Assessing the Performance of Product Families

by

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Submitted to the Alfred P. Sloan School of Management
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Abstract

Success for a research and development group lies in its ability to generate a continuous stream of new products based on product platforms. A quantitative assessment of the success (or failure) of this effort is key to effective product family management.

The topic of research and development metrics was studied in the literature, and there was nothing found specific to the product platform framework. However, the study did reveal valuable insights into the elements of successful and unsuccessful R&D performance measurement systems.

A set of 'meta-metrics' was proposed as being appropriate for assessing the performance of product platforms within, and across product families. Based on the findings in the literature study, and subsequent testing on live data, two meta-metrics were found to be effective: R&D cost leverage, and sales productivity. They are simple, easy-to-use, and honor the criteria for successful R&D measurement systems.

Formulated to suit a generic product family structure, the meta-metrics were applied to product family data from a medical equipment manufacturing company with recent sales over $1 billion. The resulting post-audit showed the effects of both good and bad platform design, and also the effects of resource allocation changes.

The implications of this study are discussed, and areas of further research are proposed.

Thesis Supervisor: J. M. Utterback, Professor, Sloan School of Management

For Janet and Alexander.

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1 Introduction and Context

A successful research and development group must create a continuous stream of new products for the marketplace. To do so, the group's effort should be based on creating successive generations of product platforms, and follow-on products[1] [2] [3]. Such platform-based *product families* necessitate that the R&D group produce modular product designs, and assemble the constituent component technologies[4] [5]. It must also understand its target market requirements sufficiently so that their resulting products are the ones that customers yearn to purchase[6]. Within the firm, it stands to reason that these activities must be supported by a process of product generation that encourages platform development, and the integration of marketing knowledge with technical knowledge across the full product cycle[7].

If these are the keys to success for an R&D group, how can firms assess the performance of the effort? Several corporate surveys have shown that the measurement of the research and development process is at the forefront of problems in technologically intense companies[8] [9] [10]. This thesis is aimed at the

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[1] Meyer, M., and J. Utterback, "The Product Family and the Dynamics of Core Capability," *Sloan Management Review*, Spring 1993, pp. 29-47.

[2] Sanderson, S., and Uzumeri, M., "Managing Product Families: The Case of the Sony Walkman", *Renesslear Polytechnic Institute*, Troy, NY, October 1993

[3] Wheelwright, S., and K. Clark, "Creating Project Plans to Focus Product Development", *Harvard Business Review*, March-April 1992, pp. 70-82

[4] Ulrich, K., and K. Tung, "Fundamentals of Product Modularity", *MIT Working Paper*, September 1991, WP#3335-91-MSA.

[5] Smith, P., and D. Reinertsen, "*Developing Products in Half the Time*," Von Nostrand, NY, NY, 1992 (Chapter 6 in particular).

[6] Hauser, J., and D. Clausing, "The House of Quality," *The Harvard Business Review*, May-June, 1988, pp. 63-73.

[7] Cooper, R. G., "Stage-Gate Systems: A New Tool for Managing New Products," *Business Horizons*, May-June 1990, pp. 44-54.

[8] Booz Allen Hamilton Survey 1982

[9] Roberts, Edward B., "Strategic Management of Technology: Global Benchmarking (Initial Report)", *MIT Working Paper*, 1994, WP #101-94.

decision-makers in those companies. For those decision makers, this thesis proposes and tests a set of *product family*[11] performance measures termed "*meta-metrics*"[12].

There are broad implications to the effective assessment of product family performance. Learning from the past is the key to doing better in the future. A company needs to learn from past performance if it is to make timely, prudent decisions on current, and future product family management. Intuitively, learning facilitates better innovation strategies for new platform and product development. This first chapter presents the product family and its connection to the broader perspective of the learning system.

Chapter two reviews the literature and addresses the issues relative to R&D productivity measurement. From that review, three sets of meta-metrics are proposed and mathematically formulated. The proposed meta-metrics are specifically suited to understanding occurrences within the product family framework.

In chapter three, the meta-metrics are applied to actual company data. The results are graphed, analyzed and discussed.

Measurement at one point in time is not sufficient. A long term regimen for performance assessment is necessary. As well, competitive data, which is external to the firm, must be amalgamated with internal metrics for a complete analysis. The final chapter of this thesis, chapter four, explores the limitations and broader implications of this work. Further areas of research are proposed.

Throughout this thesis, the industrial context is that of technology-based companies.

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[10] Industrial Research Institute, Survey of R&D directors as of May 17, 1993.

[11] See for example, Meyer M., and J. Utterback, 1993, op. cit.

[12] The latin term 'meta' implies an external view of the product development process within. In other words, we seek to measure the performance of product families as objective outsiders to the process. The context will become clearer in subsequent Sections.

1.1 Terminology

Clarification of some terminology serves to establish a basis of understanding. This section provides contextual definitions of a few key terms.

1.1.1 Technology

To most people the term technology invokes visions of products such as computers, lasers, and compact discs. Certainly technology is a ubiquitous component of these products. But these products should not be misrepresented as being technology. Technology is a *process*. According to Webster's[13], 'technology' derives from the Greek '*technologia*'. Three definitions are given; (1) the systematic *treatment* of an art; (2) applied science, a scientific *method* of achieving a practical purpose; and (3) the totality of the *means* employed to provide objects necessary for human sustenance and comfort.

Technology is the process of converting scientific knowledge into practical results. For a firm, practical results must ultimately imply profits. For the end-user a practical result implies 'sustenance and comfort'. The practical application of scientific knowledge and design in a certain specialized discipline, say semiconductors, therefore relates to the design, and implementation of the design, by which semiconductors are made. This process would be termed 'semiconductor technology'.

Some firms are more technologically 'intense' than others. Technological intensity is usually proportional to a firm's research and development effort. A firm's R&D effort breeds new technologies. The commercial agenda of the firm is to ensure that the bred technologies become embodied into profitable products in the marketplace.

A standard industrial classification of technology has been constructed by the Organization of Economic Cooperation and Development (OECD). Table 1.1 shows the OECD classification.

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[13] Webster's Ninth New Collegiate Dictionary

Table 1.1: OECD Technology Classification by R&D Intensity

Low Technology	***Medium Technology***	***High Technology***
Stone, Clay, Glass	Automobiles	Aerospace
Food, beverages, tobacco	Chemicals	Office machines, computers
Shipbuilding	Other manufacturing	Electronics and components
Petroleum refineries	Non-electrical machinery	Drugs
Ferrous metals	Rubber, plastics	Scientific instruments
Metal manufacturing	Non-ferrous metals	Electrical machinery
Paper, printing		
Wood, cork, furniture		

Note that Table 1.1 has been broken down into divisions of low, medium, and high technologies. Within each division, the technologies are hierarchically ranked in order of decreasing R&D intensity[14]. In this thesis, product families are viewed from the perspective of technology-based industries; mostly those in the 'medium' and 'high' technology categories.

Technology can also be quantified according to age and diffusion; in other words, how long the technology has been around and, how pervasive it is in the public domain. In technologically intense industries, metrics on the state of technology are important to plotting competitive moves[15].

To summarize, technology implies a means, not an end. Different industries use varying levels of technology to achieve many 'practical purposes' for their customers. These 'practical purposes' yield profit. A manager's objective is to maximize long-term profits through the efficient leverage of technologies available to the firm. The meta-metrics proposed in this thesis serve to assess the performance of such leverage.

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[14] Source: OECD 1993; R&D intensity is a normalized measure of how much money is spent on R&D by the industry.

[15] Utterback, J. M., and J. W. Brown, "Monitoring for Technological Opportunities," Business Horizons, v. 15, October 1972, pp. 5-15.

1.1.2 Products vs Processes

According to Ulrich and Tung[16]; "A *product* can be described functionally by a collection of functional elements linked together by exchanges of signals, material, and power." As before, the knowledge and design that goes into linking a product's 'functional elements' together is the *technology*. Bringing it all together in a physical sense requires *process*. A *process*, therefore, is the method by which the functional elements are brought together to make a *product*. Note that technology is equally important to processes as it is to products.

Product and process innovation are inseparable in the life cycle of a product[17] [18] [19]. Remaining competitive, and maximizing income over time depends critically upon the application of new technologies to *both* products and processes.

1.1.3 Product Cycle

The term 'Product Cycle' generally refers to the activities that span the time involved in the development and commercialization of new products. In their 1968 report, Booz-Allen Hamilton defined six distinct stages in the cycle: *exploration, screening, business analysis, development, testing, and commercialization*. The report noted that these six stages effectively represented the common practice of prominent companies at that time. Other authors have either combined, sub-divided, or renamed these categories. The semantics are not really important. What is important is when the process starts and ends, and how much money is spent and received over that period of time.

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[16] Ulrich, K., and K. Tung, "Fundamentals of Product Modularity", *MIT Working Paper*, September 1991, WP#3335-91-MSA.

[17] Abernathy W., and J. Utterback, "Patterns of Industrial Innovation." *Technology Review*, vol. 80, no. 7, pp. 40-47.

[18] Utterback, J., and F. Suarez, "Innovation, Competition, and Industry Structure," *MIT Working Paper*, June 1991, WP#29-90.

[19] Utterback, J., *Mastering the Dynamics of Innovation*, Harvard Business School Press, 1994, Boston, MA., USA.

In this thesis, the product cycle has clearly defined time boundaries. The product cycle starts when the first dollar is invested into the research and development of a product, and ends when the last dollar is received from the product's final sale in the marketplace. For simplicity only *two stages* in the cycle are considered: the ***R&D** stage*[20] , and the *commercial stage*. Transition between the two occurs at the beginning of the commercial stage. This is when the first dollar is received from the sale of the product in the marketplace.

Note that this simplified definition of the cycle does have its shortcomings in some realistic corporate situations. For example, for some early stage research projects, it is difficult to assign a start time to the product cycle. This is because these research projects are not clearly defined to be a part of any particular product. On the commercial side, a firm may choose to strategically withhold entry into the marketplace even though a product is fully developed. This delay creates a lull between the R&D and commercial cycles. For simplicity, these situations are not addressed here.

Finally, the term '*project*' is used throughout this thesis. A 'project' refers to the undertaking of a product's development and commercialization process through its full product cycle.

1.2 Product Cycle Learning

As stated earlier, measurement and assessment are foundations for learning. Figure 1.1 displays the product cycle from a learning system perspective.

The maxim, 'what is past is prologue' and 'history repeats itself', are directly applicable to research and development projects[21]. To leverage off these aphorisms, the task is to document a firm's product cycle history with

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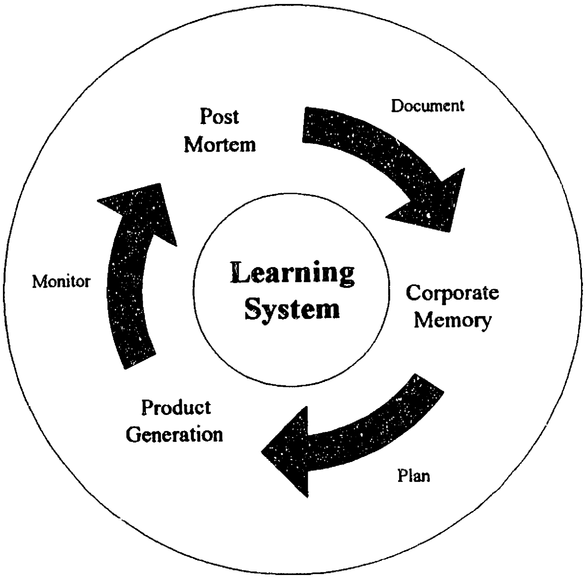
[20] R&D will be used as a convenient term for all the developmental processes, including engineering, that lead up to the commercial stage.

[21] Ellis, Lynn W., "Viewing R&D Projects Financially", *Research Technology Management*, March-April 1984, pp. 29-34.

appropriate measures. By studying documented measures, past failures can be avoided, and past successes repeated. Patterson, and Porter, echo this view by exhibiting the benefits that measured feedback provided to their respective firms[22] [23]. The circular nature of the learning system (Figure 1.1), naturally suits this feedback process.

Figure 1.1: Product Cycle Learning System



Though the cycle is continuous, consider a firm which starts with a new project ('Product Generation'; Figure 1.1). To learn the most about the success (or failure) of the project, it should be monitored through its entire product cycle: from development, through commercialization, to market withdrawal.

Measuring the performance of the project is represented in Figure 1.1 by the label, 'Monitor'. Monitoring is an ongoing process of measurement and evaluation throughout the life-cycle of the project. The frequency of monitoring will depend on the nature of the firm's business.

Note that measuring variables *external* to the firm are also necessary. Market information, competitive intelligence, and technology assessments are

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[22] Patterson, William C., "Evaluating R&D Performance at Alcoa Laboratories", *Research Technology Management*, March-April 1985, pp. 23-27.

[23] Porter, John G. Jr., "Post Audits - An Aid to Research Planning", *Research Management*, January 1978, pp. 28-30.

also necessary to learning. The scope of this thesis is limited to internal measures of product family performance.

Post-mortem is aptly named to assess the performance of the project after it has completed its cycle. Ultimately, the project dies in the marketplace (hence the name post-mortem). Post-mortems offer the opportunity to analyze the data gathered from monitoring the project. With the rapid rate of change in technologically intense industries, product mortality is occurring earlier and earlier.

Note that forecasting post-mortems is accepted practice. In other words, one can forecast the expected lifetime sales of a product before it dies in the marketplace. The ensuing analysis is valuable for making decisions on the viability of new projects. Forecasting the life of new projects becomes easier with the knowledge and experience gained from the completion of each learning cycle.

To capture post-mortems, it is necessary to document the results. In Figure 1.1, this process is labeled, 'Document'. Documentation is the process of storing the gathered information in a well organized manner. Recently, Dwyer and Mellor found that survey respondents from 96 companies often called for more formal, better documented procedures in the product development process[24] . This fact comes from their finding that only 52% of these firms have any sort of formal procedure for controlling and coordinating projects as the go through the product cycle.

At the end of the cycle, documented information is placed in a repository called the 'corporate memory'. Ideally, the corporate memory resides in an electronic relational database. This will be discussed further in chapter four.

With the cycle complete, decision-makers can address new projects with greater confidence. What will this new product cost to develop? How long will

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[24] Dwyer, L., and Mellor, R., "New Product Process Activities and Project Outcomes", *R&D Management*, 21: 1, 1991, pp. 31-42.

it take? Do we have the human and technical resources? The corporate memory can be a valuable source of information to help answer these and other important questions. Learning from past experiences is an effective way of helping to assess new project decisions. Patterson[25] confirms this with the following assessment of R&D auditing at Alcoa Laboratories:

> "Feedback from economic audits reveals why some projects succeed while others fail. As more data are gathered, we expect to be able to sharpen our project selection criteria to weed out those which are destined for failure." (p.26)

The success of a corporate learning system depends on many factors including: ease-of-use, information integrity, data maintenance, and so on. At the root of the system is the issue of what should be monitored.

1.3 The Product Family Concept

The concept of *product families* and *platforms* is a highly intuitive way of organizing a firm's projects[26] [27]. Yet intuition seems to be lacking in most companies. Wheelwright and Clark comment that:

> "Platforms offer considerable competitive leverage and the potential to increase market penetration, yet many companies systematically underinvest in them. The reasons vary, but the most common is that management lacks the awareness of the strategic value of platforms and fails to create well-thought-out platform objects. To address this problem, companies should recognize explicitly the need for platforms...(p. 74)"

The statement that, "management lacks the awareness of the strategic value of platforms," lends credence to this thesis. In other words, the strategic value of a product platform can only be recognized if its performance is measured, documented, and presented to management.

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[25] Patterson, William C., op. cit.

[26] Meyer, M., and Utterback J., op. cit.

[27] Wheelwright, S., and Clark, K., 1992, op. cit.

1.3.1 Product Family Genealogy

Similar to human families, the product family can be thought of as having a hierarchical genealogy. Figure 1.2 shows the basic genealogy of a product family.

A *family* of products are composed of product *platforms*. Product platforms each encompass sets of *follow-on products*. Therefore, one product family can have several product platforms within it. In turn, each product platform within the family can spin off a multitude of follow-on products.

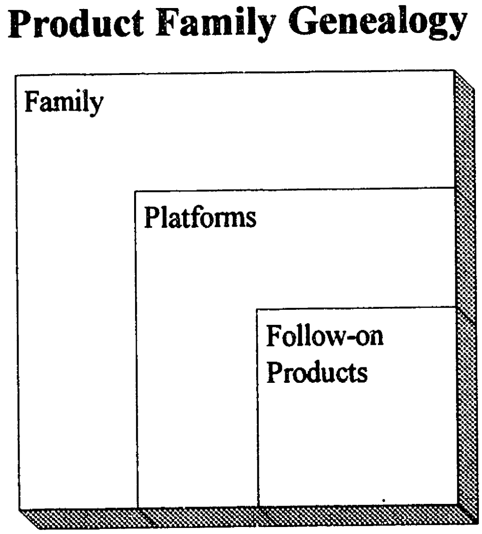
Product Family Genealogy

Figure 1.2: Product Family Genealogy

The following definitions help clarify the product family concept.

- ***Product Family*** - A family of products draws from a common foundation of technologies, components, and corporate resources. From a market perspective, product families address a common market segment. The commonalty of technologies and markets leads to efficiency and effectiveness in manufacturing, distribution, and service. Ideally, each general resource of capability within the firm is tailored to the needs of specific products and market niches. For example, a range of stereo equipment can be considered a product family. Power supplies, dials, knobs, and electrical engineers are all part of a common foundation to a family of stereo equipment.

The common marketplace for stereo equipment is consumer electronics. A well planned product family will spawn high levels of customer recognition.

- ***Product Platform*** - Platforms form the organizational backbone and technological foundation of the product family. They are tailored to address specific niches within the marketplace addressed by the family. Each platform within a product family provides a *base architecture*. The architecture consists of a set of subsystems and technologies drawn from the family pool. From this base, follow-on products can be quickly developed and commercialized into the marketplace.

  Sanderson and Uzumeri[28] have viewed product platforms as the implementation of "virtual designs" that serve as the basis for a series of "product realization." Each significant improvement of a product platform leads to a new generation of follow-on products. The product family therefore evolves based on both the renewal of its underlying platform, and the specific product offerings generated from successive platforms.

  In some ways, the development of a platform is analogous to climbing a mountain. A 'base camp' is established from which various sets of climbers can scale the peak. This avoids numerous logistical problems. Most importantly, an established base camp serves as a platform from which different sets of climbers can repeatedly, and

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[28] Sanderson, S., and M. Uzumeri, 1993, op. cit.

quickly, scale the top. There is no need for each group of climbers to start all the way from the bottom.

