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Portfolio management of R&D projects: implications for innovation management

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Abstract

Globalization of markets and new business practices are prompting high-tech firms to reconsider their competitive strategy. The increasing complexity of technologies in addition to shorter product life cycles are also forcing firms to rely on R&D as a source of strategy. More importantly, firms are inclined to evaluate their technologies from a portfolio's perspective in which a set or a sub-set of R&D projects is evaluated together, in relation to each other. Portfolio techniques can help strategic managers in evaluating whether a portfolio of products is adequate from the perspective of long-term corporate growth and profitability. Obviously, when R&D projects are evaluated relative to one another, technical capability management of such projects must be carried out concurrently. In this paper, R&D Project Portfolio Matrix is used as a tool for analyzing a portfolio of R&D projects by linking competitive advantages of a firm to benefits these projects may provide to customers. Examples of batteries for electric vehicles (EV) and hybrid electric vehicles (HEV) are provided to illustrate how such a matrix is used, and some of the implications for innovation management of such projects. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

In recent years, there has been an increasing interest in the area of portfolio management of R&D projects. Portfolio matrices have been used by Boston Consulting Group (BCG), McKinsey, and others (Abell and Hammond, 1979) to characterize product–market alternatives in terms of the attractiveness of the market, growth rate of the market, and the ability to create a distinctive advantage, such as high market share and competitive leadership of a firm's own projects. The portfolio approach to R&D management points out the different cash flow implications and requirements of different projects. Also worth mentioning is the graphic presentation of the projects, allowing managers to identify relevant adjustments with respect to the composition of a company's portfolio.

Portfolio techniques are powerful tools in that they allow products and R&D projects to be analyzed in a systematic manner, providing an opportunity for the optimization of a company's long-term growth and profitability. One of the main challenges of portfolio techniques is the selection of variables and sound indicators. The question arises as to how many variables need to be taken into consideration in order to make correct assessment of the projects. How can these variables be combined in order to ensure orthogonality? How does subjectivity influence consensus across different organizational functions for managing a portfolio of R&D projects? What are the implications for innovation management?

In the seventies, BCG Growth-share Matrix was a popular strategic analytical tool applied by multinational corporations for aiding in assigning priorities, investment, and resource allocation decisions. Similarly, the McKinsey Matrix[1] suggests a priority for resource allocation by taking into account critical internal and exter-

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[1] Other names used to describe the McKinsey Matrix include GE Matrix and Industry Attractiveness–Business Strength Matrix. For a detailed procedure of its application, see Hax and Majluf (1983).

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nal factors. Its primary importance is to assign priorities for investment in the various businesses of the firm. The popularity of these matrices, however, was matched with equally outspoken criticisms.

Some criticisms of the BGC Matrix are derived from the difficulties in measuring market share and market growth rates. Common pitfalls include difficulties in defining the relevant market, wrong assumptions about the validity of the product life cycle, the value of the market share, the effect of market structure, market stability, interrelatedness of product–market segments, divesting the dogs, and viewing the portfolio as a closed system (Slatter, 1980). The McKinsey Matrix, furthermore, includes a wide variety of factors in addition to market share and market growth rates used by the BCG Matrix. Some of the challenges of using this matrix are derived from difficulties in identifying and assessing external and internal factors, difficulties in dealing with multi-attributes leading to high ambiguity in measuring business strength and industry attractiveness, and the use of Net Present Value as the evaluation tool (Hax and Majluf, 1983).

A literature review in portfolio management of technology and innovations reveals that most of them have very limited definitions in characterizing project success. The BCG Matrix, a four-cell matrix, uses relative market share and industry growth rates as determinants of success (Slatter, 1980; Henderson, 1979). Similar to the BCG Matrix, the McKinsey Matrix uses competitive position of a company and industry attractiveness in a nine-cell matrix (Hax and Majluf, 1983; Segev, 1995). One of the first product portfolio models is the Product Portfolio Matrix. This matrix was developed as a guide to allocation of a firm's resources based on business strength and industry attractiveness, but it offers no advice for the types of technologies and associated products with which the firm should be involved (Day, 1977). In order to address this issue, the Technology Portfolio was developed by Capon and Glazer (1987) which is a framework used for integrating technology and marketing strategies. Although the Product/Process Development Projects Matrix by Wheelwright and Clark (1992a,b) characterizes product changes relative to process changes and their impact on allocation of resources, it does not address other factors influencing the success of a company. Cooper and Kleinschmidt (1993) introduced the Performance Map which basically used factor analysis techniques to identify the success dimensions of new products. It also measures five performance types in relation to two performance dimensions: time performance and financial performance. Perhaps a more comprehensive framework is introduced by Arthur D. Little (Roussel et al., 1991) in which four key elements of individual projects are evaluated: technological competitive strength, technology maturity, competitive impact of technologies, and R&D project attractiveness.

