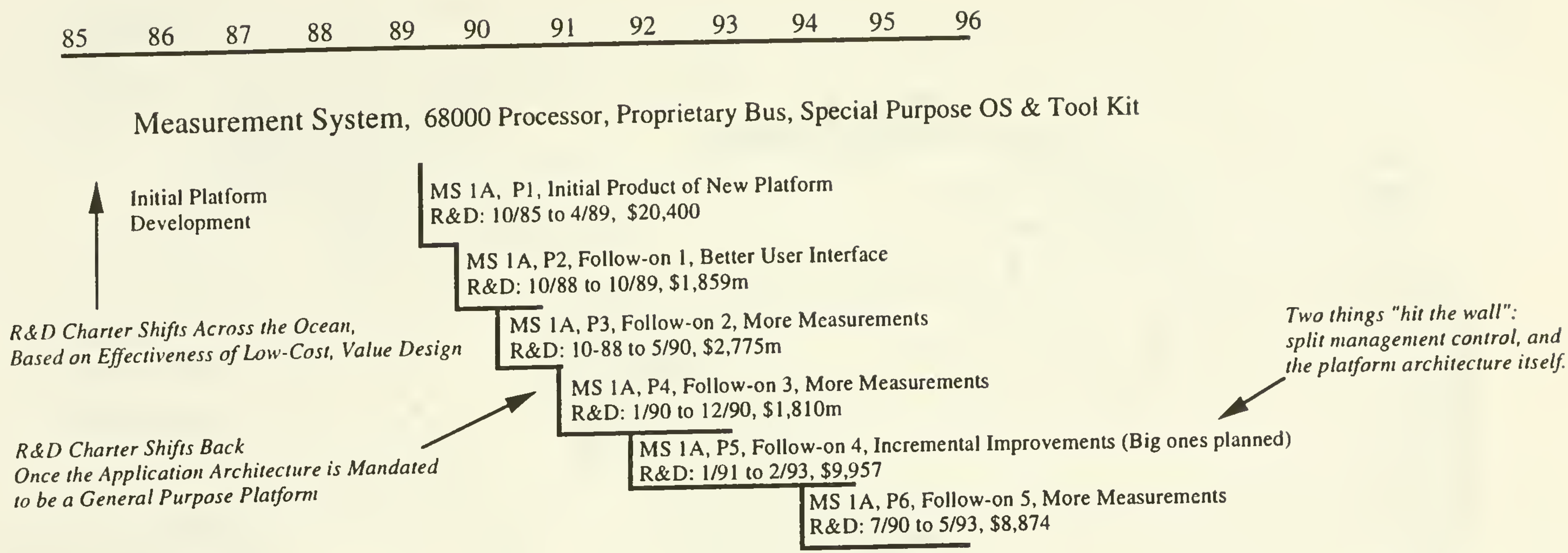


Figure 6
Platform Effectiveness and Efficiency:
By Product Within Family B

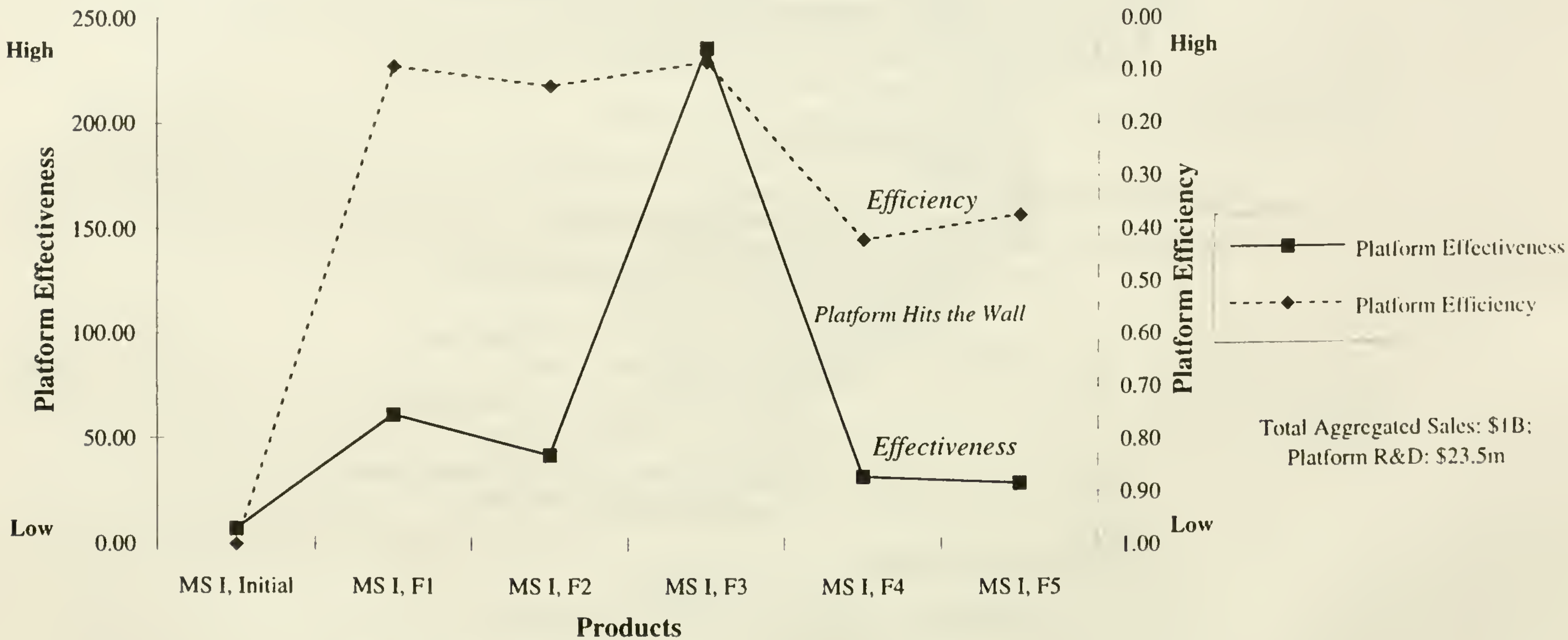


Figure 7: Product Family Map of Family C

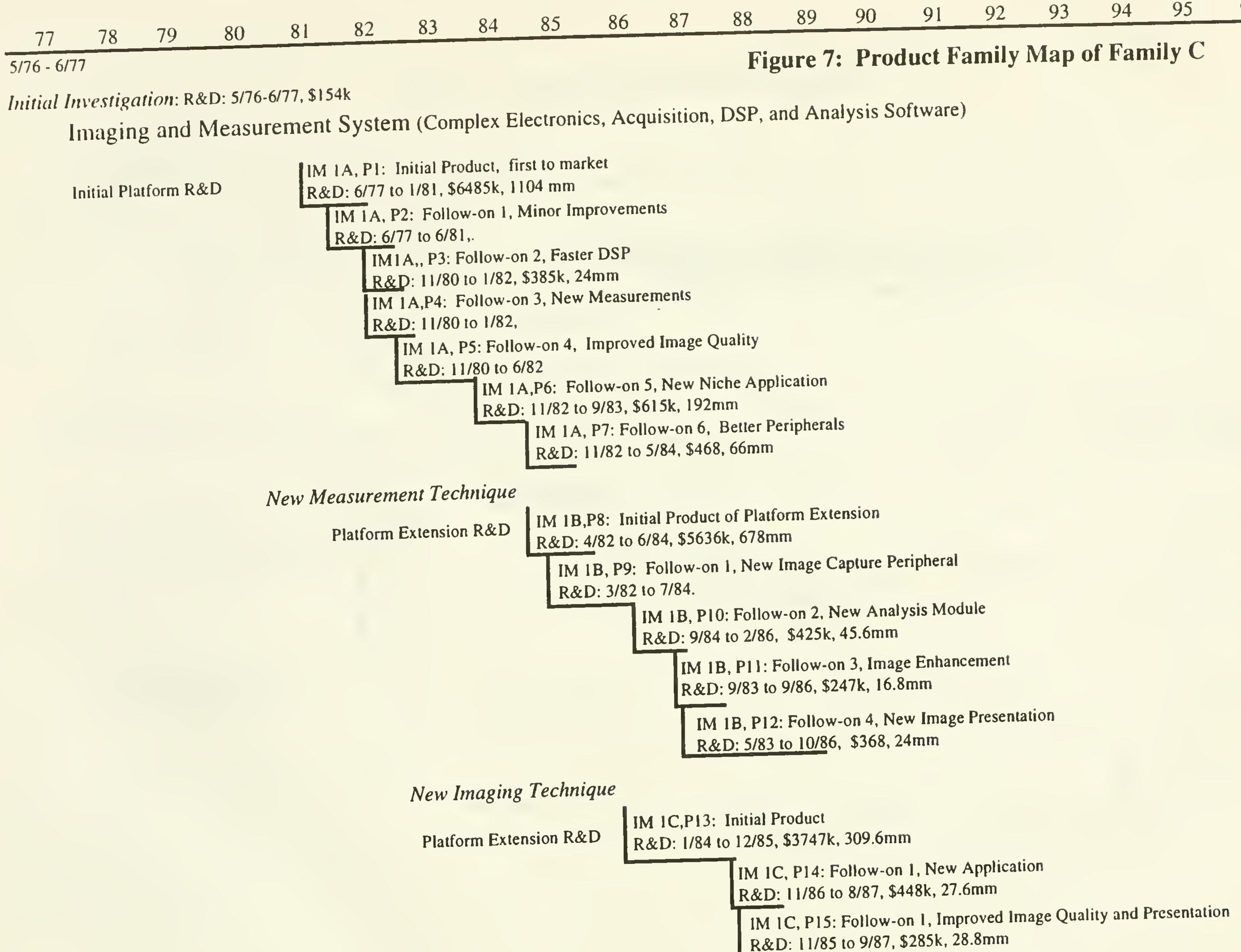


Figure 7 (Continued):
Product Family Map of Family C

86 87 88 89 90 91 92 93 94 95 96

IM Platform 2: Doubled Data Aquisition DSP Power and New User Interface

Initial Platform R&D

IM 2A,P16: Initial Product of New Platform
R&D: 9/86 to 4/89, $10,353k, 690mm

IM 2A,P17: Follow-on 1, New OEM Peripheral
R&D: 12/85 to 10/88, $120k, 6mm

IM 2A, P18: Follow-on 2, Step back to lower DSP Rate
R&D: 9/86 to 3/89, $120k, 6mm