Similarly, a well designed product platform serves as a 'base camp' from which the marketplace can be repeatedly attacked without having to start from scratch everytime. This helps ensure a smooth and continuous stream of new products with market longevity.

- ***Follow-ons*** - Follow-ons are the final products that are spun off a platform. They share all the subsystems, and technologies inherent in the platform. A set of well designed follow-ons will absorb as much of the market niche as possible. Technological advances in subsequent follow-ons almost always represent incremental innovations.

  In follow-ons, innovation can be either technological or *topological.* Topological innovations relate primarily to changes in industrial design for the purposes of targeting very specific market niches. The underlying subsystems generally remain constant.

Figure 1.3 displays a comprehensive view of how families, platforms, and follow-ons relate.

Sony's Walkman line of portable cassette players is one of the most commonly cited examples of a successful product family[29]. One platform within the Walkman family would be the assembly of subsystems designed for waterproof players. The follow-ons would be the different models -- high end and low end -- that are all waterproof.

1.3.2 Extensions and Renewals

Occasionally, the designation of an entirely new platform is not warranted. A platform can evolve through incremental innovations in the embodied technology and subsystems. The evolution of such a platform is

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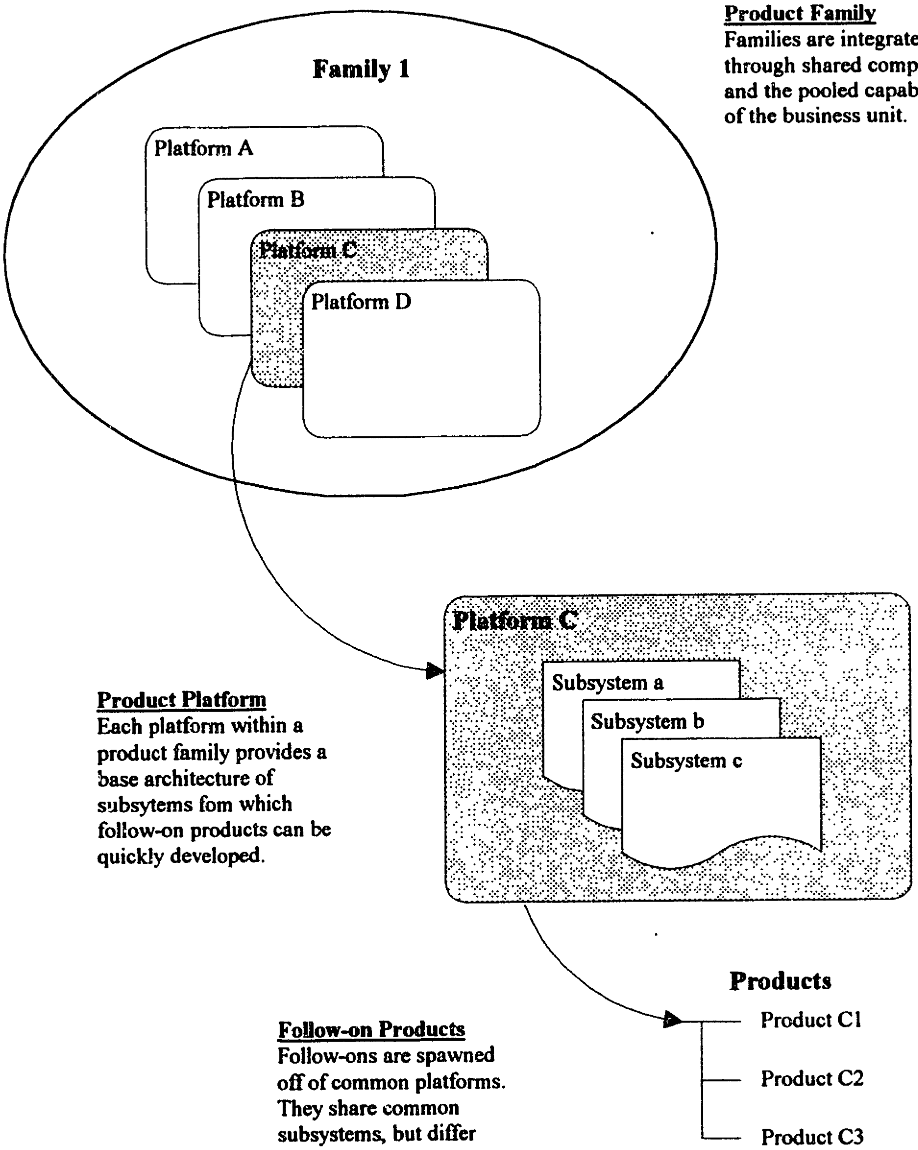
[29] Sanderson, S., and Uzumeri, M., op. cit.

Product Family Concept



Product Family
Families are integrated through shared components and the pooled capabilities of the business unit.

Product Platform
Each platform within a product family provides a base architecture of subsytems fom which follow-on products can be quickly developed.

Follow-on Products
Follow-ons are spawned off of common platforms. They share common subsystems, but differ otherwise so as to address different market niches.

Figure 1.3

termed a *platform extension.* For example, a computer manufacturer may replace a particular processor subsystem with progressively faster processors[30].

Figure 1.4 shows how a platform extension can evolve off the original platform architecture.

A *platform renewal* occurs when the architecture of the product design is changed to incorporate major new subsystems and new subsystem interfaces. This defines a totally new platform within the product family. For example, new digitally based technologies have replaced analog instrumentation. Although the target markets have remained the same, the digital revolution has spawned many new platform renewals.

1.3.3 The Product Core

Meyer and Utterback[31] extend the common definition of a *product platform* to that of the *product core*; "A product core is the heart of a successful product family, serving as the foundation for a series of closely related products." While the platform is understood to encompass design and components shared by a set of products, the product core encompasses all shared functional elements. These elements include such items as distribution channels, manufacturing processes, service infrastructure, and market segments.

1.3.4 Managing the Product Family

The concept of platforms, product follow-ons, and renewal is not novel to this thesis. Wheelwright and Clark differentiated between platforms, their follow-on products, and platform 'extensions' or renewals for vacuum cleaners; Meyer and Utterback did the same in their study of electronic imaging systems and peripherals, and Lehnard for power tools[32] [33] [34].

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[30] Intel has continuously renewed its microprocessor product line with new platforms and their follow-on products: the 80286 replaced the 8086, the 80386 replaced the 80286, and the 80486 replaced the 80386. Most recently, the Pentium microprocessor replaced the 80486. Within each of these platforms, follow-on microprocessors were introduced: for example with different operating frequencies.

[31] Meyer, M., and Utterback, J., op. cit.

[32] Wheelwright, S., and Clark, K., 1992, op. cit.

Platform Extensions and Renewals

Original Architecture
Common subsystems and interfaces which are the basis for multiple follow-on products.

Platform Extensions
A new generation of products are created from enhanced subsystems and interfaces. Numbers and types of subsystems and interfaces remain the same as the original architecture.

Platform Renewal
The evolution of a new architecture, where subsystems and interfaces from prior versions may be carried forward and combined with new subsystems and interfaces in the new design.

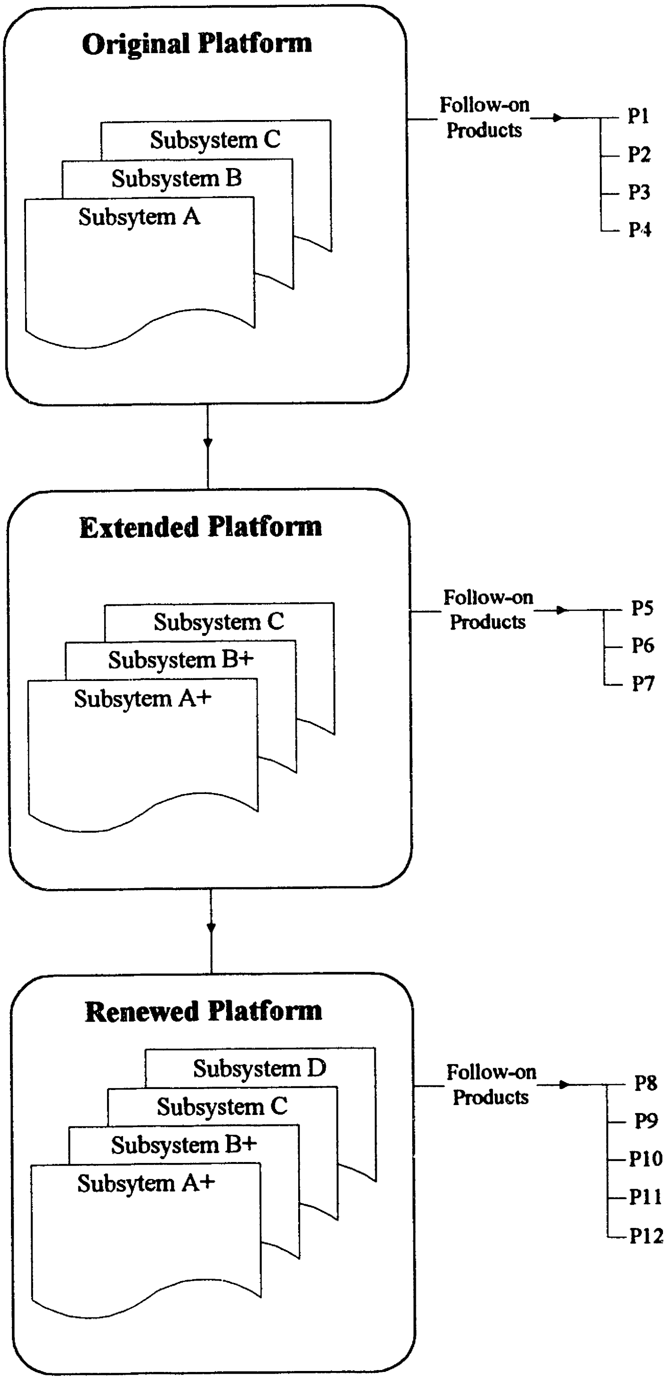

Figure 1.4

Timely platform renewal has been essential to Intel's success. While follow-on products are generated off the current platform, resources are already allocated to a new platform version. The current platform is continuously planned for obsolecense.

All this leads to an essential point: to achieve sustained commercial success, a firm must seek to continuously renew its base product architectures. Engineering activity must be focused on specific product development projects which derive from existing architectures.

Successful planning under the product family framework is in the management of the linkages between follow-ons, between platforms, and between families. Figure 1.5 illustrates this concept.

The concept of the product core fosters a mindset for managers to think holistically about their businesses. Meyer and Utterback offer two basic recommendations for the product family idea to have impact[35]:

- *Product planning* must be transformed from a single product mindset into, "product family planning that includes several versions of product cores, the product platforms within these cores, and the market niche product variations within a family."
- *Budgeting* for projects must be adapted to the holistic concept of the product core. Competition for financial resources and turf issues must be set aside for new product planning. A longer term commitment to the product core concept is required from senior management.

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[33] Meyer, M., an d J. M. Utterback, op. cit.

[34] Lehnerd, Alvin, "Revitalizing the Manufacture and Design of Mature Global Products," *Technology and Global Industry: Companies and Nations in the World Economy*, ed. B. R. Guile and H. Brooks, Washington D. C.: National Academy of Engineering Press, 1987, pp. 49-64.

[35] Meyer, M., and Utterback, J., op. cit.

Product Family Integration

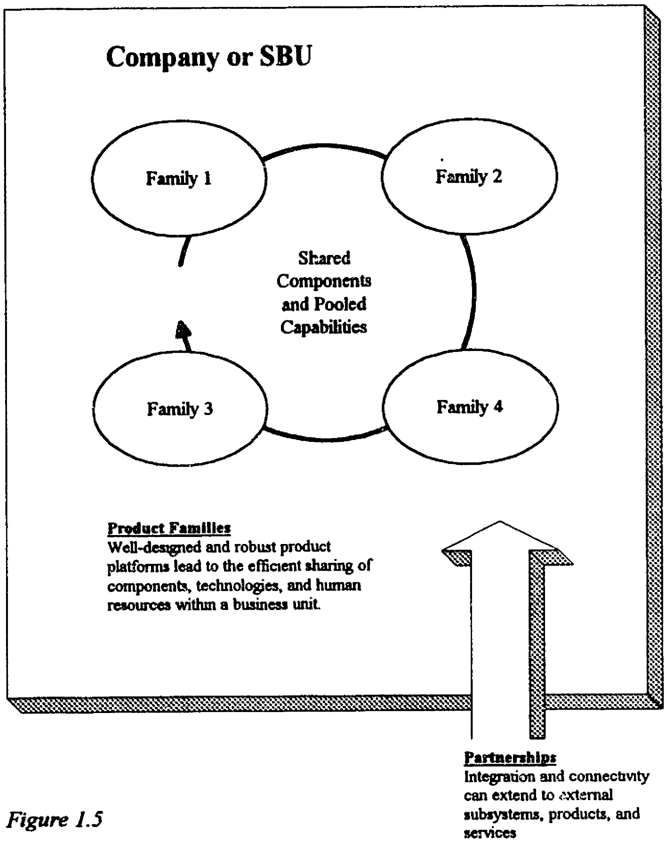

Figure 1.5

1.3.5 Mapping Product Families

Visualization of product evolution under a platform framework is natural and insightful[36]. Conceptually, Figure 1.6 shows a typical product family 'mapped' in time. In chapter three, this framework is applied to a set of actual product families.

The entire product cycle of a platform is represented in Figure 1.6. Note that the cycle time of follow-on products is considerably less once the initial platform has been developed.

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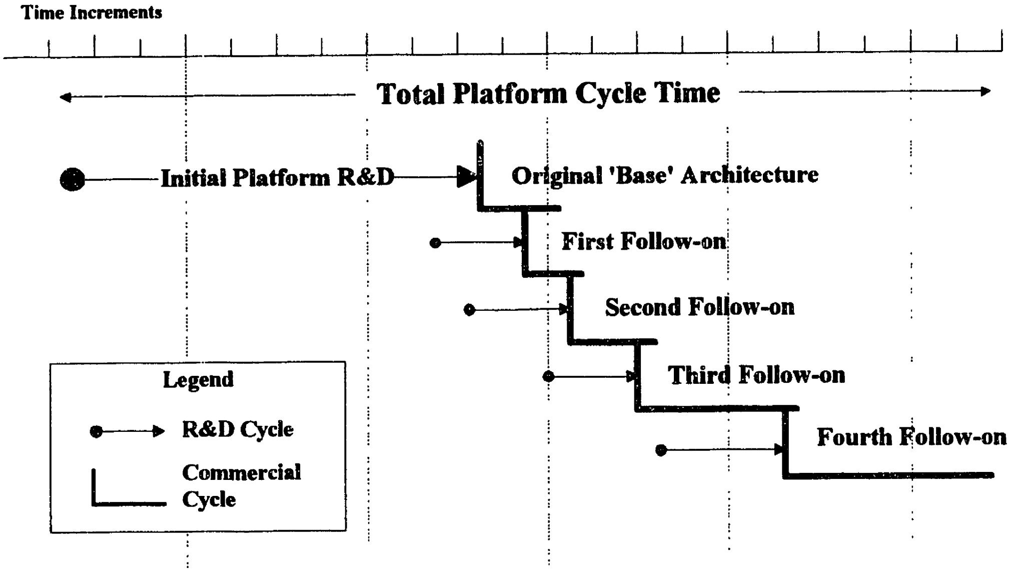
[36] Meyer, M., and Utterback J., op. cit.

Figure 1.6 **Product Platform Map**



Finally, a welcome offshoot of the product family framework is its ability to help a firm assess its core capabilities. As a planning framework, it helps a firm stay within the bounds of its core capabilities. The benefits of focusing on core capabilities is fundamental to organized planning and operations[37].

1.4 The Strategic Context of Performance Measures

> *Gathering data is a waste of time unless they are used in formulating strategy, and creative ways must be devised to put these data in concise and usable form to top management.*
>
> Michael Porter[38]

The premise of this thesis, and its supporting frameworks, have now been introduced. But objectives are always clearer when taken in the larger context. This section discusses the strategic relevance of measuring product family performance.

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[37] Prahalad, C. K., "The Role of Core Competencies in the Corporation", *Research Technology Management,* Nov-Dec 1993, pp. 40-47.

[38] Porter, M., *Competitive Strategy,* The Free Press, New York, NY, 1980.

1.4.1 Industry Trends

In North America, the corporate trend for technology-oriented companies is to uncouple the R&D function[39]. The development function is being organizationally moved to the division level, while basic research remains autonomous. In many instances, the basic research function is being terminated altogether.

The implications of this uncoupling are many. One consequence is that the focus of product development is being put onto short horizon projects. Incremental, low risk, innovation is being favored over long-term, risky projects. Another consequence is that divisional managers now have the responsibility for orchestrating the product cycle. Traditionally, division managers have little experience in the product development process and are discovering the intricacies 'on the job'.

This uncoupling of the R&D function is in line with Prahalad's proposition that the real issue in the 1990's is *growth*[40]. The fastest way to achieve growth is to concentrate on lower risk, short-term development projects. Prahalad goes on to suggest that the managerial 'scorecard' is now based on *value creation*. Value creation, according to Prahalad, consists of managing two issues:

- ***Performance gap*** - issues such as quality, cost, cycle time, productivity, and profitability.
- ***Opportunity gap*** - issues relating to the deployment of corporate resources to create new markets, new businesses, and a sense of broad strategic direction.

Product families are ideally suited to handle the trends and corporate objectives of the 1990's. The ability to quickly spin off new follow-on products

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[39] Roberts, Edward B., op. cit.

[40] Prahalad, C. K., op. cit.

off an established platform dramatically reduces cycle time and head count. Costs are minimized through the use of pooled resources and subsystems. Quick cycles enhance the learning system. Managed well, product families offer an efficient and productive method of creating value.

1.4.2 Technology Strategy

Technology and technological innovation are at the heart of new product development. Therefore, the entire product cycle is dependent upon a well planned *technology strategy.* And that technology strategy must be concordant with the firm's overall business strategy. Indeed, Schmitt[41] emphatically writes that, "Business strategy must be the scale of measure for R&D".

The phrase 'technology strategy' requires insight as it is often used loosely in the literature. Indeed, Kantrow's[42] words are still mostly true today, "... the most basic categories and terminology of technology strategy have not yet been determined." This does not bode well for formulating competitive product innovation strategies in technologically intense industries.

