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Towards the Fifth-generation Innovation Process

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Introduction

Today manufacturing companies are faced with intensifying competition and a turbulent economic environment. To some extent technology is seen as a means by which firms can strive to adapt to the requirements of this difficult and uncertain environment. On the other hand rapid rates of technological change and associated shorter product cycles are themselves part of the difficulty, as is the increased blurring of long-established industrial boundaries — Kodama's (1985) process of "technological fusion". The growing complexity and pace of industrial technological change are forcing firms to forge new vertical and horizontal alliances and to seek greater flexibility and efficiency in responding to market changes. This adaptation process is leading some companies towards greater and more strategically directed integration and networking with external agencies, and to the adoption of a sophisticated electronic toolkit in their design and development activities to enhance developmental flexibility, speed and efficiency. In the language of this article, these leading edge innovators are beginning to take on elements of the fifth-generation (5G) innovation process. Developments towards the 5G innovation process are described below.

The First-generation Innovation Process (1950s — Mid-1960s)

During the first 20 years or so following the Second World War, the advanced market economies enjoyed unparalleled rates of economic growth largely through rapid industrial expansion. There was the emergence of new industries based largely on new technological opportunities, e.g. semiconductors, pharmaceuticals, electronic computing and synthetic and composite materials; at the same time there was the technology-led regeneration of existing sectors, e.g. textiles and steel, and the rapid application of technology to enhance the productivity and quality of agricultural production. These developments resulted in rapid employment creation, rising prosperity and an associated consumer boom, leading to rapid growth of the consumer white goods, consumer electronics and automobile industries, with demand during the earlier years sometimes exceeding production capacity (Freeman *et al.*, 1992).

During this period attitudes in society at large were generally favourable towards scientific advance and industrial innovation, and science and technology were seen to have the potential for solving society's greatest ills.

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These attitudes were reflected at governmental level and public technology support policies focused largely on the supply side, i.e. on stimulating scientific advance in universities and government laboratories and the supply of skilled manpower, with some financial support for major R&D programmes in companies (normally, in the United States, in relation to defence and space requirements). In manufacturing companies the main corporate emphasis was on R&D to create new product ranges and on manufacturing build-up to satisfy the burgeoning demand for them.

Under the above conditions it is not, perhaps, surprising that the process of the commercialization of technological change, i.e. the industrial innovation process, was generally perceived as a linear progression from scientific discovery, through technological development in firms, to the marketplace. This first generation, or technology push, concept of innovation (Figure 1) assumed that “more R&D in” resulted in “more successful new products out”. With one or two notable exceptions, little attention was paid to the transformation process itself (Carter and Williams, 1957) or to the role of the marketplace in the process (Cook and Morrison, 1961).

The Second-generation Innovation Process (Mid 1960s — Early-1970s)

Towards the second half of the 1960s, while manufacturing output continued to grow, and general levels of prosperity remained high, in many countries manufacturing employment was more or less static or grew at a much reduced rate, while manufacturing productivity increased considerably (Rothwell and Soete, 1983). During this period of relative prosperity there was corporate emphasis on growth, both organic and acquired, and a growing level of corporate diversification. Levels of industrial concentration increased with more importance being placed on static scale economies. While new products were still being introduced, these were based mainly on existing technologies, and in many areas supply and demand were more or less in balance.

During this period of intensifying competition, investment emphasis began to switch from new product and related expansionary technological change towards rationalization technological change (Clark, 1979; Mensch *et al*., 1980). This was accompanied by growing strategic emphasis on marketing, as large and highly efficient companies fought for market share. Perceptions of the innovation process began to change with a marked shift towards emphasizing demand side factors, i.e. the market place. This resulted in the emergence of the second generation or “market-pull” (sometimes referred to as the “need-pull”), model of innovation shown in Figure 2. According to this simple sequential model, the market was the source of ideas for directing R&D, which had a merely reactive role in the process.

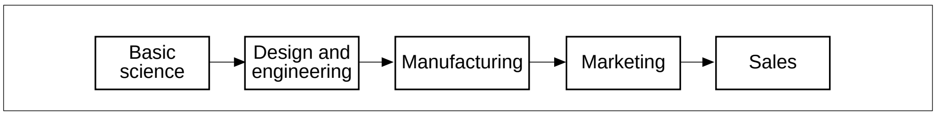


Figure 1.
Technology Push
(First Generation)

One of the primary dangers inherent in this model was that it could lead companies to neglect long-term R&D programmes and become locked in to a regime of technological incrementalism as they adapted existing product groups to meet changing user requirements along maturing performance trajectories (Hayes and Abernathy, 1980). In doing so they ran the risk of losing the capacity to adapt to any radical market or technological changes that occurred.

During the latter part of this period, at least in the United States, public policymakers began emphasizing more the importance of demand side factors. This resulted in some experimentation in using public procurement as a means to stimulate industrial innovation, both at the national and local levels, further stimulating the shift in perception towards the need-pull model of innovation (Herbert and Hoar, 1982; Roessner, 1979; Rothwell, 1984).

The Third-generation Innovation Process (Early 1970s — Mid-1980s)

The early to late 1970s, with two major oil crises, was a period marked by high rates of inflation and demand saturation (stagflation) in which supply capacity generally outstripped demand, and by growing structural unemployment. Companies were forced to adopt strategies of consolidation and rationalization, with growing emphasis on scale and experience benefits. There was associated concern with accountancy and financing issues leading to a strategic focus on cost control and cost reduction.

