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**Managerial Determinants of Industrial
R&D Performance: An Analysis of the
Global Chemicals/Materials Industry**

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ABSTRACT

A general framework has been proposed for analyzing the impact of various managerial strategies on the overall outcomes of a firm's research and development efforts. It suggests that three elements are critical: posture and direction; systems; and adjustment processes. The framework led to the development of a series of twenty hypotheses regarding managerial practice. These hypotheses were tested using data gathered from 29 chemicals/materials firms as part of a global assessment of strategic management of technology. Multifaceted measures of R&D impact were evaluated: (i) an index of R&D performance; (ii) time from concept to realization of product and process innovation; and (iii) satisfaction of three different stakeholders of the firm's R&D undertakings. Important differences were indicated among the strategies that most affect each performance measure, although the use of multi-functional teams and the corporate-level development and acceptance of technology strategy mechanisms were significant factors across the board. The results support the framework in that key contributors to R&D outcomes were found in managerial approaches that relate to each of the three elements.

The Technological Innovation Process

Adler, McDonald and MacDonald (1992)¹ have proposed a general framework for analyzing the process of technological innovation in organizations. According to these authors, three elements emerge repeatedly as indicators of sustained technical accomplishment and business success: posture and direction; systems²; and adjustment processes. Figure 1 illustrates their framework. Rather than taking it as a definitive standard, we use the framework here as an instrument to assess the process of technology management in the global chemicals/materials industry.

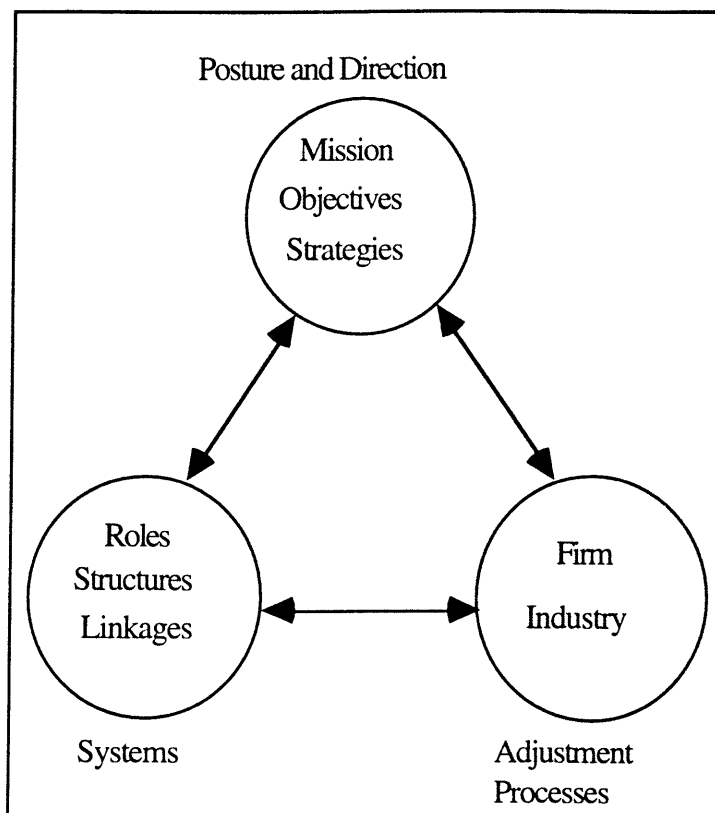


Figure 1. Strategic management of technology framework.

Posture and Direction Posture and direction of the R&D function comprise the formulation of a technological mission and strategy, the communication to and acceptance of this mission and strategy by the whole organization, and the compatibility between

¹ Adler, P. S., McDonald, D. W., and MacDonald, F. "Strategic Management of Technical Functions", *Sloan Management Review*, Winter 1992, 19-37.

² The authors call this second element "policies". We prefer to call it "systems" to avoid any confusion that may arise with the policy/strategy options developed in this paper, which apply to all three elements of strategic management of technology.

technology strategy and overall corporate-level strategy. Underlying the acceptance of the technology strategy by the whole organization is the issue of how the culture of the organization perceives and shapes the technology strategy process.

Systems Systems involve all the structures that are required to support the technological innovation process. They can be grouped into three other categories: structures; roles; and linkages.

Structures are the result of the formal organization of assets, resources, and responsibilities. As examples, structures involve: the organization of technology resources at the corporate and business unit levels; the allocation of funds across technical functions (research, development, and engineering); the use of multi-functional teams; the configurations used to move products from concept to implementation; the decision-making forums; and R&D facilities and equipment.

Those structures are the formal mechanisms that help to shape the pattern of communication in the R&D process. Management, however, can exert a more extensive and direct control over the volume, content and direction of information flows depending on its roles in adapting the various administrative systems, hierarchical channels and informal relationships. Important roles in influencing the R&D process include: the degree of involvement of the CEO; the participation of the CTO in corporate strategy formulation; and the participation of the marketing executive in the technology strategy process.

The R&D organization cannot stand alone in achieving technological innovation. It is embedded in a larger context, both internally, as a function of a specific organization, and externally, as recipient and supplier of technical information and innovations. In this context, linkages bond the R&D function both externally and internally. Within the firm internal linkages include interfunctional relationships with other functions like manufacturing, marketing, finance. Externally, its linkages entail ties with customers, universities, consortia, experts.

Adjustment Processes Adjustment processes are aimed at identifying both threats and opportunities in the industrial environment and strengths and weaknesses at the firm level. They involve: technology monitoring and assessing; analysis of competition; and answers to global technological issues, like internationalization of R&D and external sourcing of technology.

These three elements -- posture and direction, systems, and adjustment processes -- form a triad that supports the innovation process in organizations by complementing each other. The assessment of strategic management of technology practices in the chemicals/materials industry is conducted in this paper by applying this framework as a basis of analysis.

The Global Chemicals/Materials Industry

Structural Analysis It is difficult to define the chemicals/materials industry, mainly because of its complexity. According to the United Nations (1992)³, the chemicals/materials industry consists of many segments: inorganics; fertilizers and agrochemicals; petrochemicals; artificial fibers and synthetics; pharmaceuticals; and others. Although these products hardly match the strict definition of an industry -- groups of firms whose products are close substitutes to each other -- the economics of these segments have some similarities that support important generalizations. The only exception is the pharmaceutical industry, which has different structural characteristics in terms of regulation on a global basis (product, process, and price), intellectual property protection, and research and development orientation. For these reasons this study does not include the pharmaceutical industry as part of the broader category called chemicals/materials industry.

Annual worldwide sales from inorganics, fertilizers and agrochemicals, petrochemicals, and artificial fibers and synthetics are around \$1.2 trillion. Production is widespread, with developed countries accounting for 65% and less developed countries producing 35% of total consumption (United Nations, 1992)⁴.

The chemicals/materials industry can be segmented into synthesis and formulation. Basically, synthesis involves the production of molecules or substances through chemical and mechanical processes. Formulation involves the production of substances through mechanical operations, without changing the basic structures of molecules. Historically, firms operating in synthesis were among the first to support company-owned research laboratories. These investments not only created new products to sustain growth but also new low-cost manufacturing processes, both of which have traditionally given the industry its particularly dynamic characteristics. Formulation firms are more focused on development, adapting product characteristics to meet customers' needs. This activity

³ United Nations. Annual Review of the Chemical Industry, 1992.

⁴ Op. cit.

usually requires a high degree of service. The focus of this study is mainly on firms operating in the synthesis segment.