An informed 'technology strategy' is essential for new product development as opportunities appear and disappear quickly. Mistakes, languor, neglect, and oversights in a firm's technological positioning can be very costly. In the mid-1970's, Xerox's Palo Alto Research Center (PARC) had created at least three radical innovations as we know them today: the laser printer, the personal computer, and ethernet[43]. Xerox lost the opportunity to dominate the market in all three cases. In an analogy to chess, Xerox PARC had the right pieces in the right positions, but was blind to knowing where they were. Further, Xerox forfeited several moves to its competitors, and in the end lost its competitive position. The game was over. Luckily for Xerox, their enormous

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[41] Schmitt, R. W., "The Strategic Measure of R&D", *Research Technology Management*, Nov-Dec 1991, pp. 13-16.

[42] Kantrow, A., "The Strategy-Technology Connection", *Harvard Business Review*, July-August 1980, pp. 6-21.

[43] Smith, D., and Alexander, R., *Fumbling the Future: How Xerox Invented then Ignored the First Personal Computer*, William Morrow and Company Inc., New York, NY, USA, 1988.

photocopier business mitigated the lost opportunities. Had they been smaller, or more financially vulnerable, the outcome for Xerox could have been much worse. Skinner[44] correctly points out, "Unwise decisions on technological issues are frequently fatal in small business."

Numerous books and articles cite examples of firms being attacked and defeated on the technological front[45] [46]. A recent editorial in the Wall Street Journal stated,

> "Technology will continue its relentless penetration of businesses and industries. What is clear... is that technology strategy is becoming a central art of business leadership. Executives need to invest in mastering this art."[47]

This line of thought is neither new nor unrecognized within corporations and academia. Executive level surveys from industry have shown that there is a demand for effective technology strategy directed from the top[48]. These survey results support Kantrow's contention that, "The major unfinished business of the research literature is to provide managers with needed guidance in their formulation of a technological strategy for their companies.[49]"

To this end, several technology strategy frameworks have been proposed in the literature[50] [51] [52] [53] [54]. Most offer only general recommendations and static solutions; solutions where strategic positions are formulated at the current point

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[44] Skinner, W., , *Manufacturing in Corporate Strategy,* Wiley, New York, NY, USA., 1978.

[45] Foster, R., *Innovation: The Attackers Advantage,* Summit Books, New York, NY, USA., 1984.

[46] Utterback, J., (1994), op. cit.

[47] Wall Street Journal, *Manager's Journal,* August 16, 1993.

[48] Booz Allen Hamilton, 1982, op. cit.

[49] Kantrow , 1980, op. cit.

[50] Stacey, G., and Ashton, W., "A Structured Approach to Technology Strategy," *International Journal of Technology Management,* vol. 5, issue 4, 1990, pp. 389-407.

[51] Maidique, M., and Patch, P., "Corporate Strategy and Technology Policy," *Harvard Business Review,* 1978.

[52] Kantrow, A., "The Strategy-Technology Connection," Harvard Business Review, July-August, 1980, pp. 6-21.

[53] Dodgson, M., "Managing Corporate Technology Strategy," *Int. J. Technology Management, Special Publication on the Role of Technology in Corporate Policy,* 1991, pp. 95-102.

[54] Roussel, P. et al, *Third Generation R&D: Managing the Link to Corporate Strategy,* Harvard Business School Press, Boston, MA, USA., 1991.

in time, and are too cumbersome to handle quick, dynamic changes. In short, the solutions proposed in the literature are too general, and therefore inadequate for rapid product innovation cycles. Further, most current methods are strictly analytical, and lack any sort of *visual creativity* in their presentation. This important shortcoming ignores the cognitive needs of a decision-making executive. Just as a board is required to play chess, a clear picture of a firm's competitive position is required to formulate strategy.

Strategy must be concordant with an implementation process. Chess strategy is formulated by knowing the rules of the game and how the pieces may move. Technology strategy is no exception: it has to support a coherent regimen for product and process innovation. Again, product families, platforms, and follow-ons, offer a highly organized approach to extract the most revenue from a market segment, while providing a common-sense approach to product and process innovation.

Effective management and strategy-making requires a continuous level of understanding; both historic and current. Perhaps the chess analogy is too simplistic for the technology trade. Today, participating in globally competitive technology industries is tantamount to fighting an all out war. From his book, *On War*, the famous military strategist General Carl Von Clausewitz states:

> **"Strategy must go with the Army to the field in order to arrange particulars on the spot, and to make the modifications in the general plan which incessantly become necessary in War. Strategy can therefore never take its hand from the work for a moment."[55]**

To ensure that strategy, "never takes its hand from the work for a moment", military planners have highly detailed maps and charts of up-to-the-minute troop movements, supply chains, and enemy positions. All pertinent processes are measured. They learn from the past and are highly informed at all times. If firms are to survive the battles on the technology front,

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[55] **Carl Von Clausewitz, *On War*, Chapter III, Book I**

their executives -- like military planners or chess players -- need to be better informed.

Without a set of measures and maps for assessing product family performance, a firm cannot effectively formulate its new product strategies.

1.4.3 Speed and Strategy

Time is an important dimension for competitive firms -- especially in technology-based industries. Speed in making strategic choices has been demonstrated to be a common element in successful firms; procrastination and vacillation being common to inferior firms. Eisenhardt[56] finds that,

> "Strategy making has changed. The carefully conducted industry analysis or the broad-ranging strategic plan is no longer a guarantee of success. The premium now is on moving fast and keeping pace."

Laggard decision-making on technological issues is a contributing factor to Morone's paradox which states that, "Technologically rich companies, in a technology-rich society, [fail] to compete effectively in technology-intensive industries.[57]"

Eisenhardt[58], finds that, among other things, managers of technology based-firms make high quality decisions by continuously *tracking real-time information.* Tracking information necessarily implies the need for well-thought-out measures for evaluating performance.

As we shall see in the next chapter, numerous schemes for tracking the effectiveness of a firm's product development cycle have been proposed. Few are appropriate for firm-level decision-making. None address the product development cycle from the perspective of the product family.

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[56] Eisenhardt, K., "Speed and Strategic Choice: How Managers Accelerate Decision Making", *California Management Review*, Spring 1990, pp. 39-53.

[57] Morone, J., "Technology and Competitive Advantage - The Role of General Management", *Research-Technology Management*, pp. 16-25.

[58] Eisenhardt, K., op. cit.

1.5 Presentation of Performance Measures

Conveying information by mere numbers is no longer acceptable for problem solving activities; especially in an age where we are inundated with data. Daniel Eisenberg writes[59]:

> "...Managers have an organized mental map of all the problems and issues facing them. The map is neither static nor permanent; rather, managers continually test, correct, and revise it. In the words of one CEO, the executive takes advantage of the best cartography at his command, but knows that is not enough. He knows that along the way he will find things that change his maps or alter his perceptions of the terrain. He trains himself the best he can in the detective skills. He is endlessly sending out patrols to learn greater detail, overflying targets to get some sense of the general battlefield."

Without effective presentation of information, a 'mental map' is difficult to construct. Visualization is a powerful means to convert data into information and convey a concise message for the brain to process. Edwin Tufte[60] writes:

> "Modern data graphics can do much more than simply substitute for small statistical tables. At their best, graphics are instruments for reasoning about quantitative information. Often the most effective way to describe, explore, and summarize a set of numbers -- even a very large set -- is to look at pictures of those numbers. Furthermore, of all methods for analyzing and communicating statistical information, well-designed data graphics are usually the simplest and at the same time the most powerful."

The key phrase in Tufte's statement is *well-designed* data graphics. Today's proliferation of personal computers and graphics software allow anyone to easily produce sleek looking graphs and charts. But that does not mean that these displays of quantitative information are conveying an effective message. Many graphs and charts are so cluttered that they serve to hinder the thought process. Care must be taken to present the information in a manner which enhances one's mental map, and amplifies the cognitive processes of the brain.

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[59] Eisenberg, Daniel J.

[60] Tufte. E., *The Visual Display of Quantitative Information*, Graphics Press, Cheshire, CN, USA

If the metrics in this thesis are to be used for learning and decision-making, then they must be presented in a form other than mere numbers. Wheelwright and Clark, propose 'maps and mapping' when formulating an 'Aggregate Project Plan'[61]. Following their lead, wherever appropriate, the proposed meta-metrics and supporting data are mapped and graphed in a straightforward manner which facilitates understanding.

1.6 Summary

Technology has been defined as the process by which products are created in technology-based companies. Managing technological innovation is therefore key to managing new product development.

Managing the development process under a *product family* framework enables more efficient leverage of resources, and if carefully managed, can substantially reduce costs, and shorten development cycles. Further, the product family framework positions companies to effectively renew their product platforms in an environment of rapid technological change.

Successful management, is predicated on well presented, and timely information. Learning from past projects, and keeping abreast of the current situation is essential. But what measures indicate success or failure in product family management? The next chapter studies the academic literature as it relates to measuring product development performance.

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[61] Wheelwright, S., and K. Clark, *Revolutionizing New Product Development: Quantum Leaps in Speed, Efficiency, and Quality*, The Free Press, New York, NY, USA..

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2

Assessing Product Family Performance

The literature is void of performance measures which specifically address product families, platforms, and follow-ons. Today, metrics for R&D productivity tend to be single project based, and confined to only portions of a product's life cycle. To fill the void, three sets of meta-metrics for product families are proposed. The meta-metrics are applied to a real dataset in chapter three.

Relative to general R&D performance measures, there is a fair amount of literature in two broad groupings: (1) articles that concentrate on defining systems and measures of R&D performance; and (2) articles that concentrate on the use of these measures for new project selection. The two groups are closely related as one feeds off the other. Together, the groupings are captured in the learning system model (Figure 1.1). Therefore, both groups of articles are used as a source of study for this chapter.

Section 2.1 provides a background of specific issues that are pertinent to product development metrics. In section 2.2, the literature is reviewed and classified. From sections 2.1 and 2.2, the criteria required for effective measurement systems are summarized. Finally, Section 2.4 proposes and formulates the meta-metrics for assessing the performance of product families.

2.1 Issues

The background information for this section is taken primarily from the literature. Three general sources of literature were used: management of technology, general management, and engineering management.

2.1.1 The Intent of Measurement

Prior to measuring anything, Pappas and Remer[1] provide two guiding thoughts for top management. First, management should decide what they expect to get from their research and development effort, and second, they must establish the *intent* of the productivity measurement system.

Schmitt[2] in his paper on the strategic value of R&D, encourages the thinking on an even higher plane by suggesting that:

> "One ought to think about the strategy and not just the methodology to measure R&D. Further, that strategy should be more than a measurement by numbers. Numbers are fine, but they need to be part of a larger context."

From these statements it is clear that understanding the *value* of the R&D effort, and the measurement of that effort is key. Brown and Svenson[3] give insight by stating that, "The real value that the R&D facility adds to the organization can only be assessed by measuring outcomes." Porter recognized this view at Mobil Research when responding to the executive question, "What have you done for me?"[4] Fifteen years later, in the era of the profit squeeze, that question has become routine for R&D managers. But the question is not only, "What have you done for me?", but more importantly, "What can you do for me?"

With a firm-wide perspective, Foster clarifies the overall intent of R&D performance measures by stressing their importance toward aiding the overall business strategy[5]. Too often, this 'big picture' view is forgotten. The result is that measures, and systems of measurement are developed that are of little or no

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[1] Pappas, R., and Remer, D., "Measuring R&D Productivity," *Research Technology Management*, May-June 1985, pp. 15-22.

[2] Schmitt, R. W., "The Strategic Measure of R&D", *Research Technology Management*, Nov-Dec 1991, pp. 13-16.

[3] Brown, R., and Svenson, M., "Measuring R&D Productivity," *Research Technology Management*, July-August 1988, pp. 11-15.

[4] Porter, John G. Jr., "Post Audits - An Aid to Research Planning", *Research Management*, January 1978, pp. 28-30.

[5] Foster, R. N., et al, "Improving the Return on R&D - I," *Research Technology Management*, Jan-Feb 1985, pp.12-17.

use. Packer recommends that the first step in developing measures is to define the uses of the performance information, and hence make sure that data is generated for that purpose[6] .

Within the product cycle a vast amount of information can be captured. Batson studied the information needs of R&D management and proposed nine candidate databases[7]. Technology, project control, personnel, customers, and competitors are among the few areas where Batson suggests that information be gathered and stored. This is only a partial list of the possibilities. Common-sense must prevail as an overload of information is as debilitating as not enough information. Richard Wurman writes:

> "Everyone spoke of an information overload, but what there was in fact was a non-information overload.[8]"

Indeed, one of the requirements of a successful performance evaluation system is that the cost of collecting and using the system should not exceed the benefits to be gained from better decision-making[9].

Therefore, meta-metrics for a product family must be carefully chosen so as to optimally serve the intent of the measurement system.

2.1.2 Usage

To be useful, project measurement information must be understandable, relevant, and reliable[10]. This leads to an important consideration: *who* will measure and *who* will use the information that is deposited in the corporate memory. Multi-function data can be generated; however, it is imperative that everyone who uses common information speaks a common language.

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[6] Packer, Michael, B., "Analyzing Productivity in R&D Organizations," *Research Technology Management, Jan-Feb 1983, pp. 13-20.*

[7] Batson, Robert, G., "Characteristics of R&D Management which Influence Information Needs," *IEEE Engineering Management,* 34:3, 1987, pp. 178-183.

[8] Richard Wurman, "What-if could-be", 1976.

[9] Packer, Michael B., op. cit.

[10] Packer, Michael B., op. cit.

Financial decision-makers generally do not speak the alien language of the engineer. Ellis says that engineers, as a result of their highly quantitative training, tend to use arbitrary scoring techniques which are viewed with disdain by the financially minded executive[11]. In other words, a common language is not being spoken in the firm. Strategic decisions are hard to make in this environment.

Rarely do complicated systems of measurement survive. Complicated systems -- generally developed by engineers -- are usually highly specialized and understood only by its authors. Following an author's departure, the specialized system dies a quick death[12]. Neither the system nor the language survives.

Foster[13] articulates that one of the main priorities of an R&D director is an understanding of the contribution of R&D to the corporation. Schmitt[14] expands this point by saying that the, "measures of R&D must be designed to tell the CEO about the health of the enterprise."

Given this strategic perspective, combined with a call for relevance and understanding, the arguments are compelling that projects be founded primarily (but not exclusively) from a *financial perspective.* Like Foster, Ellis is a strong proponent of financial metrics because, "In the end, the industrial research manager is part of a system that measures efficacy in terms of money."

2.1.3 The R&D Environment

Inherently, the R&D environment can be classified as one of *uncertainty.* Schon[15] eloquently states that:

> "A corporation cannot operate in uncertainty, but it is beautifully equipped to handle risk. Therefore, the innovative

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[11] Ellis, Lynn W., "Viewing R&D Projects Financially", *Research Technology Management*, March-April 1984, pp. 29-34.

[12] Baker, N., and Freeland, J., "Recent Advances in R&D Benefit Measurement and Project Selection Methods," *Management Science*, 21:10, 1975, pp. 1164-1175.

[13] Foster et al., 1985, op. cit.

[14] Schmitt, 1991, op. cit.

[15] Schon, D., *Technology and Change: The New Heraclitus*, Delacourte Press, New York, NY, USA, 1967.

> work of a corporation is to convert uncertainty to risk. At this point management can play the investment game."

Therefore, an effective R&D manager is dependent on having the right information at the right time[16]. Batson categorizes the uncertainty across the product cycle into three parts:

- Technical uncertainty - Can it be done?
- Historical uncertainty - Has it been done before? By whom?
- Marketing uncertainty - Who is doing it now? Who will buy it? How many? For how long?

Jensen and Lawson attempt to quantify the risks associated with these uncertainties by assigning transition probabilities to projects[17]. A transition probability is characterized by the probability that a project will transition from one stage of development to the next. As discussed in section 1.2.4, the product cycle can be simplified as a transition between two stages. Success in each stage can be characterized as follows:

- ***R&D stage***- all the required technologies are developed, proven, and embodied into a working, finished product ready for the marketplace. Research, development, and engineering (termed R&D for convenience) embody this process.
- ***Commercial stage*** - the finished product is accepted by the marketplace and achieves the desired financial returns.

Success for each stage is also associated with time variant levels of risk. The question becomes, "What are the risks and how can they be quantified?"

Competition, and the long length of time associated with R&D projects tend to increase the risk. What we do know is that risk generally decreases as a

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[16] Batson, 1987, op. cit.

[17] Jensen, F., and Lawson, J., "Quantifying R&D Expenditures in the Face of Uncertainty," *Research Technology Management*, March-April, 1985, pp. 29-33.

project transitions from pure research to quick developmental projects. In other words, incremental innovations are more certain to succeed than radical ones.

Batson's category of *historical uncertainty* is important[18]. The probability of success of the current project is much greater if a similar project succeeded in the past. If the same personnel from the past are working on the project, then the probability of success is even greater. Of course, the converse to these statements follows: the probability of a project succeeding is less, if comparable projects failed in the past, and if novice personnel are assigned.

Viewed in the context of product families, the development of an entirely new platform is riskier than the development of the follow-on products off of it. This is because platforms involve a greater innovation effort -- and hence greater technical uncertainty -- than follow-ons.

Successive follow-on products have progressively less technical risk, and often lesser market risk as well. Tremendous leverage can be gained by effectively interpreting this risk. Much of the leverage can come from applying what has been learned from past platform and follow-on projects to future ones.

In summary, a historical record of successive performance is key to reducing technical and market uncertainties. By doing so, management can gauge risk more intelligently, and play Schon's 'investment game'.

2.1.4 Frameworks and Systems

The literature is void of frameworks and systems for evaluating *product family* performance. However, much can be inferred by studying the frameworks and systems proposed for single projects.

Trying to define quantity and order in the uncertain process of research and development is difficult. As a start to overcoming this difficulty, several articles in the literature have proposed frameworks of thought for generic projects[19] [20] [21]. The common line of thought is to describe a product

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[18] Batson, 1991, op. cit.

development project as a series of *inputs* and *outputs*. Quantification of the inputs and outputs lead to measures of efficiency and productivity. For example, a common definition of productivity is the ratio of outputs to inputs. If successfully captured, these measures may be used for project control and planning purposes.

Brown and Svenson[22] propose a system with inputs which include people, ideas, equipment, facilities, funds, and information. Generally, funds are easy to quantify; ideas are not. The outputs of the model are measured throughout the system. In the end, it is the final outcomes that matter. The final outcomes in this model are categorized by metrics such as: cost reduction, sales, improvement, product improvement, and capital avoidance.

Foster et al define a simple, profit-oriented framework[23]. In sticking to his theme of corporate level thinking, Foster proposes the following seven definitions:

- ***R&D Return*** - The amount of profit, or net present value, expected from an investment in R&D. This is assumed to be the objective, at least implicitly, for which most CEO's strive. It is the consequence of a corporation's success or failure in achieving a sustainable competitive edge. The units of return are measured in currency (say dollars) of net present value per currency invested.
- ***R&D Productivity*** - The improvement in key performance parameters (product or process) due to investment in R&D. Productivity is

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[19] Foster et al, 1985, op. cit.