IM2A,P19: Follow-on 3, New OEM Peripheral
R&D: 1/88 to 6/89, $120k, 6mm

IM 2A,P20: Follow-on 4, Improved Image Quality
R&D: 2/88 to 1/90, $180k, 9mm

New Market Application

Platform Extension R&D

IM 2B, P21: Initial Product, Increased DSP Power
R&D: 9/86 to 5/90,$1617k, 138mm

IM 2B, P22: Follow-on 1, Closeup Look at Images
R&D: 8/90 to 7/92, $206k, 29mm

IM 2B,P23: Follow-on 2, Adapted to Specialized Application
R&D: 7/90 to 2/91, $90k, 7mm

IM 2B, P24: Follow-on 3, New DSP Power
R&D: 1/90 to 4/91, $777k, 63mm

IM 2B, P25: Follow-on 4, Added Sound to Measurement
R&D: 8/90 to 5/91, $917, 132mm

New Measurement Technique

Platform Extension R&D

IM 2C, P26: Initial Product
R&D: 10/84 to 7/91, $972, 132mm

IM 2C, P27: Follow-on 1, New Storage Technique
R&D: 11/89 to 1/92, $2787k, 226mm

IM 2C, P28: Follow-on 2, Enhancement Measurement
R&D: 8/90 to 5/92, $798k, 85mm

IM 2C, P29: Follow-on 3, New Application, New Storage Technique, a major effort
R&D: 8/88 to 11/92. $3163k, 268mm

New Market Application and Measurement Techniques

Platform Extension R&D

IM 2D, P30: Initial Product
R&D: 5-87 to 11/92, $4918k, 362mm

IM 2D,P31: Follow-on 1, Measurements on Sound with Images
R&D: 3/90 to 3/93, $2167k, 88mm

IM 2D,P32: Follow-on 2, Sound Analysis Enhancements
R&D: 5/91 to 11/93, $2400k, 150mm

IM 2D,P33: Follow-on 3, Adapted to New Application
R&D:5/91 to 3/94, $2100k, 183mm