The chemicals/materials industry can also be divided into commodities and high value-added products (specialties). Commodities are products sold on the basis of well-defined characteristics, targeting non-differentiated market segments that have high price elasticity of demand. Specialties are products sold on the basis of performance, targeting differentiated markets that have lower price elasticity. Specialty status most often occurs in the early years of the product's life cycle with commodity status coming in later years.⁵ As is also the case with synthesis and formulation, firms that produce commodities are subject to a different set of industry forces than firms that produce specialty substances.

Although the industry faces significant challenges in the years ahead, opportunities do exist. Management of technological innovation is an important dimension in the industry's process of continuous restructuring. Effective technology development or acquisition can help firms to reduce costs through process innovations and to move into more attractive markets through new product development.

Innovation in the Chemicals/Materials Industry Innovations can be divided into product and process innovations. Product innovation is the set of activities that start with basic knowledge and end with either a new commercial product or an improved version of an existing product (Stobaugh, 1988). The firm that first produces a commercial product is called the product innovator. Initially, the innovator is the sole manufacturer of the product and acquires monopoly profits from its innovation.

The profitable monopoly attracts the attention of other firms that then try to enter the new economic sector. These firms can enter the new business through process innovation (i.e., producing the same product via a different process), through imitation or, when possible, through purchasing technology. As these new economic agents enter the business, the monopoly is changed to an oligopoly and subsequently to a competitive industry. At this stage profits are not so high and may attract new investments only to fulfill demanded capacity. Not only entrepreneurs, seeking monopoly profits, innovate. Innovation can also be a response to a specific problem, constraint or threat, such as excessive costs (royalties or raw materials) or difficulties in process operation, or a new more stringent regulation.

⁵ See Utterback, J. *Mastering the Dynamics of Innovation*. Harvard Business School Press, 1994.

Technological innovation may have an important role in chemicals/materials firms' survival and growth. In the commodities segment, strong rivalry pushes firms for cost reduction. In addition, stricter environmental or health standards demand product and process redesign. In specialties, new processes and products are a requirement for entry. Furthermore, product development, marketing, and service capabilities are prerequisites for long term profitability.

In the chemicals/materials industry an innovation seldom derives principally from the unique knowledge coming from basic research. Rather, it results mostly from the large number of interrelated activities required to produce a product for a selected market. Stobaugh (1988) points out that the needs of commercial firms for fundamental knowledge are so diverse and unpredictable that it is usually not economical for them to produce this knowledge themselves. Thus, commercial monopoly in the industry is typically not built upon control over basic research. Monopolies of product innovators are based on their ability to build upon basic knowledge and to develop markets and production processes by which the products can be made at satisfactory costs⁶.

Commodity producers seldom compete in the same market with different product concepts. Chemicals/materials products are usually well defined molecules or substances, with specific performance characteristics. As a result, commodities allow little product experimentation. Competitors or new entrants do not have other choices than to explore different process concepts. Once the product innovator has established a market, other firms may enter the business in a relative short time by developing a new process to make the product⁷. These firms are called process innovators.

The rewards to a process innovator and the effects of its innovation on the industry depend on the extent that the new process is better than the old and on the degree of competition in the industry. If the process innovation is truly radical, old plants are closed and dismantled. The specialized nature of chemicals/materials plants usually makes the conversion of old plants into the new process uneconomical⁸. This is an important characteristic of the commodities segment. The process is designed to be rigid, since it is initially developed for

⁶ Since product innovation is a result of both engineering problem solving and market concept specification and building, large markets and industrialized countries have advantages over small and less developed countries.

⁷ Although product innovations may take a considerable amount of time, process innovators usually follow product innovators by a short period. Stobaugh (1988) estimates that period as 6 years for petrochemicals.

⁸ In 1960, for example, Standard Oil introduced a new process to manufacture acrylonitrile and subsequently cut the price from \$0.26/lb to \$0.18/lb, thereby causing widespread shut downs of existing acrylonitrile plants (Stobaugh, 1988).

continuous production of large volumes and to meet specific criteria. The use of new raw materials or other reaction and separation mechanisms usually requires completely different vessels, flow patterns and control strategies.

New processes, however, do not always cause existing plants to shut down. Sometimes, the capital intensive nature of the chemicals/materials industry makes the marginal costs of operating existing plants lower than the average costs involved in building and operating a new plant. Moreover, even a less efficient new plant can be built to operate in an oligopolistic market. The coexistence of old and new processes is then feasible. An example of this pattern involves the polyolefins segment, where high pressure processes continue to coexist with low pressure catalytic processes.

Process innovations can be divided into major and minor. Major innovations are fundamentally different from existing processes, involving different raw materials and/or radically different reaction conditions. Major innovations are more important to competitive advantage because they are more likely than minor innovations to make existing processes obsolete. However, the importance of minor innovations, including improvements due to the learning process, should not be underestimated. For example, Hollander (1965) has demonstrated the importance of minor process innovations in productivity growth in the rayon industry⁹. Actually, they generally play an important role in a mature industry, changing the competition and trade pattern (Stobaugh, 1988).

Technological innovations do not appear from nowhere, however. A carefully designed and managed process of technology acquisition and commercialization is much more likely to support the strategic objectives of an organization.

Research Methodology

Strategic management of technology practices in the global chemicals/materials industry were assessed as part of a broad-based multi-industry study of data collected by mail questionnaires distributed initially to the most senior technology officers in leading European, Japanese and North American companies. The detailed questionnaire was developed in a joint effort between the senior author and a team from PA Consulting Group. The companies solicited were the 244 firms in all industries whose R&D expenditures cumulatively equal approximately 80 percent of the R&D spending in each of three regions: western Europe, Japan and North America. The resulting annual R&D spending per firm

⁹ Hollander, S. *The Sources of Increased Efficiency: A Study of Du Pont Rayon Plants*. The MIT Press, 1965.

ranged from over \$100 million to over \$5 billion. Usable responses were received from 95 companies, or 39%, with comparable response rates across regions and with an almost precise size match with the R&D spending pattern of the underlying sample. The responses reflect neither geographic nor size biases relative to the underlying global industrial sample of R&D-intensive firms.¹⁰ Those solicited to respond were guaranteed anonymity. Consequently company names were removed from each questionnaire when it arrived at the M.I.T. Industrial Liaison Program office and replaced with a numerical code. In that broad multi-industry survey 20 sets of usable responses came from firms that identified themselves as primarily in the chemicals/materials industry -- 5 from Japan, 7 from Europe, and 8 from the U.S.¹¹ To supplement these data with some comparative evidence on Latin American industry as well, the co-authors slightly modified the questionnaire and gathered additional data from 9 Brazilian chemicals/materials firms out of 30 firms sampled (response rate of 30%), bringing the total data points to 29 chemicals/materials companies.

Hypotheses

Two major parts of the overall questionnaire are important to this study. Part I aims at establishing benchmarks in management of technology practices. It has seven subparts to evaluate the three elements of strategic management of technology at the firm level, pictured in Figure 1: posture and direction; systems; and adjustment processes. Part II assesses the firm's experience of managing technology within the recent difficult global economic climate. In this section the structure of the questionnaire is used to elaborate the framework of Figure 1 into specific hypotheses that relate management of technology practices and R&D performance.¹²

Posture and Direction Posture and direction of strategic management of technology at the firm level is explored in subsection A of the questionnaire. Specifically, subsection A aims at understanding: the nature of the firm's technology strategy; how it is communicated and understood in the organization as a whole; and how it is linked with overall corporate-level strategy and with business unit strategy. It also assesses the frequency with which

¹⁰ Initial analyses of those data, primarily reflecting overall global characteristics and regional differences, are presented in Roberts, E. B. " Benchmarking the Strategic Management of Technology- 1 and 2", both articles forthcoming in *Research/Technology Management*, January-February 1995 and March-April 1995.