[20] Brown, M., and Svenson, R., "Measuring R&D Productivity," *Research Technology Management*, July-August, 1988, pp. 11-15.

[21] Cordero, Rene, "The Measurement of Innovation Performance in a Firm," *Research Policy*, v. 19, 1990, pp. 185-192.

[22] Brown, M., and Svenson, R., 1988, op. cit.

[23] Foster et al, 1985, op. cit.

measured by units of performance improvement per currency of R&D investment.

- ***R&D Yield*** - The profit made from improvement in technical performance -- that is , the economic reward for the investments made. The unit of measurement is currency net present value per unit of performance improvement.
- ***Potential Productivity*** - The maximum possible productivity improvement as set by the limits of the technology and the best technology development organizations.
- ***Technology Development Efficiency*** - The efficiency of the R&D organization compared to the maximum possible as conceptualized in "Potential Productivity." Said another way, this is the relationship of the development effectiveness of a given competitor to the best possible competitor.
- ***Potential Yield*** - This is the maximum economic return possible given the structure of the market. To achieve these returns would imply perfect operational effectiveness - no mistakes in plant start-up, communication, or planning.
- ***Operating Efficiency*** - The efficiency of "commercialization effort." This term relates the actual costs and rewards of commercialization to the costs and rewards of a "no error" introduction.

The first three definitions lead to Foster's simple formula[24]:

$$\text{R\&D Return} = (\text{R\&D Productivity}) \times (\text{R\&D Yield}) \qquad (2.1)$$

Equation 2.1 is an insightful approach to understanding the role of R&D in a technological and business setting. However, the units of *performance*

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[24] Foster et al, 1985, op. cit.

improvement are generally difficult to measure -- particularly for early stage research. In turn, this makes the R&D productivity and R&D Yield terms difficult to assess individually. Fortunately, equation 2.1 reduces to:

$$\text{R\&D Return} = \frac{\text{(Profit made from improvement in technical performance)}}{\text{(Investment in R\&D)}} \tag{2.2}$$

Note that equation 2.2 relies only upon financial measurement. The formula can be used as a tool for planning future products, or for conducting post-audits of past projects. A variation of this simple, yet effective, formula is used to assess the 'productivity' of product families in the next section.

Continuing with Foster's set of definitions, the *potential* productivities and yields relate to the future of a product line in the context of technological and market limits. The definitions for efficiency assign best-scenario benchmarks against which productivity and yield can be compared. These ideas are important for understanding marketplace drivers and the dynamics of technological innovation within that marketplace.

Similar to Foster, Cordero[25] proposes an input/output framework across the entire product cycle. Based on the typology of measurement intent, Cordero breaks the problem down into three classes of performance measures: technical, commercial, and overall. Cordero's taxonomy of intent in an input/output context is used in section 2.2.

Within each class of measurement, Cordero proposes numerous qualitative and quantitative measures. While many of these proposed metrics may contain useful information, care must be taken to ensure that an excessive amount of irrelevant information is not being generated. It is recommended that prior to implementation, any proposed metric be subject to the criteria for success summarized in section 2.3.

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[25] Cordero, Rene, 1990, op. cit.

Without full-cycle quantification of inputs and outputs, the fruits of effective R&D cannot be demonstrated to executive management. Nix and Peters[26] found that of 200 US R&D directors, 50 percent of them felt that their budgets were greatly affected by the state of the corporation's current operating profit. Fifty-two percent of them reported that expenditures on short-term projects were decreased if the firm's current operating profits were unsatisfactory.

Nix and Peters' study highlights the fact that R&D managers must think financially if they are to effectively compete for corporate funds[27]. Knee-jerk cuts in research budgets stem from the inability of R&D managers to quantify inputs and outputs.

To conclude, frameworks offer an organized way of examining a problem. The three frameworks above highlight an important way of thinking: the product cycle, as a system of inputs and outputs, must be measured from beginning to end to have meaning at the corporate level. R&D productivity must be presented to executive decision-makers in financial terms if it is to compete effectively for corporate resources.

2.1.5 The Nature of R&D Information

Within the product cycle, R&D performance measures compose an important -- and very difficult -- set of information. The problem lies in the fact that the nature of the information changes as the product cycle progresses. Pappas and Remer articulate the problem by stating that, "... R&D has so many different stages that no single measurement technique is best at each stage.[28]" Given this spectrum, it is not surprising to see why Schainblatt concluded that,

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[26] Nix, P., and Peters, R., "Accounting for R&D Expenditures," *Research Technology Management*, Jan-Feb, 1988, pp. 39-40.

[27] Nix, P., and Peters, R., 1988, op. cit.

[28] Pappas, R., and Remer, D., "Measuring R&D Productivity," *Research Technology Management*, May-June, 1985, pp. 15-22.

"there are no currently used systems for measuring R&D productivity that are not flawed."

Foster is not optimistic that the problem will be solved soon. He comments that:

> "The search for methods of characterizing, analyzing, and even describing the performance of an R&D organization has long been -- and will undoubtedly remain -- the subject of much discussion in the R&D community." (p.13)

With this problem in mind, the literature contains generally similar views on the classification of R&D productivity metrics. All authors accept the notion that productivity measures can vary from the abstract to the objective.

Packer[29] uses *two* classifications for measuring R&D performance: (1) subjective methods, and (2) structured methods with measurable indicators. Pappas and Remer break the classification down into *three* basic types of R&D metrics: *quantitative, semi-quantitative*, and *qualitative*. Techniques for deriving metrics in each of these classes are described below[30].

- ***Quantitative*** - In this class, specific mathematical algorithms and formulas are applied to raw numerical measures to generate numbers that can be compared with other projects and past experiences. Taken to the extreme, Souder best describes these methods as, "an abstraction in equations of a real world system.[31]" Simple examples of quantitative measures include: any ratio that involves costs or sales, number of citations per employee, number of patents per year, and so on.

- ***Semi-Quantitative*** - This category involves the creation of numeric values based on qualitative judgments. For example, technical quality

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[29] Packer, M., 1983, op. cit.

[30] As taken from Pappas and Remer, 1985, op. cit.

[31] Souder, W. E., "Analytical Effectiveness of Mathematical Models for R&D Project Selection," *Management Science*, 19:8, April 1973, pp. 907-923.

could be judged by a manager as a number between one and five; one being very good to five being poor. Semi-quantitative measures are usually summed or used in weighted scoring algorithms to come up with an overall measure of performance.

- ***Qualitative*** - This class of measures do not ascribe any numerical value to the productivity measures in question. Qualitative metrics rely solely on intuition and judgment and are generally communicated in an abstract manner. Ratings are fabricated on human judgment as opposed to objective fact.

In Table 2.1 Souder[32] gives examples a typical qualitative metrics:

Table 2.1: Examples of Qualitative Metrics

Variables	***Ratings***
Patent potential	High
Profit potential	Moderate
Probability of technical success	High
Cost of completion	Low

Given this three category classification, Pappas and Remer address the problem of changing information requirements in the product cycle[33]. Through their findings, they propose that qualitative measures are appropriate for the earlier stages of basic research, whereas quantitative measures apply for the later developmental stages. In other words, the evaluation techniques should change from qualitative to progressively more quantitative as the R&D stage approaches the commercial stage. Brown and Svenson[34] echo similar sentiments by stating that the evaluation of research should be separated from development as they are different functions that produce different results.

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[32] Souder, W. E., "Analytical Effectiveness of Mathematical Models for R&D Project Selection," *Management Science*, v. 19:8, 1973, pp. 907-923.

[33] Papps, R., and Remer, D., 1985, op. cit.

[34] Brown and Svenson, 1988, op. cit.

In their study, Pappas and Remer found that 'qualitative' techniques are the most widely used by industry[35]. This finding was backed up by Moser who surveyed 124 companies and found that 'soft' measures, or those that are difficult to quantify, are the most commonly used[36]. From Moser's study, Table 2.2 displays a rank order of the most commonly used categories of R&D metrics.

Figure 2.2: Common usage of R&D performance measures (from Moser, 1985)

Rank Order	***Performance Metric Used***
1	Quality of output or performance
2	Unit's degree of goal attainment
3	Amount of work done on time
4	Unit's level of efficiency
5	Percentage of project completions
6	Percentage of results adopted by company
7	Frequency of cost overruns
8	Number of patents or copyrights
9	Percentage of project approvals
10	Number of technical reports produced
11	Unit profitability
12	Number of papers presented at professional meetings
13	Number of professional rewards or honors

How do these findings relate to the input/output framework thinking? Approaches that relate engineering resource inputs to revenue-based outputs can only be effective if the inputs and outputs can be quantified, and related to each other. Therein lies the problem[37].

To start, many firms do not maintain accurate life cycle information on R&D investments for products, or groups of products. This lack of maintenance makes data capture difficult. As well, inputs to the R&D process are usually not

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[35] Pappas, R., and Remer, D., 1985, op. cit.

[36] Moser, M., "Measuring Performance in R&D Settings," *Research Technology Management*, Sept-Oct, 1985, pp. 31-33.

[37] Schainblatt, A., "How Companies Measure the Productivity of Engineers and Scientists," *Research Management*, May 1982, pp. 10-18.

fully represented; for example materials *and* direct labor costs are not captured. Even when represented, the method of accounting can make a substantial difference on a final productivity metric. For example, Nix and Peters[38] have studied the effects of classifying R&D as a current expense versus as a capital expenditure.

Problems in R&D measurement are exasperated by the time lag between exploratory research and product embodiment. The time lags are sometimes measured in years. Such lags make estimation of outputs for planning especially difficult. The estimation of sales and profits as quantitative measures of return over long time horizons can be very inaccurate. Beardsley and Mansfield[39] found that large discrepancies occurred between estimated and actual profitability of new products in a firm only one year after products were introduced to the marketplace. Of course, the forecasted success of shorter term incremental innovations are more reliable than longer-term radical product breakthroughs.

Given the problems of quantification, it is easy to see why Moser found that qualitative 'soft' measures are dominant in industry[40].

2.2 Literature Classification

There is little consensus in the literature about what specific measures are appropriate for evaluating project performance. Given the lack of consensus, insight can be gained by classifying common industrial techniques and practices.

Classifying by technique, Baker and Freeland[41], categorize *comparative approaches, scoring methods,* and *benefit contribution models* for evaluating R&D performance. Though twenty years old, the classification is perfectly applicable to the literature today. To this framework, two additional techniques

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[38] Nix and Peters,1988, op. cit.

[39] Beardsley, G., and E. Mansfield, "A Note on the Accuracy of Industrial Forecasts of the Profitability of New Products and Processes," *Journal of Business*, v.1, 1978, pp. 127-135.

[40] Moser, M., 1985, op. cit.

[41] Baker and Freeland, 1975, op. cit.

can be added: *project scheduling*, and *organizational measurement*. Each technique is discussed below:

- ***Comparative*** - Comparative measurements group projects into a forced ranking framework. A group of experts typically rank individual projects against other projects or subset of projects. Q-Sorts, standard gamble, rating, paired comparisons are but a few specific comparative measurement techniques. Meyer and Utterback[42] used comparative Q-Sorts to obtain expected success rankings for 24 major new product efforts in a photographics products company.

  Quality and merit are examples of subjective metrics used in comparative measurement. Given the unavoidable bias of the experts, the information used for comparative evaluation is highly qualitative.

- ***Scoring*** - Scoring methods are very widely used as a tool for planning and selecting new projects. With scoring methods, a merit value is calculated by subjectively quantifying a series of individual criteria. Criteria typically include estimates of cost, return, and the likelihood of success. As well, scoring criteria frequently assess variables such as time required, market attractiveness, and competitive status.

  The criteria can be weighted and processed so as to find a 'score' for the project. Calculations can range from simple addition to complicated algorithms involving factor analysis or operational research techniques.

  A recent incarnation of the scoring approach is given by Hauser and Clausing[43]. Their "House of Quality" is used to numerically quantify

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[42] Meyer, M., and J. Utterback, "Moving Ideas to Market and Corporate Renewal," *International Center for Reeearch in the Management of Technology Working Paper*, #69-92, MIT, 1992.

[43] Hauser J., and D. Clausing, "The House of Quality," *The Harvard Business Review*, May-June, 1988, pp. 63-73.

key product attributes and relate them to customer needs and competitive products.

Note that scoring methods generally attempt to find absolute measures of project worthiness. By contrast, comparative methods seek relative measures.

- ***Benefit Contribution*** - This class of techniques force the evaluation of projects against the objective's of the firm. As such, benefit contribution methods usually span the full product-cycle and are often quantified in financial terms. Patterson[44], for example, discusses how full-cycle methods of evaluating project benefits have been successfully implemented at Alcoa Laboratories.
- ***Slip*** - Measures of 'slip' are often used to evaluate variations in a project's scheduling and budget[45]. Slippage can be measured in an aggregate sense or, more commonly, broken down to measure successive stages of the product-cycle. Indeed, some firms using stage-gate product generation processes to compute slippage between phases of the process for each new product[46].
- ***Organization***- Organizational methods address metrics which relate to the allocation and performance of the human resources attached to a project. Measures can includes simple headcounts, the number of patents and citations that generated by individuals, teams, or whole organizations, and awards received.

These five categories encompass the techniques used to evaluate the performance of projects. In contrast, Cordero[47] constructs a classification

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[44] Patterson, William C., "Evaluating R&D Performance at Alcoa Laboratories", *Research Technology Management*, March-April 1985, pp. 23-27.

[45] LeVitt, R. M., "Process Measures to Improve R&D Scheduling Accuracy," *Hewlett Packard Journal*, 39:2, 1988, pp. 61-71.

[46] Cooper, R., "Stage-Gate Systems: A New Tool for Managing New Products," *Business Horizons*, May-June, 1990, pp. 44-54.

around his input/output framework. His classification is constructed from the point-of-view of *intent*. Cordero groups the intent of measurement into one of five categories: *project control*, *project planning*, *overall performance*, *technical performance*, and *commercial performance*.

- ***Project Control*** - Control metrics are used to evaluate the performance of a project while it is in progress. As time goes on, quantifiable inputs such as costs and human resources can be measured. Effective control metrics act as early warning systems for corrective action.

  The engineering profession is well versed in project control techniques which include CPM and PERT methods. Also, during the control phase future outputs can be continually re-estimated and fed back into decision-making models.

  Control metrics are very important from a project management point of view. From a strategic point of view they are important to document so that 'learning' can be transferred to the next similar project.

- ***Project Planning*** - Project planning relates primarily to new project selection and portfolio management. The literature is rife with discussions about the effectiveness of various project selection techniques. From a measurement perspective, formalized project planning techniques all rely on quantifiable inputs.

- ***R&D/Technical Performance*** - The intent of measuring technical performance is to try and quantify the output of the R&D lab prior to commercialization. As previously discussed, the earlier the stage of research, the more difficult this task. Hence qualitative measures of

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[47] Cordero, R., 1990, op. cit.

performance are more appropriate for early stage research, and more quantitative measures for later stage development.

Technical outputs cannot be measured in monetary terms until they become embodied in marketable products. The number of patents, citations, and awards are often used as measures of technical performance. From a firm's perspective, these are generally poor indicators of productivity. For example, under a patent counting scheme two commercially useless patents would register a greater level of performance than one commercially successful one; there is no measure of true performance.

- ***Commercial Performance*** - Once a product hits the marketplace, its commercial performance can be evaluated. Commercial performance measures include sales, costs, and market share. Quality is also a measure which is commonly evaluated at the commercial stage. Defects per 100,000, number of customer service calls, and other such measures assess the success of the product in the marketplace.

  Patterson[48] found that five years of financial thinking at Alcoa Laboratories helped to legitimize the R&D function in the eyes of management. An intangible benefit on the R&D side was that after five years an economic way of thinking was imparted into the researchers and engineers. This helped to put the focus on faster implementation, and an understanding of the sources of value.

- ***Overall Performance*** - Overall performance measures view the product cycle holistically. These measures are most often financial are most often financial in nature. From a planning perspective, estimates of rate-of-return, payback period, and net present value are common. Overall performance measures are also typically measured against their

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[48] Patterson, William C., 1985, op. cit.

Table 2.3: Project Measurement Classification

	Intent of Measurement				
Measurement Technique	**Planning**	**Control**	**R&D Performance**	**Commercial Performance**	**Overall Performance**
Comparative	1 4 13 25 26 27 28	4 28	1 4 16 27 28	4 27	
Scoring	1 4 13 14 18 25 26 27	4 18	1 4 14 16 18 19 20 23 27	3 4	3 4
Benefit Contribution	1 4 13 14 17 25 26 27	1 4 9 11 18	1 3 4 7 8 13 14 16 18 27	3 4 7 8 27	3 4 5 7 8 21 22
Schedule Analysis	9 14	12 13 16	12 14 16		
Organizational Analysis	13	15	2 6 15 16		2

corresponding external indicators. Industry averages, and 'best of class' measures are common benchmarks of comparison.

Between Baker and Freeland's techniques, and Cordero's framework, a two-dimensional taxonomy has been constructed[49] [50]. The horizontal axis contains the categories based on the typology of measurement intent suggested by Cordero. On the vertical axis are the five measurement categories surmised from Baker and Freeland, and the literature review.

Table 2.3 presents the taxonomy. Within each box of the table are references to pertinent literature which cover that subject. Numerical references are indexed in Appendix 2A which also provides a brief description of the salient literature.

2.3 Criteria for a Successful System of Measurement

The lack of consensus in the literature is a testament to the difficulty of measuring the performance of product development. Some of the more serious obstacles include: difficulty in defining technology, clearly defining intent and usage, differentiating between effectiveness and efficiency, overcoming the tendency to measure activities than results, matching inputs with a time frame, and understanding how to deal with the entire product cycle.

Fortunately, the literature does provide good insight into what criteria lead to a realistic system of measurement. Packer, Brown and Svenson, and Schainblatt each give prerequisites for an effective system[51] [52] [53]. Their suggestions, along with other wisdom found in the literature, can be summarized into the following points:

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[49] Baker N., and James Freeland, 1975, op. cit.

[50] Cordero, Rene, 1990, op. cit.

[51] Packer, M., 1983, op. cit

[52] Brown M., and R. Svenson, 1988, op. cit.

[53] Schainblatt, A., 1982, op. cit.

- ***Comprehensibility*** - the system must be understandable and easy to interpret for decision-making. The intent and the audience must be clearly defined. The best systems collect data on six to eight indices that combine quality, quantity, and cost.

- ***Simplicity*** - bureaucracy and information overload should be avoided.