Figure 8
Effectiveness and Efficiency by Platform Version for Family C

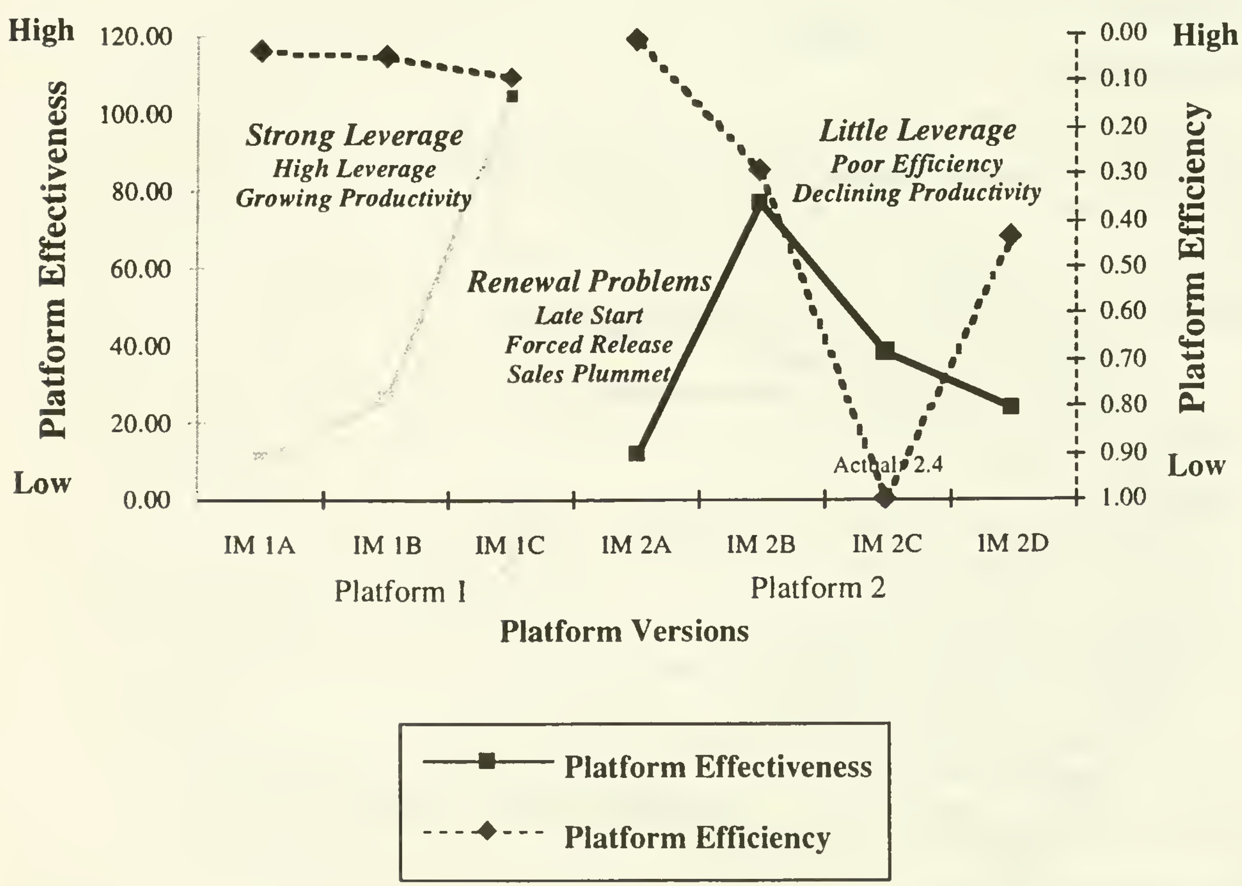


Figure 9
Platform versus Follow-on Allocation of R&D Staff for Family C