During a decade of severe resource constraint it became increasingly necessary to understand the basis of successful innovation in order to reduce the incidence of wasteful failures and, indeed, it was approximately during this period that the results of a number of detailed empirical studies of the innovation process were published (Cooper, 1980; Hayvaert, 1973; Langrish *et al.*, 1972; Myers and Marquis, 1969; Rothwell *et al.*, 1974; Rothwell, 1976; Rubenstein *et al.*, 1976; Schock, 1974; Szakasits, 1974; Utterback, 1975). This meant, for the first time, that the successful innovation process could be modelled on the basis of a portfolio of wide-ranging and systematic studies covering many sectors and countries. Essentially, these empirical results indicated that the technology-push and need-pull models of innovation were extreme and atypical examples of a more general process of interaction between, on the one hand, technological capabilities and, on the other, market needs (Mowery and Rosenberg, 1978). This third generation interactive, or "coupling", model of innovation is illustrated in Figure 3. The coupling model can be regarded as:

> a logically sequential, though not necessarily continuous process, that can be divided into a series of functionally distinct but interacting and interdependent stages. The overall pattern

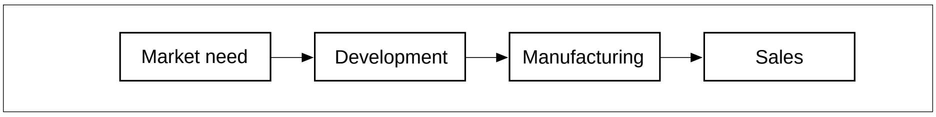


Figure 2.
Market Pull
(Second Generation)

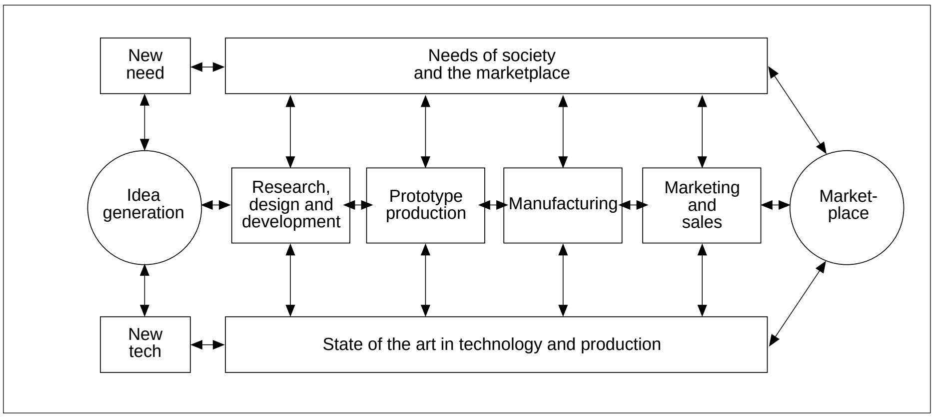


Figure 3.
The "Coupling" Model of Innovation (Third Generation)

> of the innovation process can be thought of as a complex net of communication paths, both intra-organizational and extra-organizational, linking together the various in-house functions and linking the firm to the broader scientific and technological community and to the marketplace. In other words the process of innovation represents the confluence of technological capabilities and market-needs within the framework of the innovating firm (Rothwell and Zegveld, p. 50).

The third-generation innovation model was seen by most western companies, certainly up to the mid-1980s or so, as presenting best practice. It was still essentially a sequential process, but in this case with feedback loops.

There were many similarities between the results of the spate of innovation research projects undertaken during this period which, between them, covered many countries and sectors and included firms of all sizes. There were, however, in some cases strong inter-sectoral differences concerning the rank order of importance of the different factors (Rothwell *et al.*, 1974). These factors are divisible, according to Rothwell (1992b), into two groups, namely, project execution and corporate level:

(1) *Project execution factors:*
- Good internal and external communication: accessing external know-how.
- Treating innovation as a corporate wide task: effective inter-functional coordination: good balance of functions.
- Implementing careful planning and project control procedures: high equality up-front analysis.
- Efficiency in development work and high quality production.
- Strong marketing orientation: emphasis on satisfying user needs: development emphasis on creating user value.
- Providing a good technical and spares service to customers: effective user education.

- Effective product champions and technological gatekeepers.
- High quality, open-minded management: commitment to the development of human capital.
- Attaining cross-project synergies and inter-project learning.

(2) *Corporate level factors:*

- Top management commitment and visible support for innovation.
- Long-term corporate strategy with associated technology strategy.
- Long-term commitment to major projects (patient money).
- Corporate flexibility and responsiveness to change.
- Top management acceptance of risk.
- Innovation-accepting, entrepreneurship-accommodating culture.

These studies showed that success or failure could rarely be explained in terms of one or two factors only; rather explanations were multi-factored. In other words, success was rarely associated with performing one or two tasks brilliantly, but with doing most tasks competently and in a balanced and well co-ordinated manner. At the very heart of the successful innovation process were “key individuals” of high quality and ability; people with entrepreneurial flair and a strong personal commitment to innovation.

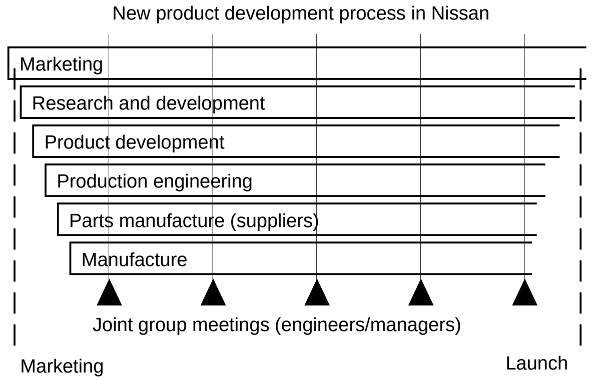
Fourth-generation Innovation Process (Early 1980s—Early 1990s)

The early 1980s heralded a period of economic recovery with companies initially concentrating on core businesses and core technologies (Peters and Waterman, 1982). This was accompanied by a growing awareness of the strategic importance of evolving generic technologies, with increased strategic emphasis on technological accumulation (technology strategy). The emergence of new generations of IT-based manufacturing equipment led to a new focus on manufacturing strategy (Bessant, 1991). The notion of global strategy emerged (Hoad and Vahlne, 1988), and there was a rapid growth in the number of strategic alliances between companies (Contractor and Lorange, 1988; Dodgson, 1993; Hagedoorn, 1990), often with government encouragement and support (Arnold and Guy, 1986; Haklisch *et al.*, 1986; Rothwell and Dodgson, 1992). Not only large firms, but also innovative small firms were engaging in intensive external networking activity (Docter and Stokman, 1987; Rothwell, 1991). Shortening product life cycles meant that speed of development became an increasingly important factor in competition leading firms to adopt so-called time-based strategies (Dumaine, 1989). A crucial feature of this period was the recognition in the West that the remarkable competitive performance of Japanese companies in world markets was based on considerably more than the combination of technological imitation, JIT relationships with primary suppliers and efficient, quality-oriented production procedures. The Japanese, it was realized, were powerful innovators in their own right and there were features of the Japanese new product development system that enabled them to innovate more rapidly and efficiently than their Western counterparts.