- ***Relevance*** - the information must be relevant, timely, and accurate. It should and have predictive value for planning activities, and feedback value for monitoring and control activities. From the *firm's perspective,* only those accomplishments and outputs which relate to financial performance should be measured. While the number of publications produced by an R&D department may be impressive, this number is an irrelevant measure of the effectiveness of the R&D effort in the context of the product cycle.

  Schainblatt also offers that relevance is tied to comparative measurement. He writes:

  > "The essence of R&D productivity measurement is finding meaningful comparison, whether over time in a given organization or across organizations, is a recognition of the fact that a productivity measurement at one point in time is of no value if it cannot be compared to another measurement."

- ***Objectivity*** - measurements should be as objective as possible and not be dependent upon individual bias.

- ***Perspective*** - unless the intent is management control, focus on measuring outcomes from the perspective of the *firm*, not the narrower perspective of the R&D lab. A holistic approach which includes both the development cycle and the commercial cycle needs to be taken. Perspective relates back to the issue of relevance, above.

- ***Reliability*** - the information must be reliable over time.

- ***Acceptance*** - the information must be collected and used in a manner that is acceptable to the employees of the organization.
- ***Cost Effectiveness*** - the cost of collecting the data and using the gathered information cannot exceed the benefits to be gained from better decision-making. The criteria of simplicity, above, generally insures cost-effectiveness.

2.4 Meta-Metrics for Assessing the Performance of Product Families

Consistent with what has already been discussed about product families in chapter one, the proposed metrics stem from the position that the effectiveness of an engineering group has two essential bases: (1) its ability to generate 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. The first base represents the firm's R&D cycle, while the second its commercial cycle.

The R&D manager's responsibility in this context is to insure that new products -- be it their underlying platforms or follow-ons -- are fully developed, tested, and ready to ship. This is different than when other managers in the firm actually decide when to ship particular products or take existing ones off the market. These latter issues, while important in the strategy of managing a product family, is not part of the present study. The information that executive decision-makers want pertain to the costs, sales, and timing associated with particular streams of products based on common architectures.

This thesis assesses these phenomenon under the evolutionary framework of the product family. With this in mind, the intent of the measurements is to assess each of the two cycles individually, and as a whole. As a result, the meta-metrics can be used for planning purposes.

The following simple measurements are proposed[54]: (1) *R&D leverage*, the degree to which the allocation of research, development, and engineering resources results in cost advantage over successive product development, (2) *Sales productivity*, the degree to which the developed products produce revenue for the firm, and (3) *Time economy*, fractional cycle time savings realized for successive follow-on product development over the original platform.

These measures are objective, but rely on accurate classification of the key engineering accomplishments within a product family, the differentiation between platforms within the family, and the classification of follow-on products within platforms. Table 2.4 shows how a product family is intuitively classified for analysis.

Table 2.4: Classification of a product family -- a generic example

Platform	*Version*	*Follow-on*	*Comments*
Base	Base	Base	Original architecture
Base	Base	1	
Base	Base	2	Four follow-on products spun off of the original architecture.
Base	Base	3	
Base	Base	4	
Base	1	Base	First extension/revision; base
Base	1	1	
Base	2	Base	Second extension/revision; base
Base	2	1	
Base	2	2	
Base	2	3	
Base	3	Base	Third extension/revision; base
Base	3	1	
1	Base	Base	Platform renewal; original architecture
1	Base	1	
1	Base	2	
1	Base	3	

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[54] These metrics were originally proposed and developed by Marc Meyer of Northeastern University.

Construction, presentation, and interpretation of the metrics are hypothesized on three levels: (1) at the level of individual follow-ons within a product platform, (2) at an aggregated level for the product family as a whole, and (3) comparatively across distinct product families. The hypothesized taxonomy is shown in Table 2.5.

Table 2.5: Classification of proposed metrics

Metric	***(A)***	***(B)***	***(C)***
Level	***Cost Leverage***	***Sales Productivity***	***Timing Economy***
(1) Product	**Shows the cost of producing follow-ons relative to the R&D costs of a single platform**	**Shows the revenue generated within a platform relative to the costs of developing it.**	**Comparison of development cycle times and new product introduction rates within a single platform.**
(2) Product Family	**Same as for platform, but across the successive version of a platform(s) within a family.**	**Same as for platform, but across the successive versions of a platform(s) within a family**	**Same as for platform, but across the successive versions of a platform(s) within a family.**
(3) Comparison Across Families	**Comparison of aggregate cost leverage metrics across different product families.**	**Comparison of aggregate sales productivity metrics across different product families.**[1]	**Comparison of aggregate time cycle metrics across different product families.**

[1] **Note: Though theoretically possible to compute, this metric does not provide an overly meaningful comparison between families. The assumed stability of cost structures within families allow the use of sales as a good relative measure of output. However, across families, the cost structure cannot be presumed to be constant and hence comparisons of sales productivity across families will not be computed. In theory, the data could be normalized across families.**

The boxes in Table 2.5 are referred to by their heading indices. For example, timing cycle metrics at the product family level will be called box 'C2'.

2.4.1 Variables and Indices

To give provide a rigorous mathematical description of the proposed metrics, a set of symbolic notation for various variables and indices is presented.

<u>**Variables**</u>

S = Sales attributable to a platform or follow-on product within a product family.

C = Costs attributable to a platform or follow-on 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 base architecture.

N_v = Number of platform extensions, or versions created off the base platform architecture, *excluding* the base platform.

N_f = Number of follow-on products in an individual platform, or platform extension, excluding the original architecture.

N_{TF} = The total number of follow-ons in a family excluding the base architectures.

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

As an example of the above notation, one can consider that the sales in period t, of the second follow-on product, for the base version of the first platform renewal would be given by:

$$S_{1,base,2,t} \tag{2.3}$$

2.4.2 Aggregated Sales and Costs of a Product Over Time

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:

$$S_{p,v,f} = \sum_{t=1}^{T_C} (S_{p,v,f})_t \tag{2.4}$$

and,

$$C_{p,v,f} = \sum_{t=1}^{T_D} (C_{p,v,f})_t \tag{2.5}$$

Over long product cycles, it is desirable to correct for inflationary effects in the economy[55]. 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 superscripted 'primed' symbol .

$$S'_{p,v,f} = \sum_{t=1}^{T_C} (S_{p,v,f})_t D_t \tag{2.6}$$

$$C'_{p,v,f} = \sum_{t=1}^{T_D} (C_{p,v,f})_t D_t \tag{2.7}$$

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

$$S'_p = \sum_{v=base}^{N_v} \sum_{f=base}^{N_f} S'_{p,v,f} \tag{2.8}$$

Adjusted costs would be computed similarly using the cost variable, C. With these definitions, it is now possible to define the proposed metrics.

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[55] Schainblatt, 1982, op. cit.

2.4.3 R&D Leverage

At the product follow-on level, average R&D leverage shall be defined as the average of the costs incurred in developing follow-on products, divided by the costs incurred in developing the base architecture of the immediate parent platform.

$$\text{Average R\&D Leverage} = \frac{\text{(Average of R\&D costs of follow-on products in platform group)}}{\text{(R\&D costs of immediate parent base platform)}} \qquad (2.9)$$

Note that measuring the leverage of an individual follow-on, independent of its successive position, is a useful metric at the platform level.

$$\text{Individual R\&D Leverage} = \frac{\text{(R\&D costs of specific derivative product in platform group)}}{\text{(R\&D costs of immediate parent base platform)}} \qquad (2.10)$$

Mathematically, the notation for leverage shall be, *L*. The indices defined in 2.4.1 shall apply accordingly. Therefore, at the individual follow-on level (Box A1; Table 2.5), the mathematical formulation for *L* is given by:

$$L_{p,v,f} = \frac{C'_{p,v,f}}{C'_{p,v,base}} \qquad (2.11)$$

For the *average* R&D cost leverage within a single platform group (for Box A1 or A2), the meta-metric is computed as:

$$\overline{L}_{p,v} = \frac{\frac{1}{N_f}\sum_{f=1}^{N_f}\left(C'_{p,v,f}\right)}{C'_{p,v,base}} \qquad (2.12)$$

This metric can also be used to compare platform groups across families (Box A3).

Finally, an aggregate R&D cost leverage value can be computed for an entire product family (Box A3) by summing across follow-ons, extensions (platform version level), and renewals (family level):

$$\bar{L} = \frac{\left(\frac{1}{N_{TF}}\right) \sum_{p=base}^{N_p} \sum_{v=base}^{N_v} \sum_{f=1}^{N_f} C'_{p,v,f}}{\sum_{p=base}^{N_p} \sum_{v=base}^{N_v} C'_{p,v,base}} \qquad (2.13)$$

Although they look complicated, the interpretation of these metrics is fairly intuitive. At an individual follow-on level, the question being asked is, "How much did it cost me to develop this follow-on product *as a fraction* of what I spent on the original architecture?"

By grouping all the follow-ons in an individual platform, or group of platforms in the family, the question is, "How much did it cost me *on average* to develop these follow-on products as a fraction of what I spent on the original architectures?"

What is a reasonable leverage value for a follow-on product off a platform? Although industry specific, it is not unreasonable to expect that the average L should be as low as 0.10, or 10% of the cost of developing the original architecture. Further, if resources are being effectively used, and learning is taking place, it is expected that L should *decrease* with each successive version.

What can be learned by studying the leverage metric, L? Clearly, the closer that L is to 1.0, the less efficient the original platform design. For early follow-ons, if it costs as much to make the follow-on product as it does the original architecture, then the platform is of very poor design.

Importantly, leverage can be used as a leading indicator of platform demise if monitored by successive follow-on development. If L starts to increase with successive follow-ons, then it may be a sign that the technology has begun to reach its peak. This is consistent with the S-curve phenomenon where, after a certain point, little additional performance is achieved for an incremental investment[56].

An increase in leverage can also signify a change in management or key resources; human or otherwise. In other words, the advantage gained by reusing a proven pool of resources can be lost through organizational change.

A post-mortem measure of leverage with each successive product can also serve as a guide to planning other product families. By studying past leverage, it becomes easier to estimate probable costs of future product development. This is the essence of corporate learning.

2.4.4 Sales Productivity

Foster's formula[57] for R&D return (section 2.1.4; equation 2) provides a simple way to relate the commercial cycle to the R&D cycle. The resulting metric provides a full product cycle measure of performance.

What is difficult to measure in Foster's formula are the profits attributable to the final product. This is unfortunate because profits are the ultimate 'bottom line' measure. Profits, though ideal in theory, are usually not consistently reported or gathered at a product level. From an accounting perspective, the definition of profit can vary from department to department. This is not desirable when comparing different product platforms and families.

Companies which have embraced modern information technologies in accounting across the *entire* organization may be able to consistently summarize profits on an individual product level. For those that have not, a more robust measure of commercial cycle performance is needed.

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[56] Foster, R. N., *Innovation the Attacker's Advantage*, Summit Books, New York, NY, USA, 1986.

[57] Foster et al, 1985, op. cit.

Fortunately, sales figures are absolute, and are more easily obtained than profit figures. It is not unreasonable to assume that sales figures are an appropriate substitute for profits when measuring product cycle performance. Sales and profits are generally linearly related over the range of units sold by a fixed cost and variable cost component. *Within a product family,* it is reasonable to assume that these costs remain fairly constant -- after all the definition of a product family stems from pooled resources.

From a post-audit perspective, a product's sales productivity is defined as follows:

$$\text{Sales Productivity} = \frac{\text{(Sum of sales attributable to product)}}{\text{(Sum of R\&D costs attributable to product)}} \tag{2.14}$$

Note that this definition can be applied to any level in the product family; platform, platform version, or follow-on product.

Mathematically, the meta-metric can be defined at the individual product level (Box B1; Table 2.5) as:

$$P_{p,v,f} = \frac{S'_{p,v,f}}{C'_{p,v,f}} \tag{2.15}$$

at the version level (Also Box B1) as:

$$P_{p,v} = \frac{\sum_{f=base}^{N_f} S'_{p,v,f}}{\sum_{f=base}^{N_f} C'_{p,v,f}} \tag{2.16}$$

and at the platform level (Boxes B2 and B3) as:

$$P_p = \frac{\sum_{v=base}^{N_v} \sum_{f=base}^{N_f} S'_{p,v,f}}{\sum_{v=base}^{N_v} \sum_{f=base}^{N_f} C'_{p,v,f}} \tag{2.17}$$

Sales productivity metrics are truly unique to their own product families. As such this meta-metric is useful from a comparative sense from one platform to the next, or one version to the next. Note that if an generalized profit margin is known, it can be multiplied by the Sales Productivity metric to yield an estimate of Foster's Return on R&D.

If the costs of an efficient platform are expected to go down from successive product developments within a platform, then the Sales Productivity metric should go up. If it does not, then it means either that costs are going up, sales are going down, or both.

Either way, the *P* metric is a simple, holistic test of how the product performs across the entire product cycle. A steady, or declining Sales Productivity, *P*, over successive products in a platform set may be a precursor to a dying platform. Certainly, a decline in *P* should alert management to potential technical, managerial, or commercial problems with the product family.

2.4.5 Cycle Time Economy

The old adage, "Time is money", makes developmental cycle time a simple, yet important, metric to monitor[28].

Similar to cost leverage, *cycle time economy* measures the time it takes to develop a follow-on product as a fraction of the time it takes to develop the base architecture. For an *individual* follow-on at the platform level (Box C1; Table 2.4) , the cycle time economy meta-metric, τ, is defined as:

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[28] Mandakovic, T., and L. Smith, "Implicit Capital Cost of Project Investments," *IEEE Engineering Management*, 34:1, 1987, 19-21.

$$\tau_{p,v,f} = \frac{T_{p,v,f}}{T_{p,v,base}} \tag{2.18}$$

In equation 2.18, *T* is the developmental cycle time for the subscripted product. As with the cost leverage formulas, an average cycle time economy can easily be computed.

A timing measure for the *commercial cycle* is not considered insightful for assessing product performance at the follow-on level. First, the decision of when to discontinue a product in the marketplace is a difficult one. While it is obvious that the R&D cycle time should be as short as possible (without sacrificing quality and integrity), it is not so obvious as to how long a product should stay on the market. The timing of such a decision is largely discretionary, and implies nothing about performance. Second, such a metric would be generally encompassed in the rate of market introduction anyway, as new product versions obsolete the old.

It seems intuitively true that a well-planned product family should survive longer in the marketplace. Indeed, measures of commercial cycle time for an *entire* product family have been studied, and are considered insightful for understanding what Sanderson calls 'Business Classics'[59]. The market drivers and other timing externalities which affect Business Classics are beyond the scope of study in this thesis.

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[59] Sanderson, Susan, Rensselear Polytechnic Institute, Unpublished Paper.

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APPENDIX 2A

Bibliometric Index and Review of Salient Literature

No.	*Author Reference*	*Area and Nature of Research*	*Summary of Work*
1	Baker and Freeland (1975)	An assessment of literature that relates to quantitative models of R&D project measurement and selection.	Develops a taxonomy of models currently in use (as 1975). Three categories given for R&D benefit measurement: comparative methods, scoring models, contribution models. Pros and cons discussed. Excellent review and classification. General recommendations and a lengthy list of additional research topics.
2	Batson (1987)	An examination of the information needs of mid and upper level R&D managers.	A good overview of the R&D environment and the ro of the R&D manager in that environment. General recommendations are given for building an effective DSS for R&D managers. Proposes nine candidate databases which would house R&D metrics.
3	Brown and Svenson (1988)	A study of the factors which contribute to the success or failure of R&D productivity measurement systems.	An input/output framework is proposed. Emphasis is placed on R&D 'outcomes'. A discussion of why R evaluation systems fail, and conversely what constitut an effective system. Framework is applied to an electronics firm.
4	Cordero (1990)	The development of a performance measurement model for firms that invest in R&D.	An input/output model is proposed along with a taxonomy of measures for: overall performance, technical performance, and commercial performance. Provides a literature review. Concludes that evaluati of innovation requires a systematic approach.
5	Ellis (1984)	A paper which argues that R&D projects should be evaluated financially.	Defines the role of the R&D director and gives strong arguments for financial metrics. Ellis is also a strong proponent of full life-cycle measurements. Four grou of 'tools' are proposed for evaluating R&D project performance.
6	Edwards and McCarrey (1973)	A literature review examining the methods used to evaluate the quantity and quality of R&D staff output.	Literature review finds that many methods have been proposed but that they are of questionable value. Pos four unresolved questions and suggests that R&D performance should be evaluated at a higher level th the individual.
7	Foster (1982)	Development of a framework which helps to understand how R&D contributes to the profits of a firm.	Defines R&D productivity, yield, and return. Places these definitions in the context of the S-curve. Recommends better R&D information systems and post-audits of technical performance. Gives four way of improving profit per dollar of R&D. No concrete metrics proposed.
8	Foster, Linden, et al (1985)	A survey which was conducted to understand further the framework proposed in Foster (1982).	Feedback from major corporations about how R&D c boost profits as related to the Foster framework. Improvement activities listed most of which lead to th need for metrics. Good discussion of how R&D fits i the 'bigger picture' of a firm's profits.
9	Gerloff (1973)	Research which tries to correlate the performance of R&D management techniques to R&D performance.	After studying a large number of R&D control techniques, no correlation was found to indicate significant improvement in R&D performance. In so cases, project performance was actually impaired by t systems.