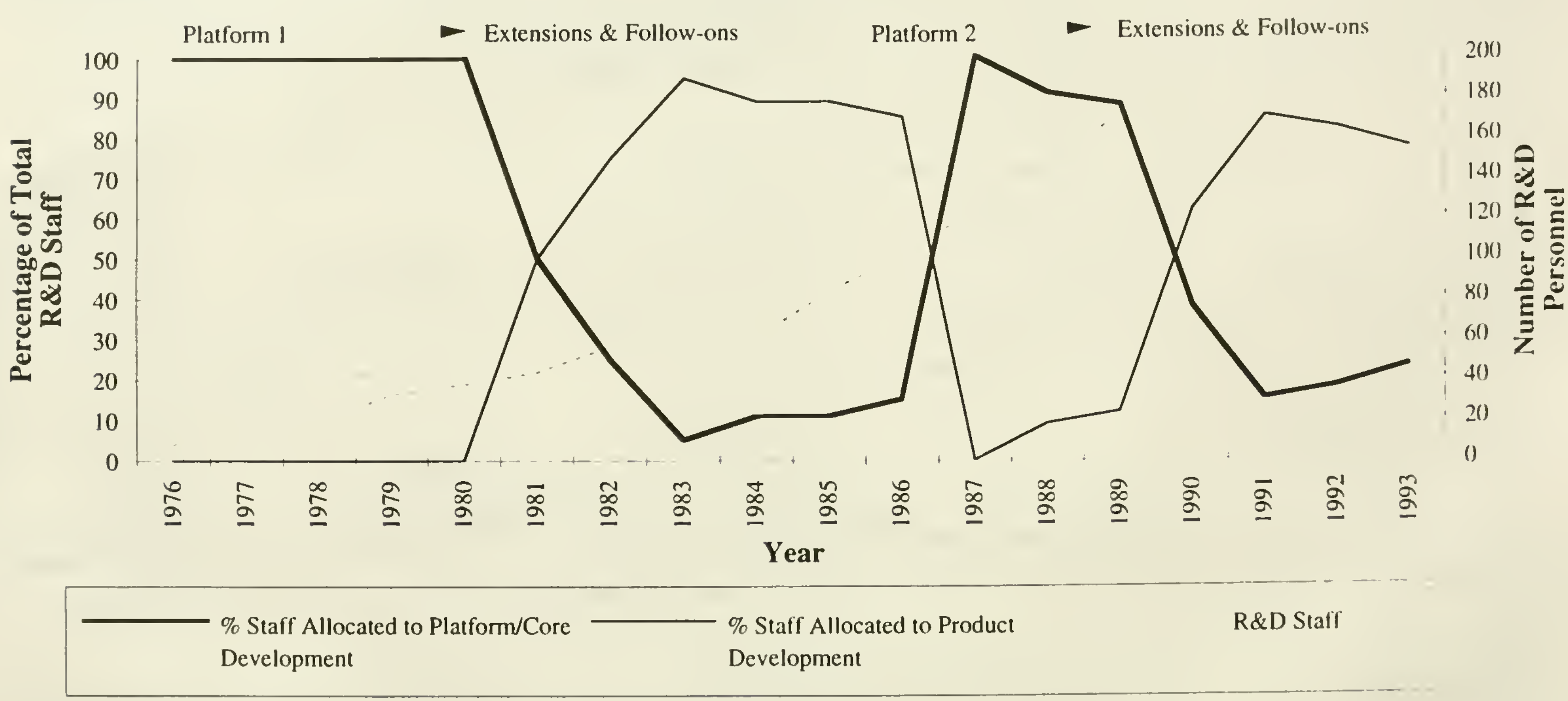
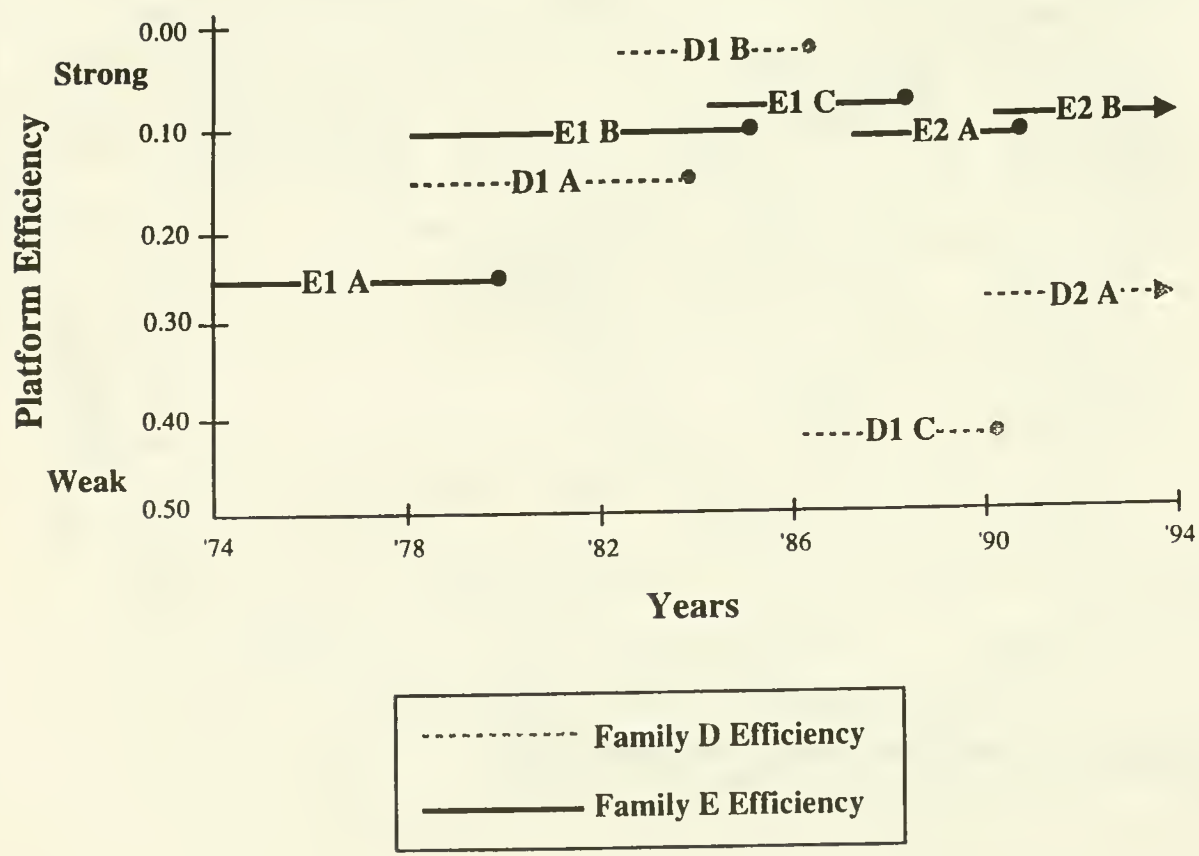


Figure 10
Comparison of Efficiency Values by Platform Versions for Families D and E