Two of the salient features of innovation in leading Japanese companies (the basis of the fourth-generation innovation model) are *integration* and *parallel development*. Innovating Japanese companies integrate suppliers into the new product development process at an early stage while at the same time integrating the activities of the different in-house departments involved, who work on the project simultaneously (in parallel) rather than sequentially (in series). This so-called “rugby” approach to new product development (Imai *et al*., 1985) is one of the factors contributing to high Japanese production efficiency through the process of “design for manufacturability”. Even when completely simultaneous development is not possible or, as in the case of science-based sectors such as pharmaceuticals not necessary, a degree of functional overlap with intensive information exchange is essential. A usefully illustrative example of the fourth generation, or integrated, innovation process as practised in Nissan is given in Figure 4 (Graves, 1987). Many leading Western companies are today striving to master the essential features of this fourth generation process.

Towards the Fifth-generation Innovation Process

Today many of the strategy trends established during the 1980s continue, with some intensifying in importance. Leading companies remain committed to technological accumulation (technology strategy); strategic networking continues; speed to market (time-based strategy) remains of importance; firms are striving towards increasingly better integrated product and manufacturing strategies (design for manufacturability); greater flexibility and adaptability are being sought (organizational, manufacturing, product); and product



Source: Graves 1987

Note: This representation of fourth generation focuses essentially on the two primary internal features of the process, i.e. its parallel and integrated nature. Around this in practice is the web of external interactions represented in the third generation process (Figure 3)

Figure 4.
Example of the Integrated (Fourth Generation) Innovation Process

strategies are more strongly emphasizing quality and performance features. In addition, growing concern over the degradation of the physical environment, which is resulting in intensifying regulatory activity, is once again placing regulatory issues firmly on the corporate strategy agenda (Rothwell, 1992a). At the same time that companies are attempting to implement this complex set of strategies, the world economy has faltered following the period of rapid growth around the mid-1980s, and levels of unemployment and business failure rates have grown apace, with many companies struggling hard to remain in profit.

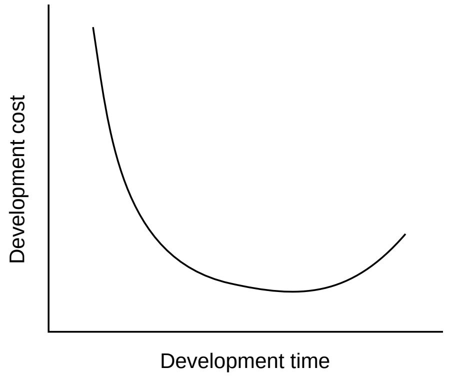
Of the various dominant elements of corporate strategy mentioned above, perhaps the one that has attracted most attention during the late 1980s and the early 1990s is that of speed of development. Being a "fast innovator" is seen increasingly as an important factor determining a company's competitiveness, especially in areas where rates of technological change are high and product cycles are short. Thus, during a period of increasing resource constraints, many companies are faced with the need to accelerate product development rates in an intensely competitive environment.

Being first to market with a new product or new model that offers customers economic benefit carries with it certain obvious advantages such as greater market share, experience curve benefits, monopoly profits and increased customer satisfaction (Reiner, 1989). Being late to market, on the other hand, can carry significant penalties in terms of reduced market share and profitability, especially where product life is short (Rudolph, 1989). Even in cases where being first is not of paramount importance, the ability to be "fast" or "timely" can be advantageous. *Certainly the ability to control product development speed can be seen as an important core competence.*

An important aspect of the speed of development issue is the question of the influence of speed on cost. In other words, does it cost more to be faster at product development? On the face of it, a reasonable answer would be "yes" since simply doubling resources should reduce development times significantly. This would, however, carry with it not just direct costs, but also opportunity costs, perhaps most notably scope diseconomies in reducing the size of the product development portfolio (assuming the company does not at the same time double overall development resources, an unlikely occurrence). Attempting significantly to increase development speed with no multiplication of resources, on the other hand, might carry "hidden" costs such as increased errors and an aversion to attempting more radical innovation (Crawford, 1992).

Several authors have suggested that there is a time/cost trade off such that as development times shorten, development costs do in fact increase. According to Graves (1989), for example, compressing development time by 1 per cent can increase costs by between 1 and 2 per cent or more. Gupta and Wileman (1990) propose a U-shaped curve (Figure 5) and, referring to the work of Mansfield (1988) they state that:

> . . . Mansfield observed that innovation time can generally be reduced by increasing innovation cost . . . he observed that even though Japanese firms operate further left than US firms on the time/cost curve, they are willing to devote twice as many resources to accomplish



Source: Gupta and Wileman (1990)

Figure 5.
Product Development Time/Cost Relationships

> time reduction. So the trade-off between cost and time, based on expected future profitability of innovation, becomes an important issue. Paying the cost of acceleration may be worth it if the project delivers value to the customers. (Gupta and Wileman, 1990, p. 12).

In considering the time/cost trade-off it is clear that a number of factors need to be considered, amongst the most important of which are:

- the direct benefits of being first (or fast) to market;
- the direct costs of accelerating product development;
- the indirect costs of accelerating product development;
- the influence of timeliness on customer satisfaction;
- the penalties accompanying lateness;
- the short-term versus the long-term perspective.,

If a company is faced with trade-offs between being late, being sub-optimal in production efficiency and spending more on R&D then, *ceteris paribus*, in terms of reduction in profit over the product's life, the latter option generally is the least costly while the first option is the most costly (Sommerlatte, 1990).