¹¹ An initial analysis of these responses was developed by Nelson Martinez, focusing upon the relationships between the corporate strategy process and management of technology at the firm level. See Martinez, N. "Management of Technology and Corporate Strategy in the Chemical Industry", unpublished Master of Science Thesis, Management of Technology Program, Massachusetts Institute of Technology, June, 1993.

¹² A copy of the questionnaire can be obtained by writing to the senior author.

corporate technology strategy is developed, reviewed, and adjusted. Finally, it explores the firm's perceptions of the importance of diverse issues to technology strategy (e.g., total quality methods in R&D, meeting market needs, decreased time to commercialization, and managing R&D with constrained resources).

It seems reasonable to expect that a well formulated, broadly communicated and accepted technology strategy should increase R&D performance¹³. A shared vision of posture and direction should facilitate agreement and work among different parts of the organization, increasing overall R&D performance. In this context the answers to question A.1 provide information to evaluate the following hypothesis¹⁴:

H.A.1: A well developed, communicated, and accepted technology strategy contributes positively to R&D performance.

One might also expect that a strong link between technology strategy and corporate-level strategy should increase R&D performance, since technology strategy would fit better with the overall purposes of the organization¹⁵:

H.A.2: A technology strategy that is strongly linked to corporate strategy contributes positively to R&D performance.

H.A.1 and H.A.2 are the two main hypotheses that are assessed regarding posture and direction of technology strategy in the chemicals/materials industry. In a broader sense they can be viewed as an approximation of the interactions between the culture of the organization and the technological innovation process.

Systems: Roles, Structures and Linkages As presented earlier, roles, structures and linkages are the important elements of the systems that support the innovation process and are assessed in subsections B, D and G of the questionnaire.

Subsection B assesses the structures and roles that support the development and use of technology in the organization. It explores: the degree of control of technology resources

¹³ A more complete discussion of the meaning of R&D performance occurs later in this paper. For now it is sufficient to think of R&D performance as measuring both the efficiency and effectiveness of the R&D organization in meeting its multiple strategic objectives.

¹⁴ The company's degree of development, communication, and acceptance of technology strategy is calculated by averaging the answers to the several parts of question A.1 for each respondent.

¹⁵ The company's degree of linkage of technology strategy to overall corporate-level technology strategy is provided by the answers to question A.4.

over time; the organization of technology resources at the corporate and business unit levels; the allocation of funds among research, development, product and process technical support; funding mechanisms of corporate-level R&D function; the roles of the Chief Technology Officer (or equivalent) and the Chief Executive Officer in the innovation process; and the use of multi-functional teams in innovation endeavors. Four hypotheses are developed below from subsection B.

First many scholars have argued that multi-functional teams can be an important organizational approach toward linking R&D results to commercial exploitation. A multi-functional team creates a mini-business organization, where members drawn from other functions of the total business work together to develop and implement a new product or process. As far back as 1979 Roberts¹⁶ indicated that

The team should be multi-functional in composition, drawing volunteers from R&D, manufacturing, marketing and even finance. When non-R&D contributors are brought together with technically innovative people they end up designing, developing and implementing a very different kind of product and product line. It's not the same product that would have been created had the technical group worked initially by itself and later transferred responsibility to another function for commercial exploitation. It's a product that instead has already taken marketing issues into account, has already considered production costs, and has already rationalized the investment requirements.

A related hypothesis can therefore be formulated stating:

H.B.1: The use of multi-functional teams contributes positively to R&D performance.

Second we should expect correlation between the role of the Chief Technology Officer (CTO) and R&D performance, as s/he is potentially a major personal instrument in shaping the flow of information, linking technology strategy with overall corporate-level strategy, and molding the strategic management of technology process. Of course, the CTO can possibly have a both a corporate-level influence as well as a downward influence on the business units of the corporation if either he/she sits in the board of directors (linkage) or if he/she is active in formulating and coordinating the whole technology process. Two hypotheses follow:

H.B.2: Participation of the CTO (or his/her equivalent) in the board of directors or the main management board contributes positively to R&D performance.

¹⁶ Roberts, E. B. "Stimulating Technological Innovation - Organizational Approaches", *Research Management*, November 1979.

H.B.3: The stronger the managerial role of the CTO¹⁷ the greater the contribution to R&D performance.

Finally, the extent of participation of the Chief Executive Officer (CEO) in the strategic management of technology may also be correlated with R&D performance because of her/his role in both developing and linking technology strategy with overall corporate-level strategy and in shaping the whole innovation process. The fourth system-related hypothesis thus assumes:

H.B.4: More active involvement of the CEO¹⁸ in technology management contributes positively to R&D performance.

Subsection D deals with how firms utilize input from external customers and the market place in the R&D process. It explores how direct customer input is used in technology strategy development, setting program objectives, obtaining innovative ideas, concept development, prototype development, testing, product refinement and commercialization, and product improvement. In addition that subsection tries to determine the structure of the company's process for obtaining customer input, as well as the role and performance of the organizational entities that participate in the process (R&D, marketing, sales).

Customer input is important not only as a source of competitive advantage in determining customer needs and fulfilling them in time with high quality products at the least possible cost. Customer input can also have a major impact in the innovation process as a source of new ideas and product concepts. Von Hippel has documented that manufacturers are not the sole sources of innovation. Users develop most innovations in some fields. In other fields suppliers of components and materials are the typical sources of innovation. Users innovate when they face needs to do so in their marketplace and are positioned to benefit

¹⁷ The strength of the managerial role of the CTO is calculated by averaging the answers to question B.6 for each respondent. More specifically, the CTO's involvement in the following activities are considered in estimating the overall role of the CTO: participation in overall corporate strategy development; formulation of corporate technology strategy development; review of corporate technology strategy; control of resource allocation between corporate and business unit R&D; control of R&D resource allocation across business units; formulation of business unit technology strategy development; review of business unit technology strategy development; participation in business unit technology strategy development; management of the corporate R&D organization; monitoring external technology; determination of the company's investments in outside technologies; assessment of technical strengths of external partners; and liaison to outside organizations.

¹⁸ The degree of involvement of the CEO is calculated by averaging the answers to question B.8 for each respondent. More specifically, the CEO activities considered are his/her participation in: technology strategy development; project selection/prioritization; establishment of overall R&D budget; internal technology resource allocation; and selection of outside technology investments.

significantly (through economic rents, for example) by obtaining a solution to those needs. The implications of this fact for technology management are far reaching. As von Hippel (1988)¹⁹ puts it:

Firms organize and staff their innovation-related activities based on their assumptions regarding the sources of innovation... most firms organize around the conventional assumption that new products are - or should be - developed by the firm that will manufacture them for commercial sale. This leads manufacturers to form R&D departments capable of fulfilling the entire job of new product development in-house and to organize market research departments designed to search for needs instead of innovations.