Appendix I
The R&D Measurement Literature

Method of Measurement — **Area of Measurement**

	Product Planning	Development Control	R&D Cycle Performance	Market Cycle Performance	Full Life Cycle Performance
Comparative	Baker&Freeland (1975) Cordero (1990) Liberatore&Titus (1983) Souder (1973) Steele (1988) van Remoortere&Cotterman (1993)	Cordero (1990) Remoortere&Cotterman (1993)	Baker&Freeland (1975) Cordero (1990) Moser (1985) Steele (1988) Remoortere&Cotterman (1993)	Cordero (1990) Steele (1988)	
Scoring	Baker&Freeland (1975) Balachandra(1991) Cordero (1990) Liberatore&Titus (1983) Mansfield&Brandenburg(1966) Pickett&Case(1991) Souder (1973) Steele (1988)	Cordero (1990) Balachandra(1991) Pickett&Case(1991)	Baker&Freeland (1975) Cordero (1990) Mansfield&Brandenburg(1966) Moser (1985) Packer(1983) Pappas&Remer(1985) Pickett&Case(1991) Steele (1988)	Brown&Svenson(1988) Cordero (1990)	Brown&Svenson(1988) Cordero (1990)
Benefits Contribution	Baker&Freeland (1975) Cordero (1990) Liberatore&Titus (1983) Mansfield&Brandenburg(1966) Souder (1973) Steele (1988)	Baker&Freeland (1975) Cordero (1990) Gerloff(1973) Lewis(1993) Pickett&Case(1991)	Baker&Freeland (1975) Brown&Svenson(1988) Cordero (1990) Foster et al (1985) Liberatore&Titus (1983) Mansfield&Brandenburg(1966) Moser (1985) Pickett&Case(1991) Steele (1988)	Brown&Svenson(1988) Cordero (1990) Foster et al (1985) Steele (1988)	Brown&Svenson(1988) Cordero (1990) Foster et al (1985) Patterson(1983) Porter(1978)
Schedule Analysis	Gerloff(1973) Mansfield&Brandenburg(1966)	Liberatore&Titus (1983) Levitt(1988) Moser (1985)	Levitt(1988) Mansfield&Brandenburg(1966) Moser (1985)		
Individual& Group Analysis	Liberatore&Titus (1983)	Meinhart&Pederson(1989)	Batson (1987) Edwards&McCarrey(1973) Meinhart&Pederson(1989) Moser (1985)		Batson (1987) Krough, et al(1988)

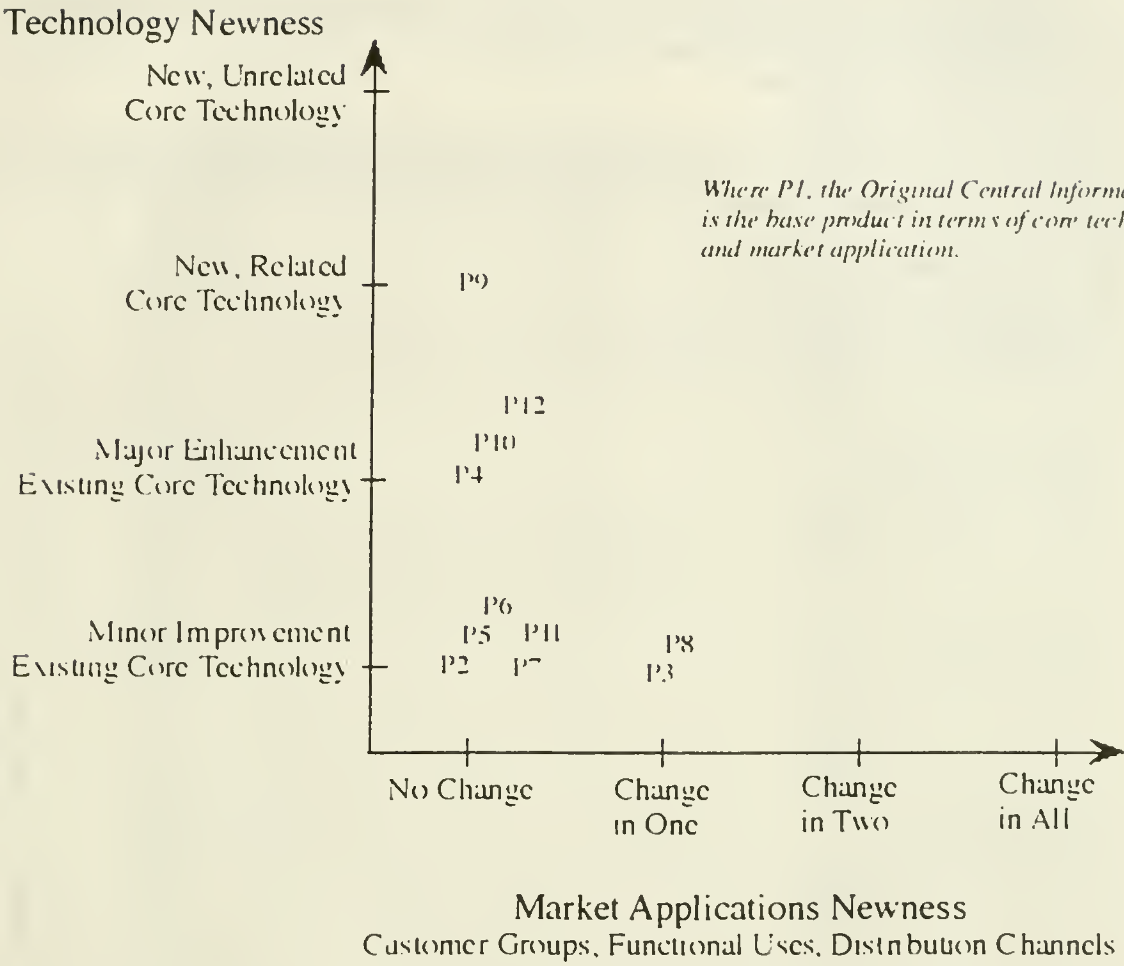
The horizontal axis represents measurement purpose following the sequential stages in a product's life cycle: measuring the effectiveness of product planning before actual development, controlling projects during development, measuring the technical outcomes of the completed development, measuring the commercial outcomes associated with completed products, and lastly, understanding overall performance across the span of a product's full life cycle.