A U-shaped cost/time curve suggests that there is an optimum range of development times across which firms can enjoy minimum development costs. It seems unlikely, however, that there is a single curve that applies equally to all technologies and sectors and we might expect sectoral specificities. Several authors, in making US/Japanese comparisons, have shown that Japanese companies can develop products faster *and* at reduced cost in sectors as diverse as marine transmissions (Stalk and Hout, 1990), automobiles (Clark and Fujimoto, 1989) and machinery and instruments (Mansfield, 1988). This suggests either that the Japanese firms were operating near the bottom of the U while the US companies were too far over to the right in the respective sectors, or that Japanese and US companies were operating along different U curves (Figure 6). It seems reasonable to suggest that the US companies were operating

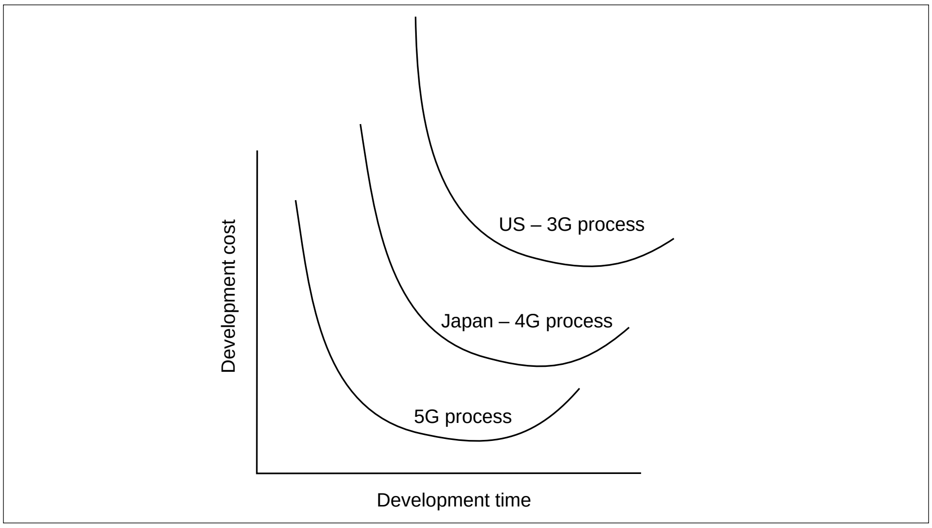


Figure 6.
Product Development Time/cost Relationships for 3G, 4G and 5G Innovation Processes

largely within the framework of the third generation innovation process, while the Japanese companies were operating within the framework of the fourth generation process which is inherently more efficient. Studies by Graves (1991) strongly support this contention in the specific case of the automobile industry. Certainly the author has been unable to discover evidence suggesting that Japanese firms are faster but more costly in their product development activities than their US counterparts.

There exists evidence to suggest that a number of leading innovators today are adopting a variety of practices that are now shifting them towards a third and even more favourable cost/time curve, i.e. towards even faster development speed and greater efficiency. These practices include internal organizational features, strong inter-firm vertical linkages, external horizontal linkages and, more radically, the use of a sophisticated electronic toolkit. The organization, practice, technology and institutional scope of product development in leading innovators, taken together, represent a shift towards the fifth generation innovation process, a process of systems integration and networking (SIN).

The process 5G is essentially a development of the 4G (parallel, integrated) process in which the technology of technological change is itself changing.

Twenty-four factors have been identified as being involved in increasing development speed and efficiency are listed below. Some of them impact mainly on speed, some on efficiency, while others offer improvement along both dimensions. Many of these factors are far from new and are well established in the literature on successful industrial innovation (Rothwell, 1992b). They are:

(1) *An explicit time-based strategy.* Given the scope of activities that needs to be addressed in order to accelerate product development appreciably, it is unlikely that significant gains could be achieved unless the issue was tackled on a broad front. This means that being a fast innovator must be at the forefront of corporate strategy.

(2) *Top management commitment and support.* Visible top management commitment and support is a significant factor in determining successful innovation. It is also important in achieving faster product development speed (McDonough and Barczac, 1991). Certainly the lack of senior management support is a major reason for product development delays, and without this support speed is unlikely to become a feature of corporate culture (Gupta and Wileman, 1990). Moreover, top management should be involved in the development process from the very beginning since, where late involvement occurs, this often results in design changes that are highly costly (Sommerlatte, 1990).

(3) *Adequate preparation: mobilizing commitment and resources.* This comprises what Ansoff (1992) terms building platforms for change. It involves careful project evaluation, analysis and planning and, centrally, gaining commitment, understanding and support from the corporate entity and from staff who will be involved in the project. Gaining consensus helps to prevent projects facing a “resistance ladder” to change. In addition platform building involves adequate training and the acquisition of new skills where necessary.

(4) *Efficiency at indirect development activities.* Activities such as project control, project administration and co-ordination can account for up to 50 per cent of total project development time (Sommerlatte, 1990). Clearly, actions that render these activities more efficient have potential for significantly reducing development times and costs.

(5) *Adopting a horizontal management style with increased decision making at lower levels.* The greater empowerment of managers at lower levels reduces the number of approvals required, and the reduction in hierarchy reduces approval delays (Dumaine, 1989). These should contribute to enhancing the efficiency of indirect development activities, not least through reducing communication complexity and facilitating decision making.

(6) *Committed and empowered product champions and project leaders.* Empowered product champions and project leaders (and *shusas* in Japan) (Graves, 1991) can play an important role in achieving both successful and faster new product development (Gupta and Wileman, 1990; Rothwell and Teubal, 1977). In projects with technical leaders, their possession of general business skills in addition to their technical capabilities is important to achieving greater development speed (McDonough and Spital, 1984). Development speed is also associated with a participative style of project leadership (McDonough and Barczac, 1991).