It is no surprise that identifying success factors of an innovation is not straightforward. Based on the competitive structure of the markets, each industry faces unique sets of challenges that are irrelevant to other industries. Hence, portfolio techniques usually serve to solve a particular set of complex issues faced by R&D management, unique to each firm. Naturally, the knowledge and technical feasibility that goes hand-in-hand with the R&D projects must be managed concurrently. Equally important is the assessment of these projects with respect to customer value as well as competing technologies.

In this paper, the R&D Project Portfolio Matrix is used as a tool for highlighting possible gaps between the competitive advantages of a high-tech firm and customer value. It is argued that R&D projects of a firm should be evaluated vis-à-vis the benefits these projects offer to customers. The paper is organized as follows. Firstly, some issues on the management of innovation are discussed. Secondly, the concept of a balanced portfolio is explained followed by the introduction of the R&D Project Portfolio Matrix. Next, dynamic issues of R&D projects are examined. Finally, the application of the matrix is illustrated with examples of R&D projects under development for electric vehicle (EV) and hybrid electric vehicle (HEV) batteries.

1.1. Management of innovation

An increasing number of scholars highlight the importance of linking technological capabilities of a firm with its customers. For instance, Cordero (1991) argues that the rate of product obsolescence is accelerating in many industries because customers are willing to pay for innovative products, and firms that cannot supply innovative products faster than competitors, lose competitiveness. He also highlights the importance of organizing product development and product manufacturing for speed, both complemented with time-saving techniques. Similarly, Pavitt (1990) and von Hippel (1986) argue that one measure of success and profitability within a firm is the ability to satisfy user's needs better than the competition. As many firms are pressured to introduce products with more variants per model and at a faster rate than before, 'time-to-market' has become a measurement for gaining competitive advantage.

The innovation process encompasses a range of activities that contribute to producing new goods and services in new ways. An innovation occurs when a new good, service or production method is put into commercial use for the first time (Hall, 1994), creating new markets and supporting freshly articulated user needs in the new functions it offers; and in practice, an innovation demands new channels of distribution and after-market support (Abernathy and Clark, 1985, p. 59). According to Pavitt et al. (1989) successful implementation of innovation depends on three factors: effective horizontal links (both internally and externally to the firm), the characteristics of 'business innovator' responsible for the innovation's outcome, and flexibility and speed in decision making. In accordance, Adler and Ferdows (1990), in their study of the responsibilities, work experiences, and authorities played by Chief Technology Officers (CTO), revealed that CTOs play an integrating role made increasingly necessary by the peculiar dynamics of technological evolution. A CTO can contribute to a firm's competitive advantage by facilitating the process of taping opportunities emerging among technology suppliers, developing products and processes that capitalize on new technological opportunities, and marshalling the complementary skills and resources needed to effectively exploit these innovations.

Entrepreneurship is another key characteristics of innovation. As Kanter (1989, p. 60) describes, "…like most entrepreneurs, in a newstream venture one must know one's particular technology or customer to be effective, whereas the mainstream businesses are routinized enough to make it possible for managers to be more interchangeable." Kanter further states that when newstream projects are carried out along side mainstream businesses, the managerial agenda of newstreams is formed by three compelling characteristics: high uncertainty, high intensity, and high autonomy. Newstreams require committed visionary leadership, capital investment that does not have to show a short-term return, and a great deal of planning flexibility. The development process of newstreams is knowledge intensive characterized by accumulation of new experiences from application of existing knowledge and interactive learning.

The creation of an innovation rests strongly in a firm's R&D capabilities and the ability to make technical changes, be they incremental[2] or radical[3]. In doing so a firm must manage the linkage between R&D as they portray contrasting characteristics (Table 1).

To increase our understanding of the complexities of innovation and its management, Christensen (1995) categorizes generic types of innovative assets across a range of product categories; with innovative assets extending from science based R&D, process development, product application (both technical and functional) to aesthetic design. A profile of product categories ranging from materials, components, complex systems, to consumer products is mapped against these innovative assets.