The vertical axis represents the *techniques* of measurement drawn from the literature: (1) comparative assessments of new products in terms of success, (2) scoring models on product features relative to competitors' products, (3) benefits contribution methods based on the sales-related outcomes of products, (4) various forms of performance to schedule analyses (the most commonly used form today being total project slip or slip at different key phases of a project), and (5) analyses of individual and organization technical accomplishment, including the counting and comparison of patents awarded to members of a group or publications emerging from them.

Appendix 2
Classification of Key Events in the Evolution of a Product Family

Platform Architecture	Platform Version	Follow-on Product	Event Type
Platform A	Version 1	P 1	Original platform architecture, first product
Platform A	Version 1	P 2	Follow on product
Platform A	Version 1	P 3	Follow on product
Platform A	Version 1	P 4	Follow on product
Platform A	Version 1	P 5	Follow on product
Platform A	Version 2	P 1	First platform extension, first product
Platform A	Version 2	P 2	Follow on product
Platform A	Version 3	P 1	Second platform extension, first product
Platform A	Version 3	P 2	Follow on product
Platform A	Version 3	P 3	Follow on product
Platform A	Version 3	P 4	Follow on product
Platform A	Version 4	P 1	Third platform extension, first product
Platform A	Version 4	P 2	Follow on product
Platform B	Version 1	P 1	Platform renewal, a new platform and first product
Platform B	Version 1	P 2	Follow on product
Platform B	Version 1	P 3	Follow on product
Platform B	Version 1	P 4	Follow on product

Appendix 3
Technology and Market Newness
Assessed for Family A



Where P1, the Original Central Information System is the base product in terms of core technology and market application.

Product	Technology [1]	Market Applications[2]
Product 1	Basis Point: Central Info System, Analog I/O	Measurement information in medical facilities
Product 2	New output peripheral	Same
Product 3	Minor improvement	New use, for smaller scale customer site
Product 4	Major enhancement: Digital I/O	Same
Product 5	New version of output peripheral	Same
Product 6	New type of data reporting	Same
Product 7	Upgrade to output peripheral	Same
Product 8	External information integration interface	New use, for exporting information
Product 9	New architecture, including new component hardware and software technologies, including a new user interface software	Same
Product 10	New analysis algorithm	Same
Product 11	Lower cost redesign	Same
Product 12	Upgrade to analysis algorithm	Same

[1] The levels of technological change (Meyer and Roberts, 1986):

1. Minor improvements to core technology(ies) that exist in earlier products
2. Major enhancements to existing core technology(ies)
3. The addition of a new core technology, which is combined or otherwise integrated with existing core technologies in earlier products to create the new product
4. New, unrelated core technology

[2] Market Applications Newness: For each product, observe relative to all prior products, any change in a) customer group, b) functional use of the product by the same or new customer group, or c) distribution channel.