(7) *High quality initial product specification (fewer unexpected changes).* Not surprisingly, when the initial definition of product requirements is

flawed, it results in unplanned changes during product development and can be a major factor in delay (Gupta and Wileman, 1990). It will also add significantly to development costs. High quality up-front analysis including, centrally, a deep understanding of user requirements, is therefore essential in firms committed to speedier and more efficient product development.

(8) *Use of integrated (cross-functional) teams during development and prototyping (concurrent engineering).* This is what Imai *et al.* (1985) refer to as the "Rugby" approach to product development. It is the core of innovation as a parallel process. Where parallel activities take place outside the framework of the fully integrated team, then continuous inter-functional interaction (information integration) is essential throughout the periods of functional overlap (Clark and Fujimoto, 1991). The concurrent approach to product development is also known as simultaneous engineering. Especially at the design/manufacturing interface, the use of CAD systems can increase development speed and efficiency while at the same time ensuring optimum "manufacturability". Concurrent engineering ensures that most significant design changes occur during early development phases when the cost of modification is relatively low.

(9) *Commitment to across-the-board quality control.* A company clearly can speed up product development if it is willing to cut corners in the process. In doing so, however, it is likely to incur high downstream costs and delays when it is faced with remedial design activity. Sometimes the results of skimped early stage design activity show up only following commercial launch when direct modification costs are extremely high, as are indirect costs due to damaged reputation. According to Hewlett Packard (1988) total quality control in product development is an essential feature in raising overall product development efficiency, including reduced cycle times.

(10) *Incremental development strategy.* There is evidence to suggest that one reason Japanese manufactures achieve relatively rapid product cycles is that they aim for smaller technological steps between successive models (Clark and Fujimoto, 1989). This "small-step" strategy is aided by the fact that each model in the series is subjected to continuous improvement over its life cycle. Using this approach ensures that new technology is, in general, incorporated into products sooner to the greater satisfaction of customers. It also facilitates manufacturing start-up of successive models. Over-emphasis on "cheap and easy" incremental changes does, however, carry the danger that more radical changes with high long-term profit potential can be rejected or ignored (Crawford, 1992).

(11) *Adopting a "carry-over" strategy.* This refers to the utilization of significant elements of earlier models in the most recent designs.

Examples are the use in the new Airbus A330 and A340 aircraft of existing wide-body fuselage cross-sections and the A310 tail fin, and the use in the top-of-the-range Toyota Lexus of a modified version of the floor pan of the well-established and successful Camry. This strategy can not only increase development speed and reduce development costs, but it can also reduce manufacturing start-up costs and afford more rapid manufacturing start-up.

(12) *Product design combining the old with the new.* This relates to factor (11) but refers to the use of major elements of existing designs as the basis for creating new product types, rather than new models of existing types. A good example of this was the use by Black & Decker of existing drill components to help create their highly successful hot air (heat gun) paint stripper. The heat gun contained about two thirds of its components in common with the drill, making it a marginal cost device to develop, manufacture, distribute and service. A complete re-design some two years later held very few components in common with the original design, but by then Black & Decker were market leaders with a highly profitable device.

(13) *Designed-in flexibility.* This refers to the creation of designs that contain inherent flexibility or technological slack such that they can be subsequently stretched into a design family of significant variants. With those so-called "robust designs" (they are robust with respect to changing customer requirements and market segmentation), the cost of the original design might be high, but the subsequent costs of creating new family members often over a period of many years, are relatively modest. A good example of a robust design is the Boeing 747. Robust designs enable companies to combine scale and experience economies in production (high commonality of parts) with economies of scope (wide product variety), while at the same time offering the customer enhanced choice of models and enhanced learning benefits in both use and servicing (Rothwell and Gardiner, 1988). The point is that the design family approach is essentially *strategic* in that the speed and efficiency gains accrue over the longer-term.

(14) *Economy in technology.* The economy in technology concept relates, in a sense, to the robust design principle. There are two aspects to this strategy: the first is the aim to apply a particular basic technological capability/understanding across the widest possible range of products (provided this does not jeopardise the overall competitiveness — inclusive cost competitiveness — of the products) (Ruffles, 1986), the second is to design core sub-assemblies that can be used across an extended range of products.

(15) *Close linkages with primary suppliers.* Close and early linkages with suppliers can reduce development costs and increase development speed.

This has long been a feature of product development in Japan, where suppliers can be an integral part of the development process, and today it appears increasingly to be occurring in Europe and the USA with the emergence of true supplier/manufacturer partnerships (Lamming, 1992; Maier, 1988; Rothwell, 1989). Supplier/manufacturer partnerships can also provide considerable advantages downstream from product development:

> Rather than simply demanding that their key suppliers cut costs overnight, as GM is now doing, Chrysler enlisted supplier support to make design and engineering changes that would add value and boost productivity. As a result, Chrysler's parts suppliers have turned in 3,900 suggestions that have saved the company an estimated $156 million in production costs (McWhirter, 1992).

(16) *Up-to-date component database.* Creating a comprehensive, up-to-date database on new component and materials characteristics and availability and the status of preferred suppliers, can facilitate design start-up and reduce the overall design cycle. It can also help ensure that new products contain the best available component/materials technology to the greater satisfaction of users.

(17) *Involving leading-edge users in design and development activities.* Users who are technologically strong and innovation-demanding can assist in increasing development speed and reducing development costs especially if, as in the case of partnering suppliers, they become actively involved in product development. Perhaps the most obvious example of this is when the user is also the inventor of the new product and has created a rough prototype for own use before transferring the design to the manufacturer. In this case, development times are shortened and development costs are effectively subsidized through the user's initial and subsequent design and technological contributions (von Hippel, 1988; Shaw, 1986). Leading edge users can also make a significant contribution to later developments along the product's design trajectory (Rothwell, 1986).