Table 1
Changing nature of R&D activities from research to development — adapted from Nixon and Innes (1997)

	From research…	…to development
Cooperation	Informal	Formal
Knowledge	Tacit	Explicit
Criteria	Qualitative	Quantitative
Evaluation	Subjective	Objective
Business goal	Strategy alignment	Operational feasibility
Risk focus	Risk	Payback period
Cost focus	Opportunity costs	Cash flow
Financial focus	Option value	Contribution margin

Given a set of R&D projects with varying degrees of complexities, the portfolio approach forces strategic managers from different organizational functions to reach consensus between R&D vis-à-vis innovation management. The accumulation of technical competencies through R&D leads to the accumulation of technological know-how for the firm as a whole. The complexity of innovation management encourages subjective evaluations of R&D projects from strategic managers of different functions to reach consensus by allowing flexibility in setting, often broad, specifications and goals. The details of the projects such as product specifications, marketing strategies, logistics targets, production technologies, etc. are often set after consensus has been reached. Subjectivity is a necessary condition for analyzing a portfolio of R&D projects, precisely because the requirements of R&D are quite different.

Some advantages provided by the portfolio approach to R&D management include:

- The relative strengths and weakness of each project are surfaced
- Decisions regarding capital investment allocation, project selection, prioritization, and resource allocation are facilitated
- Dynamics of the projects are revealed
- Projects are tied to business level performances
- Systematic analysis of the projects is encouraged
- The relative graphical positioning of the projects makes the evaluation process easier to be understood by non-technical managers
- Consensus is emphasized
- Gaps and future development opportunities are highlighted

[2] Incremental innovation introduces relatively minor changes to the existing product, often applied to existing markets and customers (Henderson and Clark, 1990; Abernathy and Clark, 1985).

[3] Radical innovation establishes new sets of core design concepts, and is driven by technological, market, and regulatory forces (Henderson and Clark, 1990; Tushman et al., 1997; Abernathy and Utterback, 1988; Utterback, 1994).

Some pitfalls include:

- Orthogonality issues seem to be an inherent challenge
- Technology interdependencies among projects are not so apparent and difficult to assess
- A fairly good understanding of each individual R&D project is needed in order make the proper evaluation, a task difficult for non-technical managers
- Identification of measurement indicators to ensure proper assessment of the projects is difficult

2. Balanced portfolio

In analyzing a portfolio, the desired combination is a balanced portfolio defined as an assortment of projects that enables a company to achieve the growth and profit objectives associated with its corporate strategy[4] without exposing the company to undue risks (Hill and Jones, 1992). Given varying levels of uncertainties faced by high-tech firms, underestimating uncertainty can lead to strategies that neither defend against the threats nor take advantage of the opportunities that higher levels of uncertainty may provide (Courtney et al., 1997). More specifically, portfolio analysis of R&D projects involves the detailed evaluation of a selected set of projects in a firm. It illustrates the competitive positions of products and projects as well as deficient gaps needing further improvement. The selection of products and projects in a portfolio should be made carefully so that they are in line with overall corporate strategy. It should force management to emphasize the importance of long-term perspectives.

One of the most important factors in analyzing a portfolio of R&D projects is the ability to link competitive advantages of a firm to perceived customer needs. Ideally, firms wish to accurately predict and translate such needs into physical products. Surely this process not only involves every organizational function of the firm, but also embraces other members of the supply chain of these products. Firms should also foster know-how of their core technologies as a continuous, never ending process. Maintaining a balanced portfolio of products and projects is building an asset base of technologies essential for competitive advantage. To effectively manage know-how impacting the dynamics of such a portfolio is, then, a powerful strategy for the future growth and profitability of high-tech firms. A portfolio of R&D products and projects in automotive electronics, for instance, is often characterized by an assortment of projects under development and non-finished projects marked by much experimentation and testing. These quasi-finished projects are not fully abandoned, however. The risks associated with this process are so high that, very often, the journey is never completed or is indefinitely delayed by technical obstacles or shifts in market conditions (Altshuler et al., 1986). The experience gained from these projects builds and strengthens the knowledge base for firms. Although the implementation of innovations is usually incremental[5] and time consuming[6], when such technologies reach customer acceptance in the market place, the return speaks for itself. As Abernathy and Utterback (1988, p. 27) describes, "…major systems innovations have been followed by countless minor product and systems improvements, and the latter account for more than half of the total ultimate economic gain due to their much greater number."