No.	Author Reference	Area and Nature of Research	Summary of Work
10	Krogh, Prager, et al (1988)	A summary of the procedures and metrics used by the 3M Company for performing technical audits.	A review of the R&D audit procedures at 3M. Technical, business, and overall factor ratings are giv Most are semi-quantitative and qualitative.
11	Lewis (1993)	A detailed study of the R&D cost metric.	Addresses the issue of accounting costs for R&D as financial metrics. Develops and presents a spreadshe program to be used for monitoring and graphing four key financial metrics.
12	LeVitt (1988)	The implementation of R&D metrics for scheduling accuracy at Hewlett-Packard.	A quantitative technical approach. Specific schedulin and quality metrics given. Emphasizes actual improvements in scheduling accuracy at HP because system implementation.
13	Liberatore and Titus (1983)	An empirical study of the usage of quantitative techniques for R&D project management.	All 40 respondents use some standard financial measurement and analysis techniques. DCF used onl where costs and rewards can be measured with certainty. However, majority of respondents do not formalized budget tracking systems. Development an engineering use some PERT/CPM for control; resear generally uses informal techniques (qualitative). Ove conclusion: heavy usage of basic financial methods, minimal usage of resource allocation models. R&D managers need better capital budgeting skills.
14	Mansfield and Brandenburg (1966)	A highly mathematical analysis of an R&D lab's project portfolio. R&D location, characteristics, and outcomes are studied.	An important finding was that failure rates and slippa in project schedules greatly exaggerate the extent of technical uncertainties. Slippage is generally not due technical uncertainty but rather human issues such as personnel transfers. Only one third of slippages were due to technical difficulty.
15	Meinhart and Pederson (1989)	A review of how 20 companies evaluate the performance of individual researchers.	A summary and analysis of methods used to evaluate individual researchers. Nine recommendations are given based on the results.
16	Moser (1985)	A survey-based study of which metrics are most commonly used for measuring R&D performance.	Perhaps the only extensive study of what type of metr are used at big companies. Excellent summary listed with a strong correlation between 'soft' metrics and early-stage research vs 'hard' metrics and late-stage development.
17	Nix and Peters (1988)	A survey which addresses the accounting techniques of R&D expenditures.	Article suggests that capitalization of R&D expenditu may reduce the clash between financial management R&D management. One of the few article which addresses the accounting issues underlying financial metrics used in R&D.
18	Pickett and Case (1991)	Discusses the factors involved in establishing expert information systems in R&D management	The development of an AI based expert system for R management is shown. Pros, cons, and costs are discussed. Westinghouse is used as an example of successful implementation. Discusses more AI issues than metrics issues.
19	Packer (1983)	Describes a technique for 'output mapping' R&D performance.	Packer uses factor analysis techniques to construct 'output maps' of semi-quantitative R&D performance metrics. Gives a detailed methodology which is akin QFD methods subsequently applied to perceptual mapping. Draws strongly from marketing methodologies.
20	Pappas and Remer (1985)	A discussion of semi-quantitative techniques for measuring R&D productivity.	Claims that semi-quantitative techniques are the best f evaluating the performance of R&D. Claim based on work done at two big companies. Suggests some sem-quantitative metrics.

No.	***Author Reference***	***Area and Nature of Research***	***Summary of Work***
21	Patterson (1985)	A study of R&D evaluation metrics based on the author's experiences at Alco Laboratories.	Feedback from accomplishment reporting improves R&D effectiveness. Stresses the importance of feedb to learning and improvement. Measurement of R&D success should begin only when accomplishments beg to 'bear fruit' in the marketplace.
22	Porter (1978)	R&D post-audits: how to quantify the value of completed R&D work. A study of the author's experiences at Mobil Research.	Lists five benefits of performing post-audits based on experiences at Mobil. Defines quantitative 'Researc Return Ratio (RRR)'. This is a full cycle methodolog Identifies several semi-quantitative and qualitative metrics.
23	Saviotti and Metcalfe (1984)	A theoretical approach to the construction of technological output indicators.	A framework for understanding the inputs and output technological innovation is developed and presented. The framework is theoretical and does not suggest specific metrics. It does however provide good insig into the inputs and outputs of technological innovatio
24	Schainblatt (1982)	A study of the R&D evaluation methods of 34 major industrial firms.	Study reveals no consistency in the approach for R& productivity measurement. Strongly recommends comparative measures as opposed to absolute measur of performance.
25	Souder (1972)	A comparative study of the usefulness of 41 R&D project investment models.	Profitability index and scoring models were easiest an cheapest to use. OR models are more costly and complicated, but are also more realistic and flexible. Models using utility metrics were inferior on all count
26	Souder (1973)	Study, development, and evaluation of four mathematical portfolio selection models. Based mainly on financial metrics for R&D project selection.	R&D project selection depends on manager's objectiv product cycle stage, and the way the selection proble is viewed. Depending on financial selection criteria, and the type of risk constraints, one or more of the fo models is recommended.
27	Steele (1988)	A historical review and perspective of R&D project measurement and selection techniques.	Increasing scale and complexity of R&D has forced increased use of formal techniques. This complexity leading toward a higher priority on understanding the context of R&D. Quantitative approaches place demands on precious managerial time; this is due to t lack of quantifiable inputs. Managerial judgment is t ultimate umpire.
28	van Remoortere and Cotterman (1993)	A paper which summarizes an R&D project management system which is being used at W.R. Grace & Co.	A 'fact sheet' approach to R&D management. Some quantitative time metrics given; however, the overall methodology is primarily qualitative.
29	Wolff (1985)	A discussion of how the Noranda Research Center measures R&D performance.	An overview of Noranda's method to perform R&D post-audits. Method is a combination of financial and qualitative technical description. Common sense advi and suggestions given.

3 Sample Data

3.1 The Data Sample

The data sample used in this thesis was originally gathered by academics. These data were kindly made available to the author for analysis. To preserve the confidential nature of the information, the product names and their specific functions have been disguised.

Data were gathered for six product families from a medical equipment manufacturer. The name of the firm is disguised as 'Generico'. A subsidiary of a large multi-national, Generico had recent annual sales over $1 billion. Initiated in the early 1960's, Generico's core capability has been in the application of measurement technologies to the practice of medicine; including patient monitors, electrocardiograms, and various types of imaging devices. It considers these products as 'front-end' devices for the clinical laboratories and patient wards in a hospital, providing real-time patient diagnosis and certain types of alarms for patient monitoring applications. The firm has also made 'back-end' information systems that allow the physician to review patients' longitudinal data and to perform specific types of empirical research. The product families presented in this paper are front-end devices labeled Family A through Family D.

Studying each product family required in-depth, iterative discussions with engineering and marketing managers working in the business unit responsible for the respective product family. This was accomplished by the academics. Their first goal was to construct product family vintage charts, using the typology described in Section 1.3 to distinguish between, (a) the initial platform development efforts, (b) extensions to existing platforms, (c) the creation of wholly new platforms or product architectures to replace those in existence (renewals), and (d) the specific products associated with each platform generation (follow-ons).

For each product within a family, the following data were captured where possible: (a) the start of the R&D cycle, (b) the end of the R&D cycle, (c) the start of the commercial cycle, (d) the end of the commercial cycle, (e) the research, development, and engineering costs, (f) the sales of the products in US dollar equivalents.

While these data might seem straightforward for a firm to maintain, in reality, they are difficult to gather. This particular company did not maintain historical product information in any electronic form. As such, some of the data are missing or incomplete.

The firm's current "R&D metrics" were annual in nature, consisting of average annual project slip for time and budget, and the number of critical hardware and software bugs encountered by customers in the current year. For development costs, old project data sheets maintained in notebooks by R&D managers were used. This data provided man-months of direct labor, and internal "cost" for labor, and materials charges. In several product families, however, only man-year allocations were available. Therefore, a mutually agreeable cost-per-man-year was used to compute cost estimates.

Manufacturing engineering, and market introduction costs were not possible to gather on a consistent basis. Unfortunately, these data were excluded from the dataset.

Sales departments for each business unit were able to provide *aggregated* sales figures over the commercial life cycle of their respective product families.

Appendix 3A contains the sample data for product families A through D. For this thesis, only *specific* product families will be used in detail to illustrate the proposed metrics in action. Following the taxonomy of metrics in Table 3.5

of the previous chapter, Family A will demonstrate the application of the metrics at the product *follow-on* level. Family B, which is composed of two multi-version platforms, will be used to demonstrate the metrics at a *family* level. Finally, cross-family comparisons of cost leverage and cycle time leverage will be demonstrated using information from families C and D.

3.2 Application of the Meta-Metrics at the Product Follow-on Level

The base architecture of the Sonata Platform (Figure 3.1) within Family A took three-and-a-half years to develop. From Sonata, five follow-on products were subsequently developed and commercialized. Average development time for the first three follow-ons was approximately 30% of the time it took to make the original platform architecture.

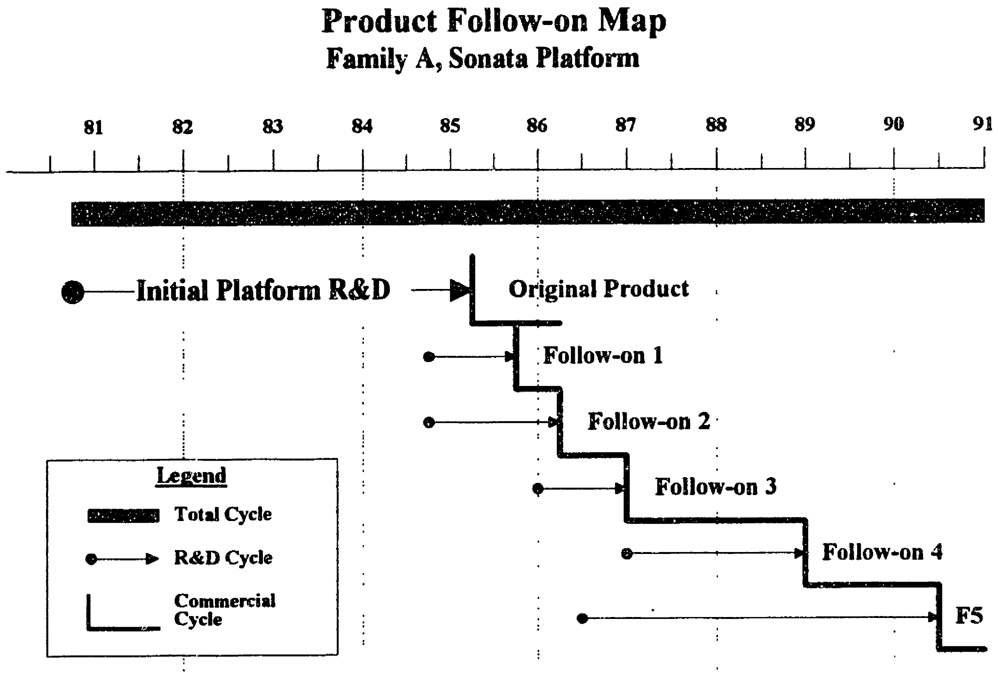

Figure 3.1: Sonata Platform Map

Development cycle times of the fourth and fifth follow-ons increased substantially. In fact, the final follow-on took as long to develop as the original architecture. This effect translated directly into the products' rate of market introduction.

The first three follow-ons were introduced at a regular rate of about six to seven months each. The slowdown in the development cycle of the fourth and fifth products translated into delayed market introductions, and hence lost competitive advantage in the marketplace. Table 3.1 demonstrates the time economy meta-metrics for the Sonata product platform. Equation 2.18 was used to compute them.

Table 3.1: Time economy metrics for Family A, Sonata platform

Product	*R&D Cycle Time Economy: by Product*	*R&D Cycle Time Economy: Running Average*
Initial	1.00	1.00
Follow-on 1	0.29	0.29
Follow-on 2	0.45	0.37
Follow-on 3	0.26	0.33
Follow-on 4	0.60	0.40
Follow-on 5	1.12	0.54

The time economy metrics show that while the first three follow-ons took 26 to 45 percent of the time of the base architecture to develop, the last two follow-ons took relatively much longer. These numbers quantify what is already visible in Figure 3.1. Graphing the data in Table 3.1 shows the implications of the time economy metrics better (Figure 3.2).

The time economy meta-metrics suggest that the platform began to lose its effectiveness and die out after Follow-on 3. Further evidence to substantiate this hypothesis can be gleaned by examining the cost leverage and sales productivity metrics.

Figure 3.2

Family A, Sonata Platform
R&D Cycle Time Economy

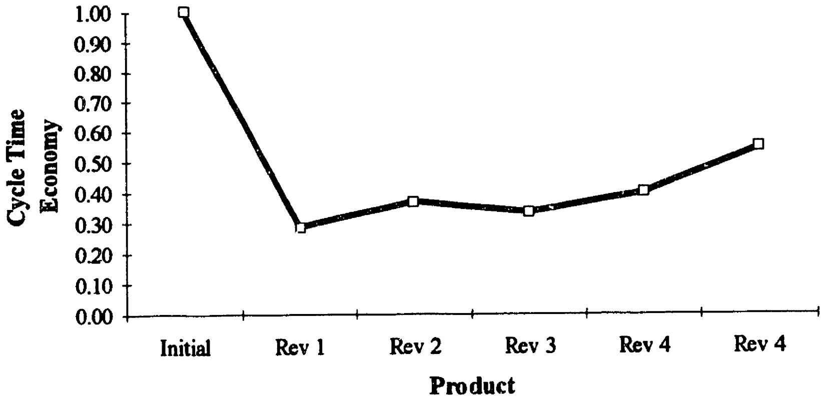

Table 3.2 displays the sales and cost figures for the base platform and the subsequent follow-ons. Both sales, and development costs were corrected for inflationary effects over the ten years that the platform survived. Deflators for this computation were derived using aggregate US CPI figures[1] normalized to 1993 dollars.

Table 3.2: Cost and sales figures for Family A, Sonata platform

Product	*Research and Development Costs ($'000s)*	*Sales by Product ($'000s)*
Initial	27,336	200,430
Follow-on 1	2,479	157,200
Follow-on 2	3,635	153,270
Follow-on 3	2,371	544,040
Follow-on 4	11,550	349,800
Follow-on 5	9,761	269,240

Timewise, sales and cost figures for this dataset only exist in aggregate form. In other words, the data were not available on a month-by-month basis;

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[1] Source: US Department of Labor Statistics

only as end-of-cycle totals. As such, the deflators for the development cycle were applied in aggregate at the *end* of the development cycle. Similarly, sales deflators were applied in aggregate at the end of the commercial cycle for each product.

From the figures in Table 3.2, individual and running metrics were computed using equations 2.11, 2.12, 2.15 and 2.16. Table 3.3 shows these results. The cost leverage of the base platform is, by definition, one. Follow-on 1, the first follow-on, had tremendous cost leverage of .09. In other words, it took only nine cents on every base platform dollar to develop this product. Follow-on 2, and Follow-on 3, were also well leveraged follow-ons with individual cost leverages of .14 and .09 respectively. Up to Follow-on 3, the average cost leverage was 11 cents for every platform dollar.

Table 3.3: Time metrics for Family A, Sonata platform

Product	*Sales Productivity by Product*	*Sales Productivity: Running Average*	*R&D Cost Leverage by Product*	*R&D Cost Leverage: Running Average*
Initial	7.50	7.50	1.00	1.00
Follow-on 1	64.86	12.27	0.09	0.09
Follow-on 2	42.16	15.58	0.14	0.11
Follow-on 3	259.12	32.01	0.09	0.11
Follow-on 4	31.94	31.99	0.49	0.20
Follow-on 5	28.62	31.34	0.44	0.25

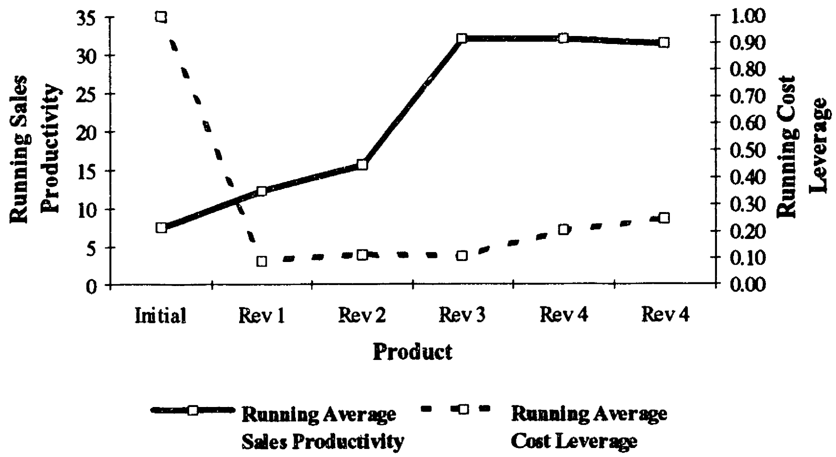
Significant leverage was lost with Follow-on 4 and Follow-on 5. Between .40 and .44, it is clear that R&D resources were no longer being used efficiently.

By the end of the platform, the average cost leverage was 25 cents for every platform dollar. Did this loss of leverage have any correlation to the marketplace?

The productivity metric relates performance in the marketplace to investment in the development cycle. Table 3.3 shows that the base platform returned $7.50 in sales for every dollar spent on development. Follow-on 3 returned a stunning $259 in sales for each development dollar. But again, Follow-on 4 and Follow-on 5 show performance well below their earlier counterparts. These metrics are captured graphically in Figure 3.3.

Figure 3.3

Sonata Platform: Sales Productivity and Cost Leverage



The hypothesis that the Sonata platform lost its effectiveness after Follow-on 3 is clearly substantiated by these figures. Note that this deduction would not have been obvious by simply examining the platform map in Figure 3.1. Nor would it have been obvious by casual inspection of the sales figures. True, sales were clearly in excess of R&D costs even for Follow-on 4; however, the real issue is that a dying platform generally leads to vulnerability in the marketplace.

What happened with Sonata after Follow-on 3? In fact there were two problems. The multi-national corporation which oversaw this product family, split the control of Sonata between Europe and North America after Follow-on

3. The localized efficiencies created by pooled resources and expertise was lost in the shuffle. Secondly, the platform architecture was dying out from a technological standpoint. By the end of Follow-on 3, it was not possible to add further value to the base architecture through technological innovation. The architecture's technical limit had been reached.

All metrics clearly reflect Sonata's problems after Follow-on 3. Because of these problems, market share and leadership was lost. From a profit standpoint, it is known that Follow-on 4 and Follow-on 5 were both money losers.

What can be learned? Sonata is a good example which demonstrates the need for platform *renewal* as opposed to incremental innovation through follow-ons alone. We can also learn that the strength of a product family is in its pooled resources; especially human. Fragmenting this pool -- especially across wide geographic and cultural boundaries -- can lead to long-term damage in the marketplace.