Indeed, if a manufacturer depends on in-house development of innovations for its new products, then such arrangements can serve well. But if users, suppliers, or others are the typical sources of innovation prototypes that a firm may wish to analyze and possibly develop, then these arrangements can be dysfunctional. (For example, one cannot expect a firm's R&D group to be interested in user prototypes if its engineers have been trained and motivated to undertake the entire product development themselves.)

Not all users can contribute innovative ideas to the firm. Only a small segment of users do so, in particular those labeled by von Hippel as lead users. Lead users are industry participants that experience market and industry conditions that will be common place to other industry members in 3 to 5 years. In addition they have some means to appropriate their innovation benefits and are therefore motivated to generate solutions to their needs. Following von Hippel's research one should therefore hypothesize that firms with high degree of user input in their innovation process might have better R&D performance:

H.D.1: The use of customer inputs in the innovation process²⁰ contributes positively to R&D performance.

Other structures, roles and linkages can be of importance to the innovation process, mainly in moving ideas to market. The last section of Part I of the questionnaire, subsection G, aims at understanding the practices for moving a product or process from concept to implementation. It evaluates the effectiveness of different approaches such as early formation of multi-functional teams, specially designated idea generators, senior management sponsors, computer-aided design/engineering, transfer of key individuals with a project as it moves from development into manufacturing, and so on. The section also

¹⁹ von Hippel, E. The Sources of Innovation. Oxford University Press, 1988.

²⁰ Customer input is calculated by averaging answers to question D.1 for each respondent. Customer input can occur in each of the following activities: technology strategy development; setting program objectives; obtaining innovative ideas; concept development; prototype development; testing; product refinement and commercialization; and product improvement.

assesses each company's perception of its degree of success in meeting or exceeding target dates for product commercialization and process implementation.

To facilitate our analysis, each firm was asked to identify the three approaches that it has found most effective in shortening the time required to move a product to market, one specific aspect of innovation effectiveness. We then selected the most frequently cited of these practices and tested the general hypothesis:

H.G.j: Approach J contributes positively toward meeting target dates for product commercialization and process implementation.

These hypotheses are presented and tested against the empirical evidence later in this paper.

Adjustment Processes Adjustment processes comprise the analysis of an industry's threats and opportunities and a firm's strengths and weaknesses. Subsection E (monitoring and assessing), all of Part II (adjustment processes in the current economic climate), and subsection C (responding to global technological issues) of the questionnaire provide extensive data to test the effects of adjustment policies on R&D performance.

Subsection E explores how firms monitor technology and acquire the requisite technologies and skills to promote success in the markets in which they compete. More specifically, the questionnaire assesses: (i) the degree of a firm's use of different mechanisms of technology monitoring; (ii) the reliance on internal or external sources of technology over time; (iii) the reasons that support acquisition of technologies; (iv) the use of university programs for monitoring and acquisition activities; and (v) perceived changes in the necessary skills of technical employees.

As pointed out earlier commodity producers in the chemicals/materials industry are facing meager returns in their operations. This situation has fostered increasing interest in the higher returns experienced in the specialty segment. The capability of monitoring external technological opportunities either to enter growing specialty markets or to defend itself from competition in other segments is extremely valuable to the firm. One might expect firms that use monitoring mechanisms to have more chance of success in their R&D efforts. It is important to note, however, that technology monitoring has to be coupled with the firm's corporate strategy and strategic intent to be effective. We thus formulate the following hypothesis:

H.E.1: More extensive technology monitoring activities²¹ contribute positively to R&D performance.

Taking this rationale one step further, it can be argued that monitoring activities conducted by internal technology steering groups are different in impact from monitoring activities that incorporate external sources of information (science/technology advisory boards, university/industry consortia, customer panels). Organizational psychology research has shown that professionals work to minimize uncertainty in their surrounding environment. Those professionals develop unconscious underlying assumptions that are very difficult to surface and challenge. Internal technology steering groups are presumably more likely to make decisions based on assumptions that diminish uncertainty. This can have disastrous effects for the organization since important threats can be overlooked. As argued by Katz (1980, 1982)²²:

... individuals, groups, and even organizations strive to structure their work environments to reduce the amount of stress they must face by directing their activities and interactions toward a more predictable level of certainty and clarity. Over time, then, engineers and scientists are not only functioning to reduce technical uncertainty, they are also functioning to reduce their "personal and situational" uncertainty within the organization. In the process ... three broad areas of biases and behavioral responses begin to emerge (problem-solving processes, communication and information processing, and cognitive processes). And the more these trends are allowed to take place and become reinforced, the more difficult it will be for the organization to consider seriously the potential, long-term advantages of the many new and different technologies ... being developed and worked on by the larger outside R&D community.

External sources of information may help to surface unrealistic internal assumptions and foster a more critical evaluation of threats and opportunities that surround the firm. From this perspective the following hypothesis results:

H.E.2: Firms that use external sources in their monitoring process have higher R&D performance than firms that use only internal steering groups or do not use any monitoring mechanism at all.

²¹ The extent of technology monitoring is calculated by averaging the answers to question E.1 for each respondent. Monitoring may be conducted by the following mechanisms: science/technology advisory boards; university research consortia; industry-based consortia; internal technology steering groups; customer panels or input; university liaison/affiliate programs; venture capital funds; and industry suppliers.

²² Katz, R. "Time and Work: Toward and Integrative Perspective", *Res. Org. Behav.*, 2, 1980, 81-127, and "The Effects of Group Longevity on Project Communication and Performance", *Admin. Sci. Q.*, 27, 1982, 81-104.

The R&D organization can also change by responding to shifts in the external environment that are beyond the development of new technologies. Those changes might involve the economic or even political climate in the regions in which a specific firm operates. Part II of the questionnaire was designed to assess the firm's overall experiences with the recent difficult economic climate. Its first section attempts to evaluate how constrained are the resources normally applied to the technological innovation process. This is done by asking firms about: (i) their actual and expected changes in total R&D expenditures, R&D capital investments, and size of the R&D staff from 1988 to 1994; (ii) the breakdown of R&D expenditures (product/process maintenance, short-term development projects, longer-term development projects, and research activity) for 1988, 1991 and 1994; and (iii) the involvement of different decision makers in setting business unit R&D budgets today compared to 2 years ago.

The second section of Part II assesses the management practices that have been adopted to adjust for an era of fewer resources. Four dimensions are addressed by the questionnaire: strategic elements; programs; productivity; and funding. Importantly, these data should be interpreted with care as there is a possibility that most of these practices were implemented recently and have not yet affected perceived R&D performance. Some of the hypotheses that were developed, however, involve measurements that may have a faster effect on R&D performance. Those measures include: (i) stronger managerial accountability; (ii) stronger identification of R&D contribution to profits; (iii) increased automation and other non-human resources in R&D; (iv) streamlining the R&D organization; (v) increased attempts to explore existing technologies; (vi) focus upon core technologies, whether for new markets or new products; (vii) increased external acquisition of technology; and (viii) more stringent requirements for program start-up and continuation. These nine hypotheses are stated below²³:

H.PII.1: Focusing on core technologies contributes positively to R&D performance.

H.PII.2: Increasing external acquisition of technologies instead of internal development contributes positively to R&D performance.

H.PII.3: Stronger managerial accountability contributes positively to R&D performance.

H.PII.4: Increasing automation contributes positively to R&D performance.

²³ All practices are measured by each respondent's answers to question B.1.

H.PII.5: Streamlining the R&D organization contributes positively to R&D performance.

H.PII.6: Adopting stricter criteria for new program start-up contributes positively to R&D performance.