(18) *Accessing external know-how.* Accessing external know-how has long been acknowledged as a significant factor in successful innovation. Gold (1987) argues that the use of external R&D can also speed up new product development, as can buying or licensing-in existing technology. This latter contention is lent some support by Stalk and Hout (1990) who, commenting on the ability of Sun Microsystems to achieve very fast development cycles, state: "Sun will use any off-the-shelf technology if the performance of its workstations can be enhanced. Each new Sun system is said to offer twice the performance of its predecessor for nearly the same price". Mansfield (1988) found, across a range of industries, that both the time and the cost of product development for products that were based mainly on existing external technology were less than for those relying mainly on in-house development, and that the effects were

particularly strong in Japan. McDonough and Barczac (1991), on the other hand, failed to find any relationship between project speed and the use of external technology. Accessing external know-how and licensing-in external technology should reduce the cost of technological development in cases where the firm is seeking to incorporate technology outside its areas of core competence. In cases of technology fusion, external alliances should, on the face of it, help to reduce both the time and the cost of developing radical new products.

(19) *Use of computers for efficient intra-firm communication and data sharing*. Not surprisingly, efficient information flows contribute to efficient product development. Increasingly, computer-based systems are being used to enhance intra-firm information efficiency, e.g.

> In an attempt to simplify information flow, Yoshiro Maruta (president, KAO Corporation, 1989) notes that in his company information is fed directly to those concerned through a computerized information network. Thus, long complex hierarchical communication paths are simplified (Millson *et al*., 1992, p. 58).

During the second half of the 1980s, Black & Decker succeeded in increasing the number of new product introductions while simultaneously reducing product lead times, a process in which computerized linkages played a key role:

> By reorganizing the design staffs and developing a computer-aided design system that links the company worldwide, B&D has been able to halve its design cycle (Stalk and Hout, 1990).

The Hewlett Packard company similarly is achieving significant efficiency gains through its policy of data sharing. Integrated computerized data systems improve manufacturing efficiency and reduce project times (in the specific case of computer storage products by up to 50 per cent). Efficiency gains are especially high when electronic linkages are established across the design/manufacturing interface (integrated CAD/CAE systems).

(20) *Use of linked CAD systems along the production filière (supplier, manufacturer, users).* Not only are electronic (CAD) linkages important across the design/manufacturing interface *within* firms, but they are also a powerful tool for closer integration *between* firms at the supplier/manufacturer and the manufacturer/customer interfaces. For example, electronic manufacturer/supplier design linkages are becoming an increasingly common feature in the design of application-specific semiconductors (ASICs):

> For ASIC design, HP-Computer Peripherals, Bristol, added library parts and created custom links between the design database and the fabrication process used by their ASIC vendor (Hewlett Packard, 1989).

Electronic manufacturer/supplier linkages are also taking place in plastic injection mould manufacturing, and linkages right across the filière are developing in the aeroengine sector. Close customer linkages not only help in reducing lead times, but also in minimizing the number of costly re-makes following customer tests and after normal customer usage.

(21) *Use of fast prototyping techniques*. One of the advantages of the use of information technology in product design is that the 3D-CAD images thus generated can, using a variety of techniques, be rapidly transferred into physical prototypes (Juster, 1992; Kruth, 1991). These can be of considerable value not only for in-house test purposes, but also in gaining early-stage customer feedback. Fast prototyping can significantly reduce development time and cost.

(22) *Use of simulation modelling in place of prototypes*. Replacing physical prototyping by simulation modelling can significantly enhance overall development efficiency. This approach is being utilized increasingly in industries as diverse as automobiles, pharmaceuticals, aero engines, mould manufacturing and electronics. Hewlett Packard's Loveland Instrument Division, for example, uses electronic product development (electronic design, simulation analysis, prototype testing), involving specially developed printed circuit board CAD tools, which has reduced PCB design cycle times from an average of 27 days in 1981 to nine days in 1987: and in pharmaceuticals the notion of "designer drugs" owes much to the use of computer simulation techniques.

Simulation does not obviate the need for physical prototyping completely. Indeed, to omit this practice entirely would in most cases be too risky. Simulation does, however, reduce the number of required physical prototype builds considerably, as well as the time and resources required to reach the final physical prototyping stage of the development cycle.

(23) *Creating technology demonstrators as an input to simulation*. In fields for which the various critical parameters and operating relationships are well understood, simulation modelling can be relatively straightforward (e.g. in circuit design). In other areas, however, basic data have to be generated as inputs to simulation models, and this can have implications for the balance of expenditure between basic and more downstream technological activity. Rolls Royce Aero engines, who have increasingly used simulation techniques to enhance the efficiency of their product development activities, have been compelled to shift from the traditional "make-it-and-break-it" approach to engine development (building and testing a series of physical prototypes, a costly and time-consuming process) to a more scientific approach, in which the percentage of R&D devoted to basic technological understanding has been increased (over a ten year period from about 8 per cent to about 25 per cent) (Ruffles, 1986). The "technology demonstrators" created through this shift to greater basic engineering activity were a crucial input to Rolls Royce's new engine simulation models.

(24) *Use of expert systems as a design aid.* The use of computer-based product design and simulation techniques enables innovators to embark on electronics-based heuristics. Several companies have taken this process further and have developed design-related expert systems. A Hewlett Packard expert system used in HP's electronic test equipment plant, analyses each new printed circuit design and improves manufacturability. This has, over a three-year period, reduced failure rates across 36 products by 84 per cent and manufacturing time by 85 per cent. In Japan, Canon have developed Optex, an expert system for TV camera lens design which, in 1988, saved the company $700,000. As an example of its effectiveness, Optex reduced one design task from six person months (4 people working for one and a half months) to half a person month (1 person working for 2 weeks) (Freigenbaum *et al.*, 1988).