3.3 Application of the Meta-Metrics at the Product Family Level

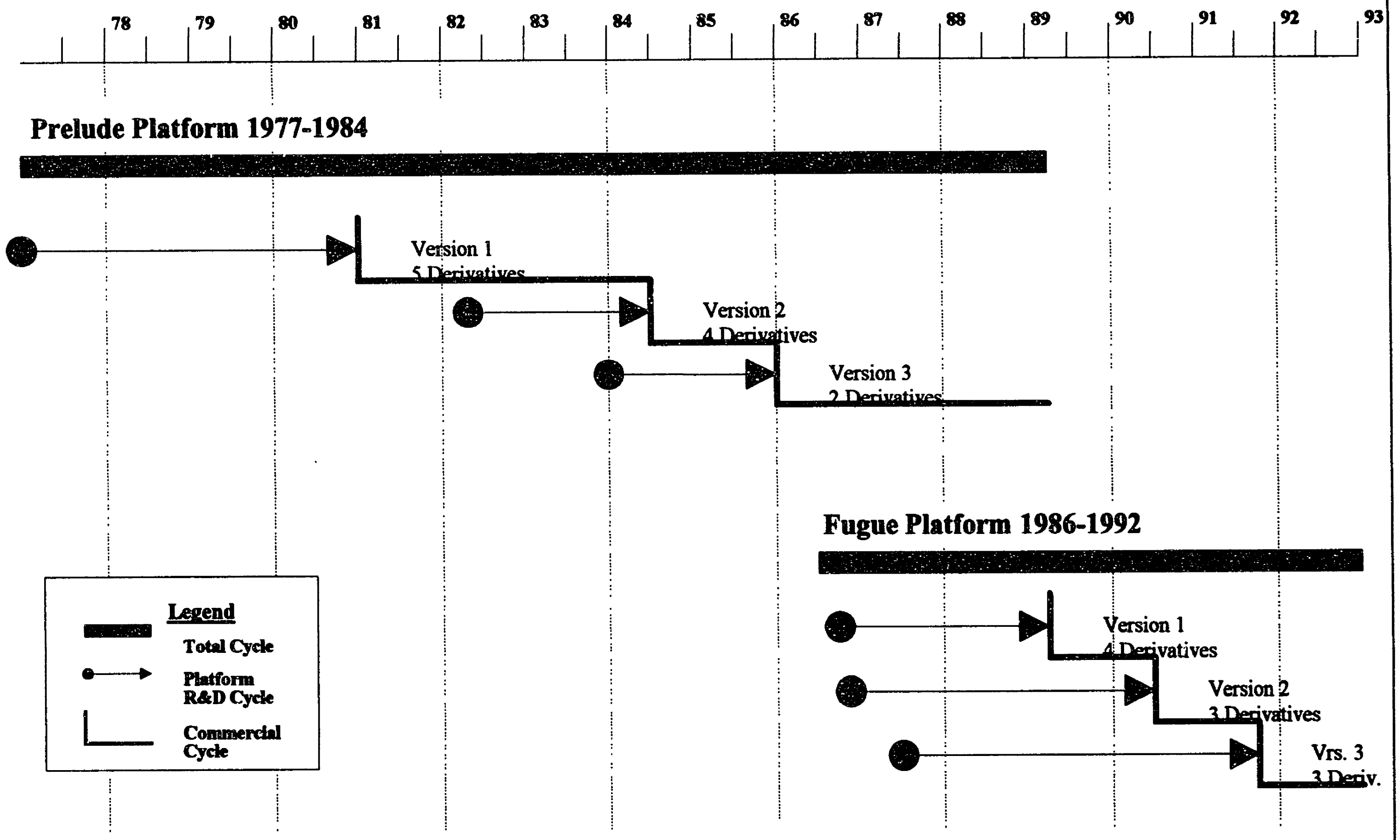
The Sonata platform illustrated an example of non-renewal. In contrast, Family B spawned two different platforms, Prelude, and Fugue, over 15 years. Within each of Prelude and Fugue, there were two platform *extensions*. A total of 21 follow-on products were spun off of these six platforms. Figure 3.4 shows the product family map for Family B.

For clarity, the detail of the follow-ons are *not* shown on the family map (Figure 3.4). Quantitatively, the follow-on data is taken in aggregate form to illustrate how the proposed metrics are applied at the family level.

Each successive platform version in Prelude represents an *extension* as discussed in Section 1.3.2. Fugue represents a complete *renewal* of the Prelude platform within the same product family. Well planned platforms allow for

Figure 3.4

Product Platform Renewal Map: Family B



continuous extensions and renewals. When to extend, and when to renew a platform is an integral part of product family management. Metrics and mapping can help make these timing decisions.

Table 3.4 shows development cost and sales data for Prelude and Fugue. The sales alone indicate a successful product: Version 3 of Fugue sold $309 million. But which platforms were the most productive and cost effective?

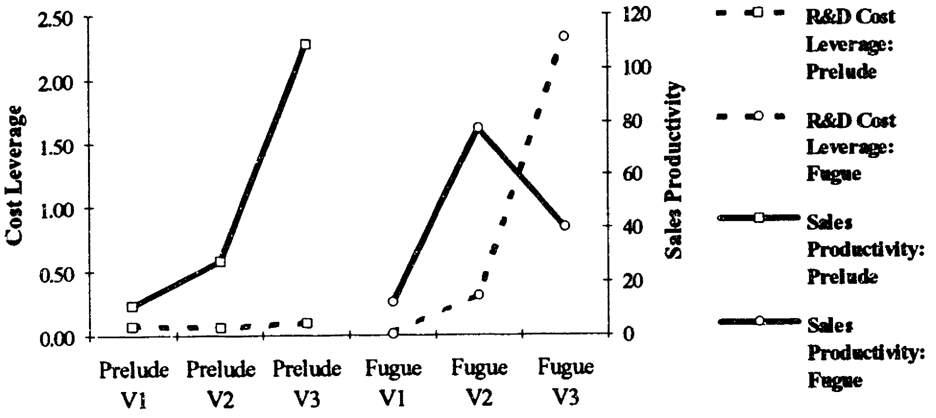
Table 3.4: Sales and cost data for Family B

Platform	***Total Platform Sales ($'000s)***	***Total Platform R&D Costs***	***Average Cost of Derivatives***
Prelude V. 1	91,000	6,485	489
Prelude V. 2	184,000	5,636	347
Prelude V. 3	487,000	3,747	366
Fugue V. 1	132,000	10,353	135
Fugue V. 2	280,000	1,617	498
Fugue V. 3	309,000	972	2,249

Applying the sales productivity and cost leverage metrics to these data yields the comparative graph shown in Figure 3.5.

Figure 3.5

Family B
Sales Productivity and Cost Leverage



The cost leverage of the Prelude series of platforms averaged a steady seven cents (.07) on every base platform dollar. Prelude's sales productivity grows with each successive extension -- as is expected with a good platform.

Figure 3.5 illustrates that Fugue led a more troubled life cycle. As a platform renewal, its metrics clearly show a severe decline in sales productivity and sharp increase in cost leverage. In fact, Version 3 of Fugue cost almost two-and-a-half times as much to develop as the base architecture!

What went wrong? The post-mortem of Family B using family level metrics indicate that perhaps Prelude was discontinued too soon. Both the cost leverage, and sales productivity meta-metrics indicate that another extension may have been possible off of Prelude without a loss of performance.

Perhaps Prelude could have been extended; however, there were other factors at play. In 1986, Generico, who was the market leader at the time, was faced with a strong new competitor. The competitor had introduced a product which was technically superior to any of Prelude's follow-ons. Generico was forced to respond quickly.

It had two choices: (1) to continue to extend Prelude, or (2) to quickly start on a platform renewal named Fugue. It chose the latter.

Tight deadlines to meet the competition forced a tremendous developmental rush. Consequently, Fugue was poorly designed as a long-term platform. The haste led to quality problems, and an inability to spin off effective follow-ons. Fugue 'died out' quickly with Version 3, with all its follow-ons being poor performers. Unable to keep up, Generico's competition made serious inroads into the marketplace.

What could have been done to avoid the demise of Family B? In such a competitive business, Prelude's renewal should have begun much earlier, and not as a reaction to new competition. In fact, a general rule-of-thumb might be to begin planning platform renewals almost as soon as the previous platform's base architecture is commercialized. For Generico, this would have meant starting on Fugue as early as 1982 instead of 1986 (see Figure 3.4).

Sonata's post-mortem clearly shows that proactive product family planning is necessary for a smooth and continuous stream of products to evolve. By doing so, companies can be better prepared for unexpected competition.

Could the metrics have *predicted* the problems in Family B? Probably not. However, this is a case where much can be *learned* from the post-mortem analysis. The meta-metrics highlight the problem, and emphasize the learning.

Figure 3.4 is especially insightful. If the dots marking the start of each of Fugue's R&D cycles are connected, one can clearly see the rush that Generico was in to develop Fugue and its three platform extensions. Had Generico started earlier, the rush could have been avoided, and the competition could have been held at bay. Product family maps such as Figure 3.4 can be very useful for planning as well as post-mortems.

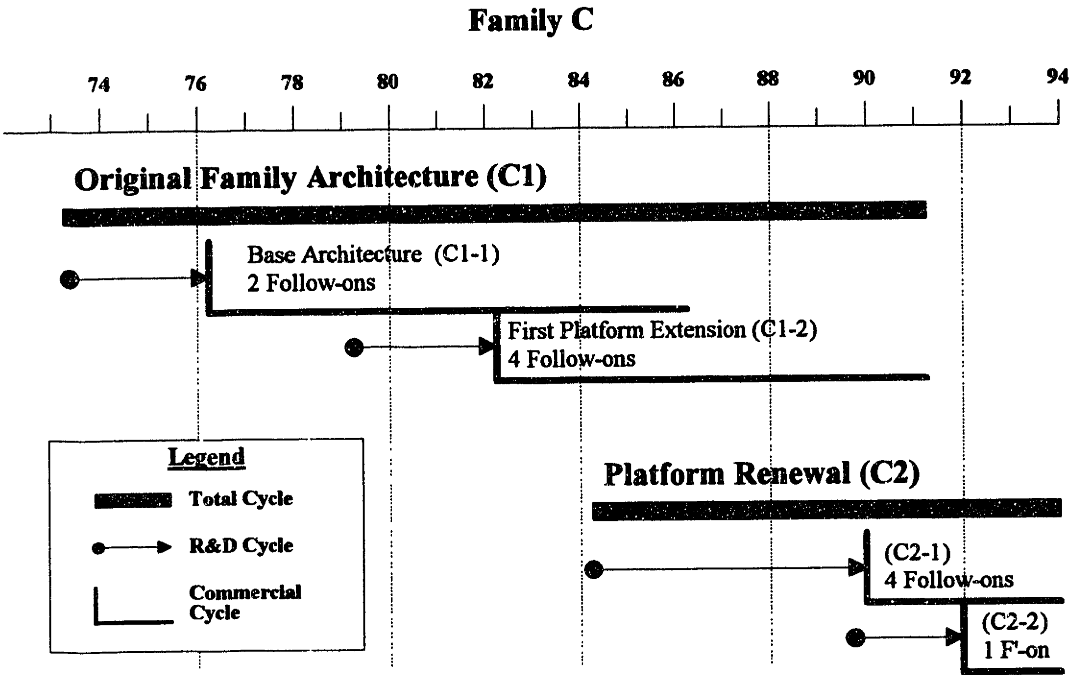
3.4 Comparative Study of the Meta-Metrics Across Families

At the firm level, it is useful to compare meta-metrics across different product families. Comparisons can reveal not only efficient or deficient platforms, but on a higher level also highlight divisional problems within the firm. Throughout this thesis the importance of planning for a continuous stream of products has been emphasized. To assess how well the firm is doing this, comparative meta-metrics are best plotted against the time dimension.

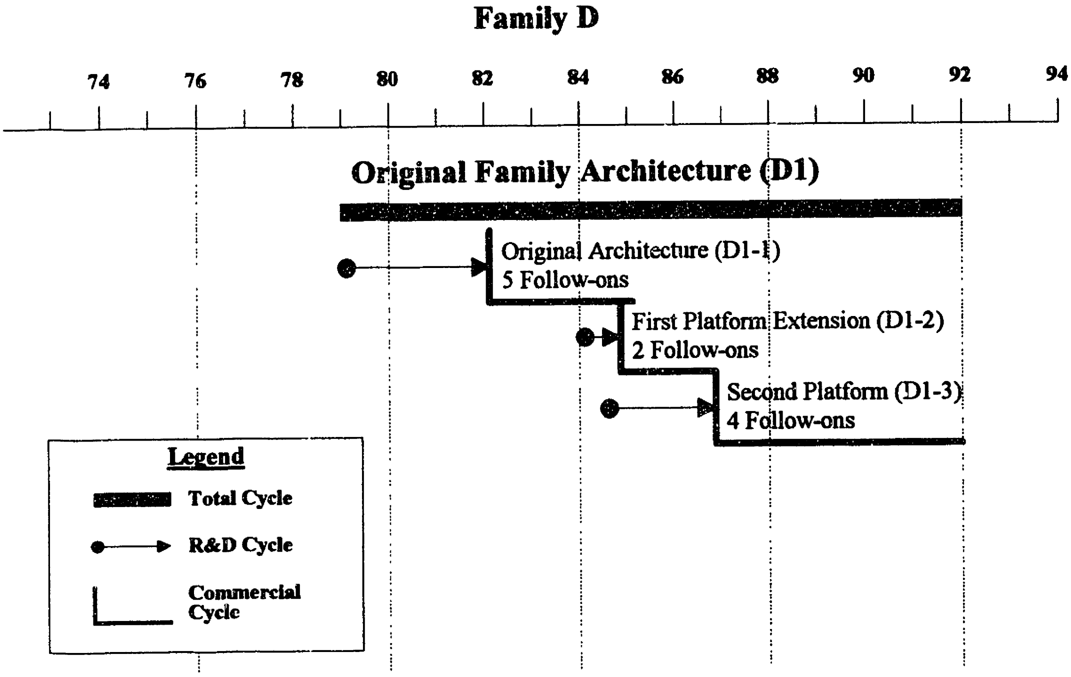
Cost leverage, and cycle time economy are analyzed *across families* in this final section of analysis (Boxes C1 and C3; Table 3.5). Two families, C and D, will be used as examples. Their product family maps are shown in Figure 3.6.

Family C originated back in the late 1960's, and is still in production today. After one extension, C1-2, the platform underwent a major renewal in

Figure 3.6: Family Maps for Product Families C and D



Family C



Family D

1984 creating the 'C2' platform architecture. The latest extension is C2-2 which is still on the market today. A total of 11 follow-on products over 20 years have been spun off of the platforms in Family C.

Family D is a subset of a much larger family. It serves the same basic hospital market as Family C, but for a different niche application. Spanning 12 years, Family C consisted of 2 platform extensions (D1-2 and D1-3) and a total of 11 follow-on products.

Table 3.5 shows a summary of the computed meta-metrics for the platforms versions within each family.

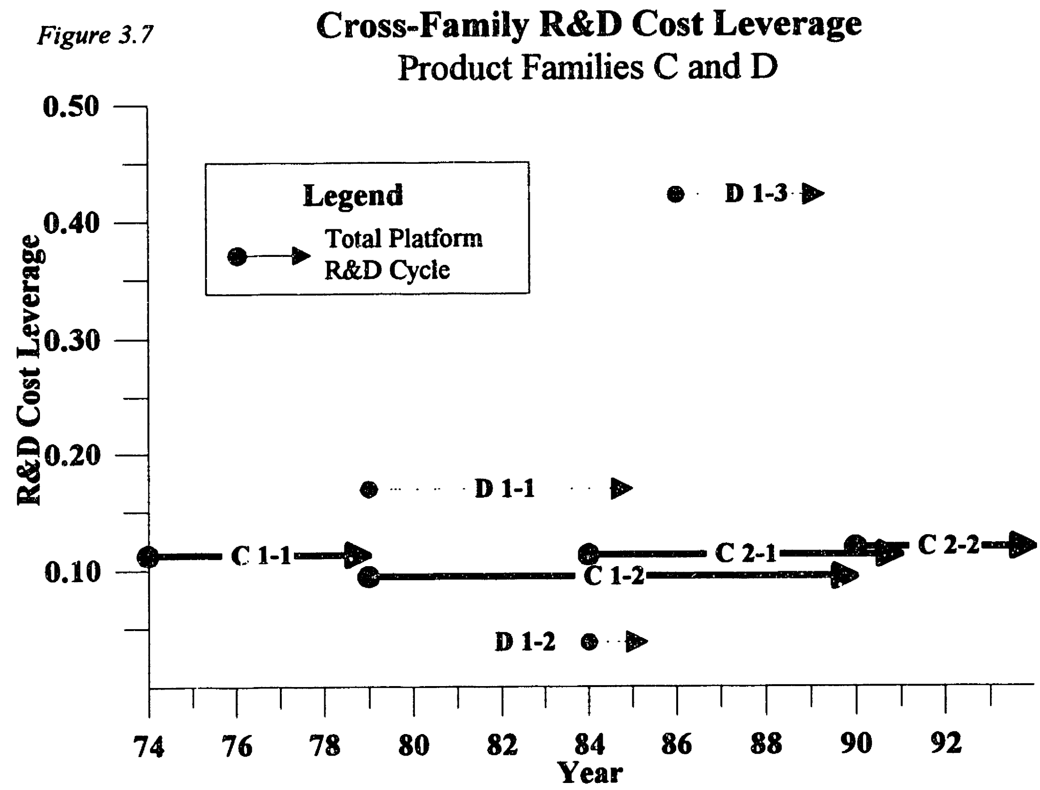
Table 3.5: Cost and Cycle Time Metrics for Families C and D

Family Platform	***R&D Cycle Dates (all follow-ons)***	***Average R&D Cost Leverage***	***Average R&D Cycle Time Leverage***
C 1-1	1973-1979	0.12	0.41
C 1-2	1979-1990	0.09	0.40
C 2-1	1984-1991	0.11	0.20
C 2-2	1990-1994	0.12	0.84
D 1-1	1979-1985	0.17	1.09
D 1-2	1984-1985	0.03	0.86
D 1-3	1985-1989	0.42	1.20

Figure 3.7 compares the average R&D cost leverage meta-metrics over time. The consistency of Family C over a span of 20 years is impressive. Even after its renewal in 1984, the average cost leverage is about 10 cents on the dollar.

Family D on the other hand is erratic. The two extensions, D1-2, and D1-3, are completely different that the original architecture. Extension D1-2 actually had better cost leverage than its predecessor. D1-3 shoots up to a much higher leverage of over 40 cents on the dollar.

Figure 3.7



Families C and D represent two independent divisions within the company. An initial inspection of Figure 3.7 would suggest that resources within C's division are being pooled effectively, with the benefits of product family thinking being realized. That is indeed the case. The division responsible for Family C has been a cohesive and stable unit of human and technical resources for a long time.

Visual inspection of Figure 3.6 would also suggest that Family C has somewhat of a *rhythm* to its platform cycles. There appears to be a flow of platform extensions and renewal. Substantial overlap in time between C1 and the C2 renewal suggests long-term thinking. This rhythm, coupled with a stable unit of pooled resources, has translated into a sustained cost leverage over twenty years. In short, Family C is a well designed and successful family. In fact, Generico is a market leader in Product Family C.

Family D, on the other hand, lacks the rhythm of Family C (see Figure 3.6). Hindsight is easy; but D1-2 looks like it should have started much earlier. In fact, the last one or two follow-ons of D1-1 should have actually been part of D1-2. That would have probably led to a longer commercial cycle for D1-2 as well.

Figure 3.7 shows that D1-2 had a very good R&D cost leverage. But caution must be exercised when interpreting this number. Platform D1-2 was short-lived and produced only 2 follow-on products. The R&D cost leverage can show misleading sensitivity with short timespans and limited follow-on data. It is always recommended that the interpreter consult a product platform map (such as Figure 3.6) to substantiate, refute, or merely question the origin of a computed meta-metric.