1. No change in (a), (b) or (c)
2. Change in one of (a), (b) or (c)
3. Change in any two of (a), (b) or (c)
4. Concurrent change in (a), (b) or (c)

Appendix 4
Product Family Data and Computed Metrics

Family A: Platform Efficiency

Platform	Product	R&D Elapsed Time: Platforms	R&D Elapsed Time: Follow-ons	Adjusted R&D Costs	Follow-on Efficiency	Running Average: Efficiency
CIS 1A	P1, Initial Platform	2.33		5841.00		
CIS 1A	P2, Follow on 1		1.25	875.00	0.15	0.15
CIS 1A	P3, Follow-on 2		2.33	1077.12	0.18	0.17
CIS 1B	P4, Platform Extension	2.33		1773.35		
CIS 1B	P5, Follow-on 1		1.17	1025.15	0.18	0.17
CIS 1B	P6, Follow-on 2		0.42	274.05	0.05	0.14
CIS 1B	P7, Follow-on 3		0.42	190.43	0.03	0.12
CIS 1B	P8, Follow-on 4		0.59	77.84	0.01	0.10
CIS 2A	P9, New Platform	2.34		5633.00		
CIS 2A	P10, Follow-on 1		0.42	524.00	0.09	0.10
CIS 2A	P11, Follow-on 2		1.33	211.06	0.04	0.09
CIS 2A	P12, Follow-on 3		2.51	620.40	0.11	0.09

Family B: Platform Efficiency and Effectiveness

Platform	Product	Adjusted R&D Costs ($k)	Platform Efficiency	Running Avg Efficiency	Adjusted Sales ($m)	Platform Effectiveness	Running Avg Effectiveness
MS 1	P1, Initial Platform	23,664			168,300	7.11	7.11
MS 1	P2, Follow-on 1	2,146	0.09	0.09	132,000	61.51	34.31
MS 1	P3, Follow-on 2	3,053	0.13	0.11	128,700	42.16	36.93
MS 1	P4, Follow-on 3	1,911	0.08	0.10	469,000	235.56	86.59
MS 1	P5, Follow-on 4	9,957	0.42	0.18	318,000	31.94	75.66
MS 1	P6, Follow-on 5	8,874	0.38	0.27	254,000	28.62	67.82

Family C: Platform Efficiency and Effectiveness

Metric Category		IM 1A	IM1B	IM 1C	IM 2A	IM 2B	IM 2C	IM 2D
Sales ('000s) Adjusted for Inflation		126,490	241,040	618,490	145,200	296,800	318,270	273,460
R&D Costs ('000s): Adjusted for Inflation	Platform Only	10,311	7,834	5,021	12,009	1,779	1,030	5,066
	Sum of Follow-on Products	2,116	1,362	930	623	2,103	7,313	6,667
	Average of Follow-ons	353	341	465	156	526	2,438	2,222
	Total R&D Costs	12,427	9,196	5,951	12,632	3,882	8,343	11,733
Platform Efficiency		0.034	0.043	0.093	0.013	0.296	2.366	0.439
Platform Effectiveness		10.2	26.2	103.9	11.5	76.5	38.1	23.3

Families D: Platform Efficiency

Metric Category		D 1A	D 1B	D 1C
R&D Costs ('000s): Adjusted for Inflation	Platform Only	7,659	3,350	990
	Average of Follow-ons	1,283	107	419
Platform Efficiency		.17	.03	.42

Family E: Platform Efficiency

Metric Category		E 1A	E 1B	E 1C	E 2A	E 2B
R&D Costs ('000s): Adjusted for Inflation	Platform Only	1,206	2,849	5,544	8,979	4,869
	Average of Follow-ons	323	662	538	985	565
Platform Efficiency		.27	12	.09	.11	.12

Appendix 5
CPI Dollar Adjustments [1]
(Multipliers to 1993 Dollar Equivalents)

Year	CPI 1983	CPI 1992	Inflation Factor
1970	38.8	26.9	3.71
1971	40.5	28.1	3.56
1972	41.8	29.0	3.45
1973	44.4	30.8	3.25
1974	49.3	34.2	2.92
1975	53.8	37.3	2.68
1976	56.9	39.5	2.53
1977	60.6	42.1	2.38
1978	65.2	45.2	2.21
1979	72.6	50.4	1.98
1980	82.4	57.2	1.75
1981	90.9	63.1	1.59
1982	96.5	67.0	1.49
1983	99.6	69.1	1.45
1984	103.9	72.1	1.39
1985	107.6	74.7	1.34
1986	109.6	76.1	1.31
1987	113.6	78.8	1.27
1988	118.3	82.1	1.22
1989	124.0	86.1	1.16
1990	130.7	90.7	1.10
1991	136.2	94.5	1.06
1992	140.3	97.4	1.03
1993	144.1	100.0	1.00

[1] Bureau of Labor Statistics, Washington, DC