H.PII.7: Adopting more stringent requirements for program continuation contributes positively to R&D performance.

H.PII.8: Adopting tighter measurements contributes positively to R&D performance.

H.PII.9: Searching for additional sources of external funding contributes positively to R&D performance.

Finally, subsection C of Part I explores the internationalization of the R&D process. The idea is to gather information on: the countries in which non-domestic technological activities are conducted; the types of technological activities that are conducted (licensing, joint technology development, acquisition of companies, own laboratory research); the changes in the extent of activities that are based in foreign locations over time; the roles and activities of non-domestic R&D centers; the methods used to transfer technology to other countries; the degree and type of technology monitoring activities in other countries; and the reasons for deciding to utilize some forms of non-domestic R&D.

One hypothesis is developed from subsection C. One should expect that global markets would require global capabilities from chemicals/materials firms. Regarding the innovation process, a global presence of R&D activities may foster the ability of companies to learn from different markets, as ideas are likely to originate in Japan, Europe and the U.S. Thus global R&D sources may leverage firm competitiveness if the firm is capable of employing this knowledge in other markets. In this context we hypothesize:

H.C.1: The level of non-domestic activity²⁴ contributes positively to R&D performance.

Subsection F of the questionnaire provides a basis for the possible development of another set of hypotheses via its data collection of several measures of R&D portfolio balance. One might expect that a "well-balanced" technology portfolio should contribute to R&D performance. For example, short-term focus provides quick responses to unexpected opportunities, but medium and long term projects are needed to ensure presence in new

²⁴ The level of non-domestic activity is calculated by averaging the answers to question C.2 for each respondent.

promising markets. In the same manner, a focus on unfamiliar areas of technology and markets contributes to learning and prepares the organization for new challenges, while familiar areas of work lead to strengthening a firm's current products and businesses. Similarly product orientation is a requirement for customer needs satisfaction and a leverage for price premium strategies, whereas process research is critical for cost reduction and safety and quality improvement. While each of these "balance" arguments is true in general, R&D performance in any specific company necessarily depends on the overall corporate-level strategy. For example, if a company's strategy is to focus on niche high value-added markets, we should expect it to spend far more on product innovations than on process cost reduction. This type of "unbalanced" portfolio therefore does not mean that the company will have low R&D performance. Alternatively, more process focus should lead to cost reduction, which may be the right thing to do in a specific industrial segment. As a result, it is not possible to assume that a more balanced technology portfolio will generate better indices of R&D performance, as this is highly dependent on the strategic objectives of the companies.

This section has developed and presented a number of research hypotheses based on the framework of the technological innovation process described by Adler et al.²⁵. Those hypotheses, listed in Table 1, aim at identifying management practices that might importantly impact a firm's overall R&D performance. Following the development of possible outcome measures we test the validity of these hypotheses against empirical data using multiple regression analysis.

Evaluating Industrial R&D Performance: A Multifaceted Approach

"R&D performance" is the key concept used in presenting a target for evaluating the principal hypotheses developed above. In the absence of any well-defined metrics, however, the evaluation of R&D performance is a complex undertaking that involves the personal beliefs and perceptions of the evaluator. To gauge these beliefs and perceptions, subsection F of the questionnaire asked each firm's respondent to evaluate its R&D organization relative to its most important competitor along many different dimensions²⁶. This was done not only in regard to multiple dimensions of impact on the overall company but also in regard to satisfying the objectives of three different sets of "stakeholders". Furthermore, as indicated above, a number of managerial approaches were analyzed with respect to their effect on "time to market", another specific outcome measure that has come

²⁵ Op. cit.

²⁶ Although this procedure does not eliminate entirely the problem of subjectivity, we consider that it is a reasonable way to account for R&D performance, given the limitations involved in survey research.

Table 1. Formulated hypotheses related to R&D performance.

| Element | Hypotheses | Correlate with R&D Performance |
|-----------------------|---|--|
| Posture and Direction | H.A.1 | Well developed, communicated, and accepted technology strategy |
| | H.A.2 | Technology strategy strongly linked to corporate strategy |
| Systems | H.B.1 | Use of multi-functional teams |
| | H.B.2 | Participation of CTO in the board of directors |
| | H.B.3 | Strong managerial role of the CTO |
| | H.B.4 | More active involvement of the CEO in technology management |
| | H.D.1 | Use of customer inputs in the innovation process |
| Adjustment Processes | H.C.1 | Level of non-domestic R&D activities |
| | H.E.1 | More extensive technology monitoring activities |
| | H.E.2 | Use of external sources in the technology monitoring process |
| | H.PII.1 | Focusing on core technologies |
| | H.PII.2 | Increasing external acquisition of technologies instead of int. devlpmt. |
| | H.PII.3 | Stronger managerial accountability |
| | H.PII.4 | Increasing automation |
| | H.PII.5 | Streamlining the R&D organization |
| | H.PII.6 | Adopting stricter criteria for new program start-up |
| H.PII.7 | Adopting more stringent requirements for program continuation | |
| | H.PII.8 | Adopting tighter measurements |
| | H.PII.9 | Searching for additional sources of external funding |

into managerial prominence during the past few years. As a result we present below a multifaceted set of evaluations of the chemicals/materials technology management strategies and practices, with measures of impacts upon: (i) an index of R&D performance; (ii) time from concept to realization of product and process innovation; and (iii) satisfaction of three different stakeholders of the firm's R&D undertakings.

An Index of R&D Performance Several measures were used to construct an index of R&D performance for testing statistically the nineteen hypotheses listed in Table 1. A firm's indexed overall R&D performance is assessed in terms of: (i) effective use of R&D resources; (ii) efficient use of R&D resources; (iii) percentage of the company's revenues derived from products/processes/services not existing 5 years ago; and (iv) success in reducing the company's cost of production over the past 5 years. The index is calculated for each firm by averaging its ratings in these four dimensions.

Time to Market A lumped index was developed of the firm's capability to meet target dates for both product commercialization and process implementation, weighting them equally

because of the high variation among specific firm overall strategies. This index is used to test hypotheses H.G.js.

Satisfaction of Stakeholders Earlier work by the senior author had identified three different major stakeholders of a firm's R&D efforts: (i) the end-use customers of the company's products and services; (ii) those senior officers of the firm who develop and implement the company's overall corporate strategy; and (iii) the manufacturing/operations aspects of the company, the likely immediate beneficiary of process innovation and cost reduction efforts by the R&D organization. Each of these stakeholders was treated separately, given the expectations that different managerial practices might influence each.

Statistical Analyses

R&D Performance

This section uses multiple linear regression techniques to evaluate the validity of the hypotheses developed earlier in regard to possible consequences on R&D performance. Before doing so, however, it is important to evaluate the degree of correlation among these hypotheses. This is a critical step as highly correlated hypotheses limit the effectiveness of a multiple linear regression test.

Table 2 [Correlation matrix.] on the next page presents the auto-correlation matrix of our hypotheses H.A.1 through H.C.1 as presented above. Hypotheses H.E.1 and H.E.2 are highly correlated (0.98), as are hypotheses H.PII.6 and H.PII.7 (0.81). The high degree of correlation between H.E.1 and H.E.2 shows that it is impossible to distinguish, for statistical purposes, between the sample's internal and external mechanisms of technology monitoring. This happens because firms that use external mechanisms also rely heavily in internal mechanisms of monitoring. As a result we decided to eliminate H.E.2 from further analysis and tested only hypothesis H.E.1. Table 2 also indicates that most companies that have adopted more stringent criteria for new program start-up (H.PII.6) have also adopted more stringent requirements for program continuation (H.PII.7). Thus we eliminated hypothesis H.PII.7 and tested only H.PII.6.