3. The R&D Project Portfolio Matrix

The R&D Project Portfolio Matrix (Fig. 1) is a communication tool with the purpose of identifying projects or products that provide benefits to customers (vis-à-vis needs and markets) and competitive advantages (vis-à-vis competitors) (Hsuan, 1998; Hsuan and Vepsäläinen 1997, 1999; Lauro and Vepsäläinen, 1986; Vepsäläinen

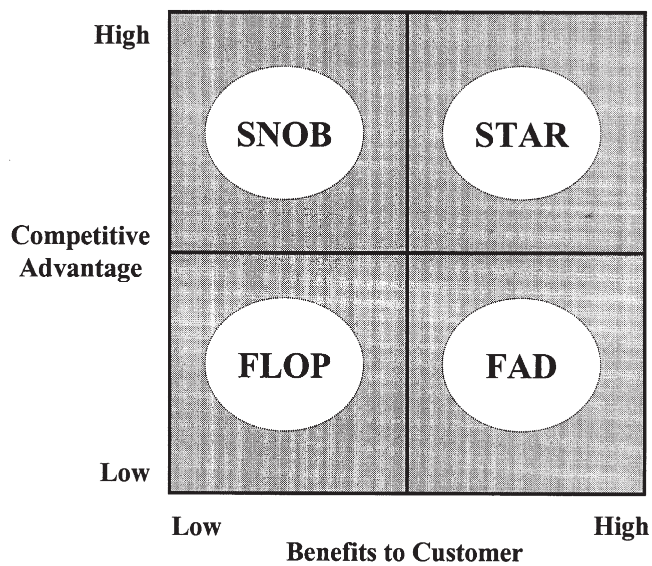

Fig. 1. The R&D Project Portfolio Matrix.

[4] Itami and Numagami (1992) define strategy as a dynamic design of the activities for the entire firm, with a fundamental policy defining the basic framework of the various activities of the firm and the basic principles of its game plan in the marketplace.

[5] It has been estimated that as much as 85% of products are estimated to be in an incremental stage at any given time (Gomory, 1989).

[6] Although the first commercially available microprocessor (Intel 4004) and the first floppy disk (IBM's 8-inch magnetic storage) were launched in 1971, the first mass-produced and marketed personal computer (MITS Altair 8800) was eventually launched in 1975 (Fisher, 2000).

and Lauro, 1988). It also facilitates the selection of projects with the highest potential for success. The matrix was first introduced to facilitate the R&D planning and competitive bidding of large industrial and government contracts. It was designed to analyze the merits of alternative engineering activities when there are multiple firms competing for contract award and multiple groups exerting influence on selection of the contract winner. The original matrix also addressed the problems of multiple criteria, quantification of R&D managers' judgment, and product performance against competing technologies (Vepsäläinen and Lauro, 1988; Lauro and Vepsäläinen, 1986). In this paper, The R&D Project Portfolio Matrix is extended to evaluate R&D projects of industrial and commercial firms where project requirements and firms' strategic capabilities are less well defined compared to those of government contracts.

The matrix is developed based on two criteria: competitive advantages of a firm and benefits provided to customers. These criteria allow the matrix to portray not only the strengths and weaknesses of a firm, but also link its distinct capabilities to perceived customer satisfaction. It also raises the question of how a firm should manage its technological knowledge asset. The matrix plays a special role in screening R&D projects taken for further development, one of the most common problems faced by R&D managers. Equally critical is the decision of capital and resource allocation to products currently being produced and sold in the market place. Which products should be given priority for financial support? Which criteria are used in making these decisions? The R&D Project Portfolio Matrix addresses these questions and guides the managers to gaining greater confidence in their decision making.

The evaluation of a portfolio of R&D projects in the R&D Project Portfolio Matrix includes

1. Specification of appropriate R&D projects
2. Classification of the projects according to sustainable competitive advantages created by the firm, such as technical advantage, vis-à-vis the benefits offered to customers
3. The management of R&D projects with respect to the risks, dynamics, and balance of the portfolio
4. Prioritization of R&D projects for execution
5. The hidden opportunities offered by various market access factors in enhancing and expanding the competitive advantages of a firm

According to Hax (1990, p. 10), *competitive advantage* is "the result of a thorough understanding of the external and internal forces that strongly affect the organization. Externally, a firm must recognize its relative industry attractiveness and trends, and the characteristics of the major competitors. Internally, a firm must identify its competitive capabilities." Such advantages can be gained through product development, design and materials, product performance, manufacturing, production technology, marketing research, firm's market share, and logistics management to name a few. In high-tech firms, for instance, the ability to manage the portfolio of products and respective technologies is highly dependent upon the manufacturing processes and technical capabilities in which such products are produced. These firms must not only continuously upgrade manufacturing technologies, efficiently and profitably, to match technological challenges of new products, but also foster the technical capabilities and knowledge generation of their R&D organizations. So, are companies being proactive or reactive in delegating R&D tasks vis-à-vis respective manufacturing capabilities[7]? To what extent is commercialization carried out in R&D projects? Are profitability incentives promoted by patents, licenses, copyrights, or temporal monopolies?