Platform D1-3 shows poor R&D cost leverage (Figure 3.7). Here the data is known to be valid. D1-3 was unable to recover from the 'patchwork' platform, D1-2. It is also known that the division that ran Family D was far less cohesive and stable than Family C. Engineers were poorly allocated; as a result tacit knowledge was lost over time. Family D never had a rhythm.

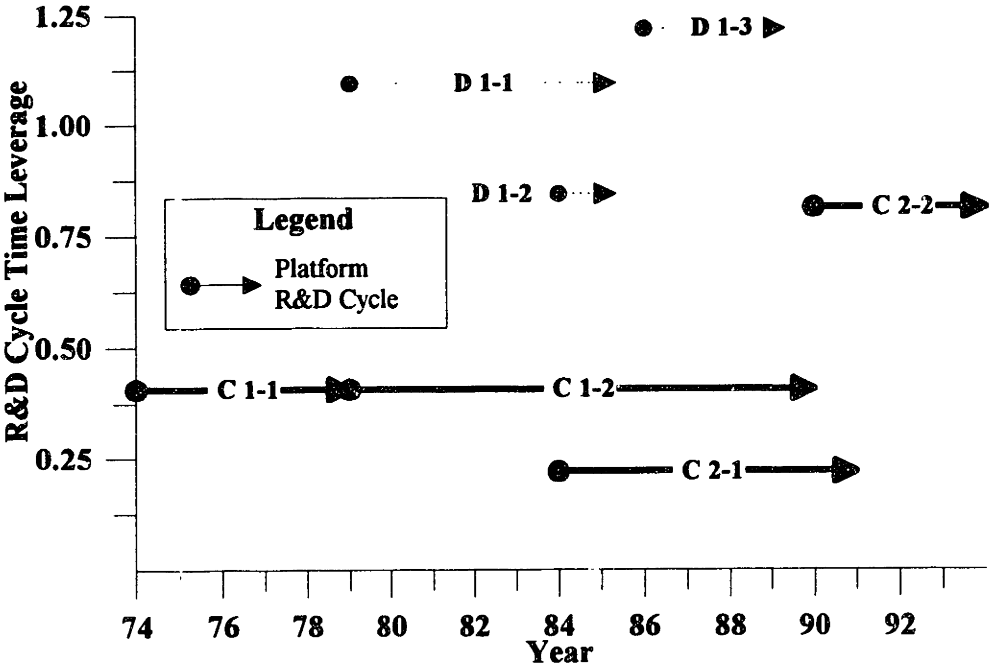
Cycle time economy can also be compared across platforms. Figure 3.8 shows the comparison.

Family D shows average time economies which exceed one for D1-1 and D1-3. This implies that the follow-ons took longer to develop, on average, than the original architecture. Once again, caution in interpretation must prevail. In general, the R&D cost leverage should closely mimic the time economy meta-metrics. This is because 'time is money', and a substantial portion of development costs are human labor. What is the source of discrepancy here?

Closer inspection of the raw data revealed that the engineering department clocked the 'start time' of the follow-ons at the same time as the

Figure 3.8

Cross-Family R&D Cycle Time Economy
Product Families C and D



original platform. This would naturally lead to cycle time economies greater than one.

This example highlights two things: (1) again, the meta-metrics should always be substantiated to ensure that they reflect meaningful information, and (2) the cycle time economy meta-metric might not be overly useful.

The second point comes as a surprise. Indeed, the cycle time economy meta-metric may be redundant, and of limited use in most practical cases. If human labor costs are directly correlated to cycle time (they usually are), then the R&D cost leverage meta-metric encompasses most of the information about cycle time anyway.

This does not mean that measuring cycle time is not important. It means that with respect to performance, *the time economy meta-metric is mostly represented by the R&D cost leverage meta-metric* -- so why have two metrics? Especially when the 'start time' is open to bias error, as was seen in this example.

Much can be learned about cycle time by studying platform evolution maps such as those in Figures 3.1, 3.4, and 3.6. In fact, these visual representations can be far more insightful than computed numbers.

What has been learned through cross-family comparisons of meta-metrics? In this example, we know that the division that ran Family C was more successful than Family D. The meta-metrics substantiate this, and suggest again that a continuous stream of well planned products based on a product family architecture leads to success in the lab, and in the marketplace.

The comparative analysis highlights divisional differences within a firm. Senior management can use comparative meta-metrics to highlight these problems. By studying this information, corrective action can be taken to ensure that all divisions are planning for long-term continuity, and efficiently pooling their resources. In this example, the division in charge of Family D needs to be reviewed.

Finally, we have learned to be cautious. Meta-metrics are computed numbers. The value of their computation lies in the integrity of the underlying data. Meta-metrics can be highly effective tools for learning and identifying problems; however, visual and numerical confirmation must always accompany any interpretation.

Indeed, visual representations are often powerful enough to make numerical computations redundant (refer back to Section 1.5). When assessing the performance of product families with meta-metrics, it is recommended that cycle time economies be interpreted visually as opposed to numerically.

APPENDIX 3A

Product Family Data

Table 3A.1: Family A; Sonata Platform

Family	Platform	Version	Follow-on	Start R&D	End R&D	R&D Cost ($'000s)	R&D Inflation Factor	Inflation Adjusted R&D
A	Sonata	Base	Base	81/09/30	85/03/31	20,400	1.34	27,336
A	Sonata	Base	Revision 1	84/09/30	85/09/30	1,850	1.34	2,479
A	Sonata	Base	Revision 2	84/09/30	86/04/30	2,775	1.31	3,635
A	Sonata	Base	Revision 3	85/12/31	86/11/30	1,810	1.31	2,371
A	Sonata	Base	Revision 4	86/12/31	89/01/31	9,957	1.16	11,550
A	Sonata	Base	Revision 5	86/06/30	90/05/31	8,874	1.10	9,761

Table 3A.2: Family A; Sonata Platform (continued)

Family	Platform	Version	Follow-on	Start Sales	End Sales	Total Sales ($'000s)	Sales Inflation Factor	Inflation Adjusted Sales
A	Sonata	Base	Base	85/03/31	86/04/30	153,000	1.31	200,430
A	Sonata	Base	Revision 1	85/09/30	86/04/30	120,000	1.31	157,200
A	Sonata	Base	Revision 2	86/04/30	86/11/30	117,000	1.31	153,270
A	Sonata	Base	Revision 3	86/11/30	89/01/31	469,000	1.16	544,040
A	Sonata	Base	Revision 4	89/01/31	90/05/31	318,000	1.10	349,800
A	Sonata	Base	Revision 5	90/05/31	91/04/30	254,000	1.06	269,240

Table 3A.3: Family B Data

	Prelude Platforms (Original)			Fugue Platforms (Renewal)		
Sales and Costs ($'000s)	V1	V2	V3	V1	V2	V3
Total Platform Sales	91,000	184,000	487,000	132,000	280,000	309,000
Base Archictecture R&D Costs	10,311	7,834	5,021	12,009	1,779	1,030
Total Follow-on R&D Costs	2,116	1,362	930	623	2,103	7,313
Average of Follow-on R&D Costs	353	341	465	156	526	2,438
Total R&D Costs	12,427	9,196	5,951	12,632	3,882	8,343

Table 3A.4: Family C Data

	Original		Renewal	
Costs and Cycle Times	**C1-1**	**C1-2**	**C2-1**	**C2-2**
Base Archictecture R&D Costs ($'000s)	2,849	5,544	8,979	4,869
Total Follow-on R&D Costs	662	2,150	985	1,696
Average of Follow-on R&D Costs	331	538	985	565
Total R&D Costs ($'000s)	3,511	7,694	9,964	6,565
Base Architecture Cycle Time (years)	2.25	3.25	6.42	1.75
Average Follow-on Cycle Time	0.92	1.29	1.25	1.48

Table 3A.5: Family D Data

		Original	
Costs and Cycle Times	**D1-1**	**D1-2**	**D1-3**
Base Archictecture R&D Costs ($'000s)	7,659	3,350	990
Total Follow-on R&D Costs	6,414	213	1,676
Average of Follow-on R&D Costs	1,283	107	419
Total R&D Costs ($'000s)	14,073	3,563	2,667
Base Architecture Cycle Time (years)	3.00	1.16	1.75
Average Follow-on Cycle Time	3.27	1.00	2.10

4 Implications and Areas of Further Research

4.1 Discussion

Senior management from Generico elected to participate in an academic study because they knew that the firm was 'in the business' of making product families, each of which bred a continuous stream of attractive products. Though they implemented product family thinking, the company's managers did not have measures to assess the effectiveness of their R&D in the evolution of their product families from the past to the present. Generico's major success and mistakes in the past with respect to product development had been related to the issue of platform development and renewal. It sought a systematic way to learn from the past to help it better plan the development of its future products.

In the past, Generico had used neither the engineering cost data, nor the sales data to assess the performance of its product families. Rather, its 'R&D metrics' were annual in nature, consisting of average annual project slip for time and budget, and the number of critical hardware and software bugs encountered by customers in the current year. The academics who collected the data have noticed that this company's pattern of use, or disuse, of product data is typical in many industries.

Assuming a product family framework, the implications arising from this work are clear. In technology-based industries, senior decision-makers need a *continuous* assessment of how their products are performing. Failure to do so will result in 'blind' planning, and product development that is reactionary rather than proactive. The financial consequences in the lab, and in the marketplace, can be significant. This was demonstrated in chapter three.

I highlighted the word 'continuous' because the assessments cannot be carried out on a once-a-year basis. The product family maps in chapter three clearly show how quickly product families evolve. Depending on the technological intensity of the firm, quarterly -- if not monthly -- reviews are more prudent. Yearly reviews do not sample the situation finely enough, nor do they foster a culture of continuous thinking.

4.2 Assessing the Utility of the Meta-Metrics

The analysis of the data in chapter three gave an insight into how the meta-metrics can be used at different levels of detail within and across product families. Of course, the meta-metrics can be graphed, or 'mapped' using dimensions other than those chosen in the examples. Different 'maps' can reveal new insights into the performance and evolution of a company's product families. In the case of cycle time performance, visual interpretation via the platform evolution maps is preferable to numerical metrics.

Implementation of the meta-metrics requires a system of data gathering and computation. If these meta-metrics are to be of any use, it is imperative to assess their use in a realistic corporate setting. Section 2.3 researched and discussed the criteria for a successful system of corporate measurement. Do the proposed meta-metrics meet these criteria?

The criteria of *comprehensibility* and *simplicity* are quite subjective. Notwithstanding the rigorous mathematical treatment of section 2.4, the metrics follow a simple framework of understanding: the product family. Intuitively, follow-on products should require less time and resources to develop than base architectures. Further, the product cycle for platforms and follow-ons is decomposed into two easily understandable and distinct phases: the development phase and the commercial phase. Sales, costs, and dates, are easy to comprehend for anyone in an organization.

Again, the platform maps and graphs are an essential part of comprehending the meta-metrics, and questioning their validity. Numbers alone never speak easily. I believe that the computed meta-metrics, presented in a clear graphical manner which conform to a product family framework, fulfill the criteria of *comprehensibility* and *simplicity*.

The hierarchical framework of the product family lends itself to interpretation from multiple *perspectives*. Studying individual product families, or groups of product families, fosters thinking at all levels of the firm -- right to the top. This flexibility in perspective, along with a full product-cycle view, gives these meta-metrics the necessary holistic character.

Sales, costs, and timing information area all quantitative, objective measures. There is virtually no bias in the meta-metrics, hence *objectivity* is preserved.

Cost-effectiveness is a contentious issue. Gathering the data can be a costly proposition. Without a good system of accounting, and a ready electronic access to sales and cost figures, it is unlikely that the meta-metrics can be computed cost effectively. However, given a good activity based accounting system -- and most companies are heading that way -- the meta-metrics are simple enough to compute inexpensively.

An effective accounting system is also at the root of *reliability*. Consistent, and accurate data recorded over time is the key to the reliability of the meta-metrics. Again, this criteria is easily satisfied with good record-keeping and an up-to-date accounting system.

I believe that the analyses of the previous chapter have shown insights into the product innovation process; especially in the context of product families. Such insights are highly *relevant* to a firm's business. The meta-metrics provide predictive value for future planning, and feedback value for learning. Objective financial, and time data are used as measures of input and output across the full cycle.

Finally, the most important criterion: *acceptance*. Will decision-makers accept these meta-metrics in a real-world corporate situation? Some managers in Generico, whose data was used in chapter three, have already embraced R&D cost leverage, and sales productivity. Nevertheless, it is too early to tell whether the meta-metrics will become a routine part of their product family assessment and planning.

Overall, I believe that the cost leverage and sales productivity meta-metrics satisfy all of the success criteria outlined in section 2.3. Further usage of the meta-metrics in real-life will continue to test them against these success criteria.

4.3 Limitations of the Meta-Metrics

The proposed meta-metrics are not without their limitations. These limitations must be balanced against their simplicity; recalling that complicated metrics are often ineffective (section 2.3).

There are a few theoretical limitations, some of which have already been discussed. Most open to criticism is the use of sales data as opposed to profit. I contend that profit is a poor, and even misleading, measure of output unless: (1) it can be measured with consistency across all product families, and (2) it can be distinctly apportioned to individual follow-on products. If not, then the safest approximation is to use sales figures and assume that the cost structure of a product family is constant across follow-ons within the family. This is a good assumption considering that the definition of a product family hinges upon the pooling of common resources.

The time value of money was not considered in the meta-metrics. To be thorough, the cash flows should be discounted at the appropriate cost of capital for each project[1]. Therein lies the problem. A project's cost of capital is difficult to ascertain; especially for base architectures which, due to their riskier nature, command a higher risk premium. As well, introducing the cost of capital introduces a new variable which takes away from the simplicity of the equations. This is not to say that the cost of capital can be ignored. Certainly for new project planning and capital budgeting, the time value of money is an essential consideration. However, for comparative studies of past performance the oversight may be acceptable.

From an operational standpoint, the major shortcoming of the meta-metrics is that they only use *internal* data. Development costs and sales are all measures that are found within the walls of the firm. External data, such as market share, market size, competitive pricing, relative technological positioning, relative quality, and other such measures all have a causal effect on the sales performance of the product family. Such external measures are not part of the current assessment technique, but can be incorporated into the overall learning system to complement the meta-metrics.

Product quality is a metric which is not *directly* measured by the meta-metrics. From a developmental perspective, it can be argued that design quality is indirectly measured; in other words, poor design quality which is inherent in a base architecture will propagate through the follow-ons and ultimately show up as a higher cost leverage. This was demonstrated with the Fugue platform which, due to haste, lacked quality design. Fugue's cost-leverage soared after the second platform revision due to deficiencies in design quality.

From a commercial perspective, it can be argued that quality is indirectly measured by the sales productivity meta-metric. A poor quality product platform and its follow-ons will not perform well in the marketplace. As a

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[1] **Brealy, R. A., and S. C. Meyers, *Principles of Corporate Finance, Fourth Edition*, McGraw-Hill, Inc., New York, 1991, Chapter 12.**

consequence, the sales productivity meta-metric will drop over successive follow-ons.

Meta-metrics are designed with strategic intent. Though the meta-metrics will reflect quality issues in the long-run, I do not suggest that cost leverage, and sales productivity act as a replacement for detailed quality metrics. Quality metrics are essential to a company's survival in the marketplace. In the development cycle, quality metrics should be handled by the engineers at the 'control' level. Sales and marketing departments should oversee how customers are responding to the quality of the products in the marketplace. Ultimately, these data should be fed into the learning system for post-mortem analysis as well.

The old axiom, "hindsight is 20-20" must be kept in mind when using the meta-metrics. It is important to remember that although the meta-metrics will demonstrate good, bad, or indifferent performance, they do not point to specific causes; technical, organizational, or otherwise. We can only speculate on these after the fact. If tracked in real-time, the meta-metrics can act as a warning flag, and lead managers to find causality. As a post-mortem tool, the meta-metrics can enhance learning through introspection.

Finally, the meta-metrics are limited by the firm's philosophy on product development. The meta-metrics proposed in this thesis are of little value unless the firm has adopted a regimen of platform based thinking for product innovation.

4.4 Areas of Further Research

There has been little research in the area of product families, let alone metrics to measure their performance. With this thesis, I have shed some light onto how to assess the performance of product families with meta-metrics.

To start, I recommend further research to address the limitations which I outlined in the previous section. In particular, the study of external metrics should be a high priority. The development and testing of external meta-metrics would make a very useful complement to this work.

Of course, more meta-metrics can be developed or the current ones can be extended. For example, the rate of change of the meta-metrics and their relative orientation (slopes) may provide useful insight. Following the lessons of Chapter 2, care must be taken to establish the intent and usage of any new meta-metrics before any work is done. Further, every effort must be made to satisfy the success criteria. Metrics are useless if nobody uses them.

This thesis concentrated only on innovation in *product* families. In Chapter 1, *process* innovation was mentioned to be of equal importance. A third category is *services* and service innovation. Adapting the meta-metrics to processes and services would comprise a useful area of further study.

Manufacturing is an integral component of a product-based business. In this thesis the manufacturing process was assumed to have no effect on the performance of a product family. Research into how manufacturing affects product family performance would be very insightful.

Finally, referring back to Figure 1.1, this thesis has addressed only a small portion of the product cycle learning system. Much work needs to be done to create a comprehensive system of product cycle learning that is realistic to use in a corporate setting. Adapting the meta-metrics to an electronic database system is a first step toward that end.

4.3 Conclusion

It is time to stand back and objectively think about the contents of this thesis. Exactly what has been accomplished? Originally, the aim was to propose and test a set of quantitative measures that assess the performance of product families. I believe that this aim has been accomplished.

The ability to quantitatively assess and analyze product performance across the entire product cycle has many managerial implications. Most significantly, it allows senior management to learn from the past so as to compete more effectively in the future. The meta-metrics are a tool to catalyze this learning process.

I believe that the meta-metrics are simple in concept, and easy to interpret. In chapter two, the bibliometric study demonstrated that simplicity was a necessary element to successful R&D measurement systems. Because of their simplicity, the two sets of meta-metrics -- R&D cost leverage, and sales productivity -- are readily computed from accounting data.

What is not so readily done is to foster product family thinking into a firm. This usually requires difficult organizational changes. However, once the transition is made, a firm becomes better able to compete with continually innovative products over the long-term. As Jim Utterback writes,

> "To avoid the grim reaper which has carried off so many proud and prosperous firms over the past century, modern managers must develop and nourish organizational capabilities that will carry them successfully from one generation of product and process technology to the next. This may the be ultimate managerial challenge[2]."

I hope that the work presented in this thesis contributes to a 'better organizational capability' for firms competing in technologically intense industries.

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[2] Utterback, J. M., *Mastering the Dynamics of Product Innovation*, op. cit., p. xix.