With these two omissions the other 17 hypotheses listed in Table 1 were tested against the empirical data collected in the survey. Multiple linear regression analyses determined the statistical significance of the relationship between each specific hypothesis and R&D performance. The statistical test involves a two-tail hypothesis test when no specific

Table 2. Correlation matrix.

| | H.A.1 | H.A.2 | H.B.1 | H.B.2 | H.B.3 | H.B.4 | H.D.1 | H.E.1 | H.E.2 | H.PII.1 | H.PII.2 | H.PII.3 | H.PII.4 | H.PII.5 | H.PII.6 | H.PII.7 | H.PII.8 | H.PII.9 | |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|--|
| H.A.1 | 1.00 | | | | | | | | | | | | | | | | | | |
| H.A.2 | 0.52 | 1.00 | | | | | | | | | | | | | | | | | |
| H.B.1 | 0.25 | 0.29 | 1.00 | | | | | | | | | | | | | | | | |
| H.B.2 | 0.12 | 0.25 | 0.25 | 1.00 | | | | | | | | | | | | | | | |
| H.B.3 | 0.30 | 0.20 | 0.46 | 0.33 | 1.00 | | | | | | | | | | | | | | |
| H.B.4 | 0.19 | 0.27 | 0.62 | 0.11 | 0.25 | 1.00 | | | | | | | | | | | | | |
| H.D.1 | 0.13 | 0.09 | 0.34 | 0.07 | -0.10 | 0.42 | 1.00 | | | | | | | | | | | | |
| H.E.1 | 0.26 | 0.22 | 0.48 | -0.08 | 0.31 | 0.45 | 0.41 | 1.00 | | | | | | | | | | | |
| H.E.2 | 0.20 | 0.14 | 0.48 | -0.07 | 0.30 | 0.42 | 0.39 | 0.98 | 1.00 | | | | | | | | | | |
| H.PII.1 | -0.28 | 0.04 | -0.23 | 0.09 | -0.38 | -0.01 | 0.31 | -0.05 | -0.05 | 1.00 | | | | | | | | | |
| H.PII.2 | -0.13 | -0.03 | -0.03 | -0.07 | -0.18 | 0.15 | 0.15 | -0.22 | -0.20 | 0.33 | 1.00 | | | | | | | | |
| H.PII.3 | -0.02 | 0.17 | 0.28 | 0.24 | 0.13 | 0.39 | 0.24 | 0.13 | 0.12 | 0.09 | 0.41 | 1.00 | | | | | | | |
| H.PII.4 | 0.05 | 0.23 | 0.31 | 0.24 | 0.00 | 0.47 | 0.47 | 0.44 | 0.41 | 0.28 | 0.29 | 0.47 | 1.00 | | | | | | |
| H.PII.5 | 0.15 | 0.28 | 0.03 | -0.01 | -0.17 | 0.15 | 0.23 | 0.16 | 0.06 | 0.03 | 0.15 | 0.20 | 0.56 | 1.00 | | | | | |
| H.PII.6 | -0.01 | 0.31 | 0.14 | 0.43 | 0.12 | 0.34 | 0.21 | 0.04 | 0.06 | 0.35 | 0.23 | 0.48 | 0.50 | 0.03 | 1.00 | | | | |
| H.PII.7 | -0.17 | 0.05 | 0.05 | 0.30 | -0.04 | 0.28 | 0.27 | -0.02 | 0.00 | 0.34 | 0.29 | 0.48 | 0.55 | 0.15 | 0.81 | 1.00 | | | |
| H.PII.8 | -0.19 | 0.02 | 0.16 | 0.06 | -0.05 | 0.35 | 0.52 | -0.03 | -0.01 | 0.39 | 0.58 | 0.42 | 0.27 | -0.03 | 0.24 | 0.36 | 1.00 | | |
| H.PII.9 | -0.08 | 0.14 | -0.11 | 0.02 | -0.14 | -0.16 | 0.06 | -0.04 | -0.10 | 0.20 | 0.14 | -0.12 | 0.03 | 0.29 | -0.06 | -0.02 | 0.20 | 1.00 | |

direction of causality is assumed and a one-tail test is used when a specific direction is expected.

As indicated above R&D performance is estimated by a compound index of each firm's perceptions of its R&D performance against competitors in four dimensions: (i) effective use of R&D resources; (ii) efficient use of R&D resources; (iii) percentage of the company's revenues derived from products/processes/services not existing 5 years ago; and (iv) success in reducing the company's cost of production over the past 5 years. The index is determined by averaging the firm's responses to these four questions.

Table 3 depicts the results of the multiple linear regression analysis on the global

Table 3. Multiple linear regression analysis results: R&D Performance index
(in declining order of statistical significance of the correlation).

| Hypotheses | Correlate | t-Student | p-value |
|------------|-----------------------------|-----------|---------|
| H.A.1 | Acc. of technology strategy | 3.001 | 0.01 |
| H.A.2 | Linked tech-corp strat. | 2.459 | 0.02 |
| H.B.4 | CEO involvement | 2.149 | 0.04 |
| H.B.1 | Multi-functional teams | 1.69 | 0.10 |
| H.PII.6 | Stricter start-up criteria | 1.2804 | 0.21 |
| H.PII.3 | Strong mgrl accountability | 1.254 | 0.22 |
| H.E.1 | Technology monitoring | 1.057 | 0.30 |
| H.PII.1 | Core technology focus | 1.025 | 0.31 |
| H.PII.5 | Streamlining R&D org. | 0.9679 | 0.34 |
| H.PII.4 | Increased automation | 0.857 | 0.40 |
| H.D.1 | Customer inputs | 0.827 | 0.41 |
| H.C.1 | R&D internationalization | 0.82 | 0.42 |
| H.B.3 | Stronger role of CTO | 0.73 | 0.47 |
| H.B.2 | CTO on the board | 0.46 | 0.64 |
| H.PII.8 | Tighter measurements | -0.449 | 0.66 |
| H.PII.9 | Additional funding sources | 0.29 | 0.77 |
| H.PII.2 | External tech. acquisition | -0.2537 | 0.80 |

chemicals/materials industry data²⁷. Two broad conclusions can be drawn. First, four (out of 17) tested management of technology policies are positively correlated with R&D performance with 90% or higher confidence levels: development, communication, and acceptance of technology strategy; linkage between technology strategy and corporate-level strategy; involvement of the CEO in the R&D process; and use of multi-functional teams.

²⁷ p-value indicates the level of significance of each hypothesis. For example, there is 0.01% chance that a well developed, communicated and understood technology strategy is randomly correlated with R&D performance (or a 99.99% chance that it is non-randomly correlated).

The first two influential variables are the full representations of the "posture and directions" element of technology management. The latter two factors indicate support for the "systems" element. Unfortunately, none of the hypotheses reflecting the influence of "adjustment processes", the third element of the Figure 1 model, showed statistically significant relations to overall R&D performance as measured here.