The above list provides some indication of the nature and scope of the actions leading innovator companies are taking to enhance the speed, efficiency and flexibility of their product development activities. These include, centrally, integrated and parallel development processes, strong and early vertical linkages, devolved corporate structures and the use of electronics-based design and information systems. At the same time, as mentioned earlier, innovation has increasingly involved horizontal linkages such as collaborative pre-competitive research, joint R&D ventures and R&D-based strategic alliances, i.e. innovation is becoming more of a *networking process*. The factors listed above will not all have an equal impact on development speed and development efficiency; they will not apply equally to radical new product developments and developments along established design trajectories; nor will they apply equally across industry sectors or even to all firms within a sector. In other words, attaining greater speed and efficiency is not an "all or nothing" process as far as this broad range of factors is concerned. Taken together, however, these factors do define the main enabling features of the emerging 5G innovation process, which is one of systems integration and networking (SIN). The characteristics of 5G, in terms both of underlying strategic elements and the primary enabling factors are:

(1) *Underlying strategy elements:*

- Time-based strategy (faster, more efficient product development).
- Development focus on quality and other non-price factors.
- Emphasis on corporate flexibility and responsiveness.
- Customer focus at the forefront of strategy.
- Strategic integration with primary suppliers.
- Strategies for horizontal technological collaboration.
- Electronic data processing strategies.
- Policy of total quality control.

(2) *Primary enabling features:*

- Greater overall organization and systems integration:
  - parallel and integrated (cross-functional) development process
  - early supplier involvement in product development
  - involvement of leading-edge users in product development
  - establishing horizontal technological collaboration where appropriate
- Flatter, more flexible organizational structures for rapid and effective decision making:
  - greater empowerment of managers at lower levels
  - empowered product champions/project leaders/shusas
- Fully developed internal data bases:
  - effective data sharing systems
  - product development metrics, computer-based heuristics, expert systems
  - electronically assisted product development using 3D-CAD systems and simulation modelling
  - linked CAD/CAE systems to enhance product development flexibility and product manufacturability
- Effective external data link:
  - co-development with suppliers using linked CAD systems
  - use of CAD at the customer interface
  - effective data links with R&D collaborators

The 5G process is essentially one of *lean innovation*.

Discussion

This article has discussed the evolution, during the post World War II period, of changing perceptions — and to a large extent changing practice — of what constitutes the dominant model of best practice in the innovation process, from the simple series technology-push model of the 1950s to the parallel and integrated model of the 1980s. The reality is more complex, in that even today all types of innovation process continue to exist in various forms. To some extent this diversity is a result of sectoral differences, i.e. innovation in certain consumer products has a strong market-pull flavour, innovation in assembly industries is becoming more integrated and parallel in nature, while innovation in science-based industries such as pharmaceuticals leans more towards the "science discovers, technology-pushes" mode. However even in areas like pharmaceuticals, few would argue for a pure technology push mode, and perhaps the coupling model with its feedback loops and market linkages, and with the addition of limited functional overlap, applies best. Certainly the many success/failure studies of innovation performance during the 1970s suggested that the coupling (3G) model more often led to success than did its linear predecessors. The use of electronic product design tools can be incorporated into any of the innovation models.

In the case of innovations involving the development of a major new technology, it would be unwise to opt initially for a fully parallel process. Such radical innovations are characterized by high technological uncertainty and a parallel process might not allow sufficient time for technological learning and the proper assessment of alternative technological pathways before major resources are committed. Unforeseen technical problems could require costly changes across the entire innovation system. Thus, with radically new innovations, a 3G process with limited functional overlap is probably best although, as the project develops and technological uncertainty is reduced, the degree of overlap could be increased. Electronic development tools and data sharing systems can, of course, be used in such radical developments since information processing efficiency is important for all types of innovation, from the incremental to the radical. The point is, it is important that fundamental technological uncertainties are largely resolved before the innovation system engages in parallel development, i.e. with radical innovations adequate technology demonstrators are an essential prerequisite to 5G.

A third important point is that the balance between technology-push and need-pull as a *motivation* for innovation might vary considerably over the industry cycle. In the new wave biotechnology industry, for example, which began very much in the technology-push mode with basic discoveries in monoclonal antibodies and recombinant DNA at universities, increasingly greater influence has been imposed by the marketplace (need-pull). The point is, it is often only as a basic technology develops and its application possibilities become evident that new uses and users emerge, at which stage the marketplace plays a greater role in directing the pace and direction of technological change. Further, as the field matures, the nature of technological change frequently shifts from the radical to the incremental. At all stages in the field's development, however, the process of matching technological capabilities to market needs remains central to success.

A fourth point is that in cases where there is convergence towards an industry dominant design, the nature of innovatory activity can shift from an emphasis on product change to one of manufacturing process change (Abernathy and Utterback, 1978). In such cases firms can become introspective in their innovation selection criteria (manufacturing cost focus), rejecting on the one hand technological possibilities for radical product change and on the other failing to respond to significant market shifts. This progressive dominance of a single corporate function, in this case manufacturing, runs counter to the "balance of functions" which is the hallmark of successful innovators and technically progressive firms. Essentially this internally-directed technological change process is one in which the necessary internal and external linkages and interactions are lacking.

Returning to the 5G innovation process, its main characteristics are:

- greater overall organizational and systems integration (including external networking);

- flatter and more flexible organizational structures, including devolved decision making;
- fully developed internal databases;
- electronically assisted product development;
- effective external electronic linkages;

In short, the key aspects of the process are:

- integration;
- flexibility;
- networking;
- parallel (real time) information processing.

Underlying all these features is the requirement for across-the-board quality control reflecting the importance of "getting it right first time". Of significance also is the related requirement better to understand in detail the product development process itself and the critical factors influencing it, in order that the appropriate product development productivity metrics can be established as a basis for quality control and productivity increase.

As stated earlier, many of the features of 5G are already in place in innovators that have mastered the 4G process; parallel and integrated operations, flatter structures, early and effective supplier linkages, involvement with leading customers and horizontal alliances. The most radical feature of 5G is the use of a powerful electronic toolkit to enhance the efficiency of these operations. While electronic measuring and computational devices and analytical equipment have for many years been important aspects of industrial innovation, *5G represents a more comprehensive process of the electronification of innovation across the whole innovation system*. Electronic development tools (and a more parallel development process) are becoming increasingly a feature of product development not only in manufacturing (hardware), but also in software (Quintas, 1993).