Conversely, numerous management practices do not seem to be correlated with R&D performance.²⁸ This is the case, for example, for: the strong involvement of the CTO; CTO on the board; tighter measurements; additional funding sources; and external technological acquisition. Importantly, failure to find significant correlations does not mean that these policies are irrelevant. Statistical limitations of our data may have limited the

establishment of more confident correlations. In the case of the role of the CTO, for example, the underlying data show that most chemical companies' CTOs have very similar roles. This limits our ability to distinguish among firms' practices and their respective R&D performance, which consequently limits our ability to assess the correlation between these variables. It would be hard to argue here, for example, that active CTOs do not make a difference in R&D performance. In addition, the size of the sample (29 data points) may limit a more accurate evaluation of those management practices.

Time for Product Commercialization and Process Implementation

Next we assess the relationships between management of technology practices and the capability of the firm to meet product commercialization and process implementation target dates. We use the hypotheses H.G.j developed earlier and test them against a lumped index of the firm's capability to meet target dates for both product commercialization and process implementation. The statistical tests are based on multiple linear regression analysis and follow the same rationale as the tests conducted above. Recalling our earlier discussion, we had:

H.G.j: Approach J contributes positively to meeting target date for product commercialization and process implementation.

The questionnaire asked firms to list three approaches that they had found most effective in shortening the time needed to move a product or process from concept to implementation. Table 4 presents the seven most used approaches to move innovations faster from concept to

²⁸ More formally, 13 of the hypotheses fail to disprove the null hypothesis.

Table 4. Most used managerial practices to move products/processes to market.

| Managerial approaches | Times listed by the sample | Hypotheses |
|------------------------------|----------------------------|------------|
| Multi-functional teams | 17/29 | H.G.1 |
| Transfer of professionals | 13/29 | H.G.2 |
| Early market test | 8/29 | H.G.3 |
| Senior sponsors | 7/29 | H.G.4 |
| Stronger mgrl accountability | 7/29 | H.G.5 |
| Total Quality Management | 5/29 | H.G.6 |
| Simultaneous Engineering | 4/29 | H.G.7 |

implementation and the respective hypotheses that were tested against the empirical data. A correlation matrix was developed to assess the relationships among these hypotheses. Table 5 depicts the results. Note that there are no high correlations among the hypotheses. As a result, the multiple linear regression analysis includes all seven of them.

Table 5. Correlation matrix among hypotheses H.G.j.

| | H.G.1 | H.G.2 | H.G.3 | H.G.4 | H.G.5 | H.G.6 | H.G.7 |
|-------|-------|-------|-------|-------|-------|-------|-------|
| H.G.1 | 1.00 | | | | | | |
| H.G.2 | 0.01 | 1.00 | | | | | |
| H.G.3 | 0.13 | 0.27 | 1.00 | | | | |
| H.G.4 | 0.19 | 0.13 | 0.34 | 1.00 | | | |
| H.G.5 | 0.36 | 0.32 | 0.34 | 0.47 | 1.00 | | |
| H.G.6 | 0.44 | 0.30 | 0.41 | 0.48 | 0.33 | 1.00 | |
| H.G.7 | 0.08 | 0.17 | 0.28 | 0.45 | 0.33 | 0.53 | 1.00 |

Table 6 presents the results of the regression analysis. Those managerial options with strongest statistical relationships to a firm's ability to meet target dates for process implementation and product commercialization, four of the seven tested, are: employing stronger managerial accountability, using multi-functional teams, early market test, and use of total quality management methods. Other mechanisms - like transfer of professionals, senior sponsors, and simultaneous engineering had lower statistical significance levels. The size of the sample again limits the testing of still other managerial approaches²⁹, although they may have important influences in reducing time from concept to implementation.

²⁹ Listed in the questionnaire but not included in Table 4.

Table 6. Correlations between managerial options and time from concept to implementation.

| Hypotheses | t-Student | p-value |
|---------------------------|-----------|---------|
| Stronger accountability | 2.3 | 0.03 |
| Multi-functional teams | 2.1348 | 0.04 |
| Early market test | 1.88 | 0.07 |
| Total Quality Management | 1.687 | 0.10 |
| Transfer of professionals | 1.37 | 0.18 |
| Senior sponsors | 1.1575 | 0.26 |
| Simultaneous Engineering | 1.041 | 0.31 |

Satisfying the Stakeholders of the Technological Innovation Process

Finally we determine here possible significant relations between management of technology practices in the global chemicals/materials industry and the satisfaction of multiple stakeholders' needs. Three sets of stakeholders of the technological innovation process have been identified above: (i) end-use customers; (ii) those responsible for corporate strategy; and (iii) the manufacturing function. The analysis was again conducted through calculation of multiple linear regressions between the different managerial strategy options and each firm's perception of the satisfaction of its stakeholders' needs relative to competitors³⁰.

End-Use Customers Table 7 shows the specific managerial options that can improve satisfaction of end-use customers. From the multiple regression analysis those options are: a well structured, communicated, and accepted technology strategy (p=0.027); use of multi-functional teams (p=0.07); use of customer input in the R&D process (p=0.065); stricter criteria for program start-up (p=0.06); and slowing the pace of some programs (p=0.006). The first three approaches all seem to contribute to broader consideration of the various factors that would indeed generate more effective product development. Stricter criteria for starting new programs achieve the same goal. The direction of causality is not as clear to us in regard to the relation between slower program pace and improved customer satisfaction³¹.

³⁰ Data for these tests are given by answers to question F.2.a.

³¹ Slower programs may cause better fulfillment of end-use customer expectations or, alternatively, companies that have been doing a good job in satisfying end-use customers may have felt comfortable in slowing the pace of some programs during the current economic climate. This rationale is also potentially applicable to the use of stricter criteria for new program start-up.

Table 7. Impact of managerial policies on stakeholders' satisfaction levels.

| Managerial Options | End-Use Customers (p-value) | Corporate Strategy (p-value) | Manufacturing (p-value) |
|--|--------------------------------|---------------------------------|----------------------------|
| Acceptance of technology strategy | 0.027 | 0.065 | 0.08 |
| Linked technology and corporate strategies | 0.125 | 0.04 | 0.245 |
| CTO on the board | 0.39 | 0.035 | 0.145 |
| Strength of CTO role | 0.145 | 0.1 | 0.075** |
| Multi-functional teams | 0.07 | 0.042 | 0.068 |
| CEO involvement with technology | 0.511 | 0.033 | 0.387 |
| Customer inputs | 0.065 | 0.707 | 0.623 |
| Highly structured customer input | 0.915 | 0.348 | 0.269 |
| Technology monitoring | 0.827 | 0.458 | 0.232 |
| Less ambitious objectives for technology | 0.421 | 0.005** | 0.395 |
| Focus on core technologies | 0.331 | 0.898 | 0.085 |
| Increase external acquisition of technologies | 0.349 | 0.098 | 0.688 |
| Exploit existing technologies | 0.734 | 0.089 | 0.085 |
| Stricter criteria for new program startup | 0.06 | 0.573 | 0.726 |
| More stringent requirements for program contin | 0.453 | 0.841 | 0.947 |
| Slow the pace of some programs | 0.006 | 0.385 | 0.574 |
| Reduction in number of products/processes | 0.3 | 0.202 | 0.979 |
| Tighter measurements (R&D \$/employee ...) | 0.308 | 0.484 | 0.431 |
| Stronger managerial accountability | 0.389 | 0.433 | 0.629 |
| Stronger ident. of R&D contribution to profits | 0.274 | 0.393 | 0.271 |
| Increased automation in R&D | 0.885 | 0.324 | 0.281 |
| Streamlining R&D organization | 0.817 | 0.061 | 0.219 |
| Additional funding sources | 0.145 | 0.619 | 0.329 |
| Idea generators | 0.87 | 0.375 | 0.324 |
| Product champions | 0.242 | 0.231 | 0.587 |
| Senior sponsors | 0.319 | 0.355 | 0.965 |
| Permanent project managers | 0.498 | 0.065 | 0.429 |
| Stage gate system | 0.217 | 0.388 | 0.378 |
| Simultaneous engineering | 0.699 | 0.437 | 0.378 |
| Total Quality Management | 0.455 | 0.197 | 0.888 |
| Flexible manufacturing systems | 0.633 | 0.635 | 0.281 |
| Rapid prototyping techniques | 0.583 | 0.874 | 0.51 |
| CADE/CAM | 0.994 | 0.532 | 0.397 |
| QFD | 0.517 | 0.169 | 0.915 |
| Early concept freezing | 0.549 | 0.903 | 0.722 |
| Early market test | 0.708 | 0.442 | 0.081 |
| Reduce number of parts | 0.197 | 0.819 | 0.738 |
| Transfer of professionals | 0.652 | 0.075 | 0.928 |

** Negative correlation; **bold** indicates statistical significance <0.10

Corporate Strategy Fulfillment of overall corporate strategy needs appears to be improved by: the utilization of multi-functional teams (p=0.042); a well developed, communicated and accepted technology strategy (p=0.065); powerful and actively participating CTOs (p=0.10 and p=0.035) and CEOs (p=0.033); a strong linkage between

technology strategy and corporate-level strategy (p=0.04); and using permanent project managers (p=0.065). All of these undertakings are prima facie contributors to tying together technological and overall corporate interests, including project managers who take on longer term understandings and incentives. Statistically significant satisfaction of corporate strategy stakeholders also relates to the firm's actions to transfer professionals in response to economic constraints (p=0.075), better exploit the use of existing technologies (p=0.089), increase acquisition of external technologies (p=0.098), and streamline the R&D organization (0.061). Each of these strategies is obviously responsive to resource constraint perspectives in the corporation. Importantly, and consistent with our own beliefs, the data show a strong negative correlation between adopting less ambitious strategic objectives for technology and satisfying corporate strategy objectives for technology (p=0.005).

Manufacturing Regarding the needs of manufacturing, several managerial options enhance that objective: multi-functional teams (p=0.068); early market test (p=0.081); development, communication and acceptance of technology strategy (p=0.08); focus upon core technologies (p=0.085); and exploiting existing technologies (p=0.085). The focus upon core and existing technologies seems especially relevant to manufacturing effectiveness, particularly during a period when resources are generally constrained. Note incidentally that a technology portfolio heavily into unfamiliar technologies would limit the organization's capability to satisfy manufacturing needs. Importantly, those companies with CTOs who are strongly involved in technology strategy determination are less likely (negative correlation) to be satisfying manufacturing needs (p=0.075). This may indicate a critical gap between the priorities of many Chief Technology Officers in chemicals/materials companies and manufacturing's objectives and interests in those firms.

Table 8 summarizes the effective managerial strategy options that most clearly impact the three sets of stakeholder's needs.

Table 8. R&D stakeholders and managerial strategy options (all statistically significant, but listed in declining order).

| <u>End-Use Customers</u> | <u>Corporate Strategy</u> | <u>Manufacturing</u> |
|----------------------------------|--------------------------------------|--------------------------------|
| Slow the pace of some programs* | Less ambitious objective for tech.** | Multi-functional teams |
| Dev. and acc. of tech strategy | CEO involvement in R&D process | Early market test |
| Customer inputs | CTO sits on board | Dev. and acc. of tech strategy |
| Multi-functional teams | Linked tech and corp strategies | Focus on core technologies |
| Stricter criteria, program setup | Multi-functional teams | Exploit existing technologies |
| | Dev. and acc. of tech strategy | |

Streamlining R&D organization
Permanent project managers
Transfer of professionals
Increase external acquisition of tech
Exploit existing technologies
Strength of CTO role

* Possible coincidental, rather than causal, relationship

** Negative correlation

Discussion and Conclusions: Sound Strategies for Improving Industrial R&D Performance

The analyses presented here on data drawn from a broad global sample of major chemicals/materials companies demonstrate that firms that adopt specific management of technology strategies consistently have higher overall R&D performance, higher capability of meeting target dates for product commercialization or process implementation, and higher likelihood of satisfying their major stakeholders. These policies form organizational systems that improve the technological innovation process regardless of regional/national or a firm's corporate strategy characteristics.

The four managerial approaches that were found to improve indexed R&D performance most strongly are³²:

- Higher formulation, communication, and acceptance of technology strategy (p=0.01);
- Stronger linkage between overall corporate strategy and technology strategy (p=0.02);
- More active involvement of the Chief Executive Officer in the innovation process (p=0.04); and
- Greater use of multi-functional teams in product and process development (p=0.10).

The four managerial policies that were found to diminish time from concept to product or process implementation are:

- Stronger managerial accountability of R&D and project managers (p=0.03);
- Use of multi-functional teams (p=0.04);
- Early market test of product innovations (p=0.07); and
- Use of the Total Quality Management approach (p=0.10).

³² The lower the p-value, the higher is the statistical significance of the statistical test.

Managerial approaches that were found to most effect satisfaction of the firm's stakeholders vary among the three different targets. Statistically significant impacts upon all three sets of stakeholder goals result from two sets of practices:

- Development and acceptance of technology strategy; and
- Use of multi-functional teams.

Table 9 summarizes the most important managerial policies that influence the multifaceted measures of effectiveness of the R&D process in the worldwide chemicals/materials industry. These are clustered in terms of the three elements of the Figure 1 strategic management of technology framework that has been applied throughout this paper. Table 9 demonstrates that the study provides important support for the framework, especially in regard to the strong contribution of (i) Posture and Direction and (ii) Systems: Roles, Structures and Linkages.

Table 9. Managerial opportunities for influencing R&D outcomes: levels of statistical significance of approaches with multiple significant relationships (all rounded off to two significant figures).

| <u>Managerial Approach</u> | <u>Indexed R&D Performance</u> | <u>Time to Market</u> | <u>End-Use Customers</u> | <u>Corporate Strategy</u> | <u>Manufacturing</u> |
|--|------------------------------------|-----------------------|--------------------------|---------------------------|----------------------|
| Posture and Direction | | | | | |
| Accptd technology strategy | 0.01 | | 0.03 | 0.06 | 0.08 |
| Linked tech-corp strategy | 0.02 | | 0.12 | 0.04 | |
| Systems: Roles, Structures and Linkages | | | | | |
| Multi-functional teams | 0.10 | 0.04 | 0.07 | 0.04 | 0.07 |
| Strength of CTO role | | | 0.14 | 0.10 | -0.07 |
| CEO involvement with tech | 0.04 | | | 0.03 | |
| Adjustment Processes | | | | | |
| Early market test | | 0.07 | | | 0.08 |
| Exploit existing technology | | | | 0.09 | 0.08 |

The strategies and tactics highlighted here do not require extensive financial investments. On the other hand, they may well involve considerable organization-wide efforts. Furthermore, some of these managerial approaches with greatest effect are not directly controlled. Rather they in turn reflect a broader set of organizational capabilities. This is the case, for example, with both technology strategy acceptance as well as with the effective use of multi-functional teams. These and other factors affecting overall R&D performance may require changes in underlying organizational attitudes and philosophy.

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