Many companies are already utilizing information and communication technology (ICT) to facilitate their innovatory and related activities. For example, companies with split R&D facilities have, during the 1980s, increasingly utilized electronic mail and video-conferencing as part of their day-to-day operations (Howells, 1992). In order to capture the full potential benefits of ICT, however, firms will need to develop the appropriate strategies and commit the necessary resources for equipment purchase and, perhaps more importantly, for adequate training programmes and this especially will be the case for multinationals operating global strategies. (In the case of multinationals operating across a variety of languages, perhaps a major advantage of linked compatible CAD systems is that they can communicate using a common technical/visual language.) Incremental learning strategies are likely to be more successful than one-off radical shifts in technique.

Some companies are already well along the pathway towards adopting and mastering the 5G electronic toolkit and towards developing the appropriate strategies:

- Hewlett Packard makes considerable and growing use of electronic product development techniques and CAD/CAE, including inter-plant linkages (e.g. computer data storage products are designed in Bristol, UK and the design data are sent directly on-line to the manufacturing plant at Boeblingen, Germany).
- Ford of Europe has installed a “worldwide engineering release system” which links between plants and shares design and manufacturing information. The company has integrated its telecomms strategy with its business strategy and has given considerable attention to the implementation of interactive remove CAD/CAM applications (Mansell and Morgan, 1991).
- Boeing designed its new 777 aircraft on a 500-workstation, 2 mainframe computer network using a sophisticated 3D-CAD programme (known as Catia and developed by Dassault Systems). This simplified aircraft design cut development costs and greatly facilitated on-going design changes and customer design inputs (Abrahams, 1990). (It is of considerable interest here that, according to Richard Nelson (1993), the old Rand R&D Group in the USA argued that, in attempting to operate parallel development practices the US Air Force, during the 1950s, almost always experienced great problems during the development of new aircraft. Rand recommended that the Air Force should proceed much more sequentially. One reason advanced by Nelson to explain the USAF’s difficulties during that period was that they were attempting to achieve major advances in the state of the art. An additional explanation is that communication and design-related information processing capabilities during the1950s were insufficiently developed to enable aircraft manufacturers to handle complex, highly dispersed design and construction activities satisfactorily other than in a sequential manner. During the intervening 30 or so years, the US aircraft industry has undergone considerable managerial and organizational learning and, crucially, has succeeded in mastering the electronic design and information processing capabilities which are at the heart of 5G.)

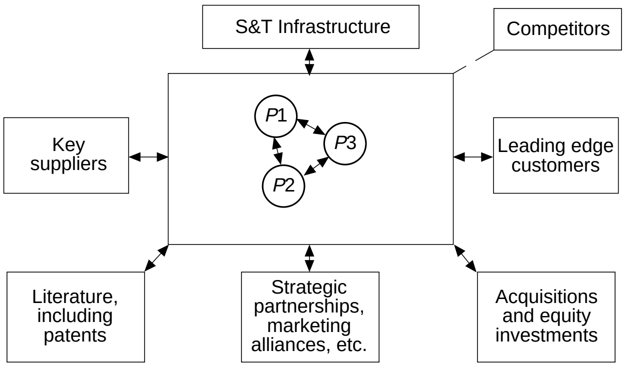
Industrial innovation can be depicted as a process of know-how accumulation, or learning process, involving elements of internal and external learning (Figure 7). Electronic product development tools can themselves become a powerful factor in company learning. Mastering the 5G process will itself involve considerable learning, including organizational learning, and this will be far from costless in terms of time and of equipment and training expenditures. The potential long-term benefits, however, are very considerable. Essentially the main benefits of 5G derive from the efficient and real time

Internal learning

- R,D and D – Learning by developing
- Learning by testing
- Learning by making – Production learning
- Learning by failing
- Learning by using in vertically integrated companies
- Cross-project learning

External or joint internal/external learning

- Learning from/with suppliers
- Learning from/with lead users
- Learning through horizontal partnerships
- Learning from/with the S&T infrastructure
- Learning from the literature
- Learning from competitors' actions
- Learning through reverse engineering
- Learning from acquisitions or new personnel
- Learning through customer-based prototype trials
- Learning through servicing/fault finding



Source: Rothwell (1992)

Figure 7.
Innovation as a Process of Know-how Accumulation

handling of information across the whole system of innovation, including internal functions, suppliers, customers and collaborators, i.e. 5G is a process of parallel information processing, one in which electronic information processing and the more traditional informal face-to-face human contact operate in a complementary manner. The formalized information contained within electronics-based systems complements the tacit knowledge embodied in the individuals involved in innovation, while computer-based heuristics (expert systems) might succeed in capturing some of this tacit knowledge. In general electronic systems will act to enhance the efficiency with which tacit know-how is deployed.

A significant factor in Japanese competitive success is the quality of informal information exchange during product development, including interchanges at the supplier interface, leading to fast, efficient and flexible development (and manufacturing) processes. This factor, it might be expected, would lead to greatest advantage in the case of complex assembly-type products and with systems integrators (e.g. automobiles, machinery, electrical equipment, aerospace) rather than in the science-based and process-based sectors (e.g. pharmaceuticals, chemicals). In the former sectors, innovation is more system based (many actors, great diversity of components and sub-assemblies) while in the latter it is internalized to a greater extent, with less input variety (Pravitt and Patel, 1992). It is significant in this respect that

Mansfield (1988) found Japanese time and cost advantages over US competitors to be more significant in machinery (including computers), instruments and electrical equipment than in chemicals (including pharmaceuticals).

It is tempting to speculate that in assembly-type industries the 5G process, properly deployed, might, given the process's inherent information processing efficiency, help to redress the product development (and manufacturing) speed and efficiency advantages currently enjoyed by Japanese manufacturers. Whatever the outcome in this specific case, it seems probably that it is those companies that invest in mastering the 5G process today who will be the leading-edge innovators of tomorrow.

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