Benefits to customers can be described as the perceived value of products provided by a firm. Such benefits can be portrayed in the form of quality and features, low prices, on-time delivery, customization, after-sales service, user information or help-desk, pride of ownership, accessibility, security and safety, recycling, etc. It is important that a firm takes customers' needs from their perspectives, assesses such needs and translates them into a common language that everyone involved in the process of research, product development, design, manufacturing, and other channel members can understand. For every set of R&D projects, there is a different set of competitive advantages and benefits these projects may bring to customers.

The matrix is divided into four quadrants: STAR, FLOP, FAD, and SNOB.

3.1. STAR

STARs are R&D projects characterized by high competitive advantage as well as high benefits to customers. Products under this category have the ability to enhance system performance in criteria with high customer priority relative to the cost of undertaking the activity, while generating levels of performance hard to be matched. STARs are equivalent to successful breakthrough innovations or products. Products targeted at niche markets often fall into this category. Specifications and market requirements can be researched more easily, enabling a firm to enhance its competitive advantages more selectively. R&D and marketing investment decisions can be made with less hesitation. In doing so, services can be better monitored and evaluated, hence

[7] For excellent reference on manufacturing capabilities, see Bessant (1991) and Noori (1990).

the opportunities for responding and satisfying customers' needs also increase. STARs have the ability to generate sufficient cash (in the long-run) for their own and other projects' investment needs.

3.2. FLOP

Contrary to STARs, FLOPs offer virtually no competitive advantages and limited ability to bring benefits to customers. Such products are unlikely to generate positive returns for a firm. They may even require substantial capital investment just for survival. When FLOPs cannot be revived into FADs or SNOBs, such projects should be eliminated from the portfolio, if possible, so their current required working capital can be invested into other projects in the portfolio.

3.3. FAD

FADs are characterized by high benefits to customers but weak competitive advantages such as inferior technical advantage. These characteristics are often found in products developed based on imitation or mass production of existing products. An explanation regarding FADs' weaknesses in sustaining their competitive advantages can be implied by a lack of opportunities for further enhancing their core capabilities. FADs' functional performance can be improved with the application of state-of-the-art technology in the design and manufacturing. Japan's Aiwa Corporation, for example, has survived the consumer electronics industry based on copying competitors' products by making them better and cheaper. This principle has transformed Aiwa from a nearly bankrupt manufacturer in Japan into a US$3-billion-in-revenues corporation in 1995. In 1987, Aiwa produced 850,000 imitations of Sony's Walkman in Singapore, where the wages were cheaper than in Japan, and called them 'personal stereos.' These personal stereos had simpler and sturdier design than those made by Sony, Sharp and other competitors. In addition, Aiwa priced them at 25–65% cheaper than other competitive models. This has enabled Aiwa to sell over 11 million personal stereos worldwide, second only to Sony. The company has enjoyed similar successes with portable CD players and small color televisions (Winberg, 1996).

3.4. SNOB

SNOBs are characterized by high competitive advantages, but unable to fully meet customers needs. Such weak benefit may be caused by high production costs, or low perceived demand. First generation innovations are often characterized by having high technical advantages such as a competitive advantage, but weak ability in providing satisfactory value to customers. These characteristics are typical of technologically demanding products. Often, the causes originate from poor implementation and planning of marketing strategies, causing the demand for the product to decrease. Other times, inefficiencies from manufacturing processes and/or logistics management can increase the operating expenditures and lead times so much that the cost transferred to the customers is too high, hence losing attractiveness in the market place. The costs associated with producing and designing technology intensive products can be very high, aggravating SNOBs to be hungry for cash. Management has to pay special attention to this type of project when deciding whether such an investment is in line with the long-term strategic plan of the firm.

4. The dynamics of a portfolio of R&D projects

Fig. 2 illustrates the dynamics of innovation vs imitation in the R&D Project Portfolio Matrix. First generation innovations need to take a closer look at the reasons for low perceived customer satisfaction. Are the underlined factors caused by the lack of customers' knowledge about the product, perhaps due to inadequate advertisement, limited accessibility, or by high technical complexity inherent in the product? Sometimes, market forces have a much bigger influence in the technology utilized, so that first generation innovations may have difficulties in surviving. Introducing products into the market at the wrong time can lead to this misfortune. For example, navigation systems for automobiles have been introduced several times in the past, but failed to survive due to unsatisfactory demand, haunted by infant

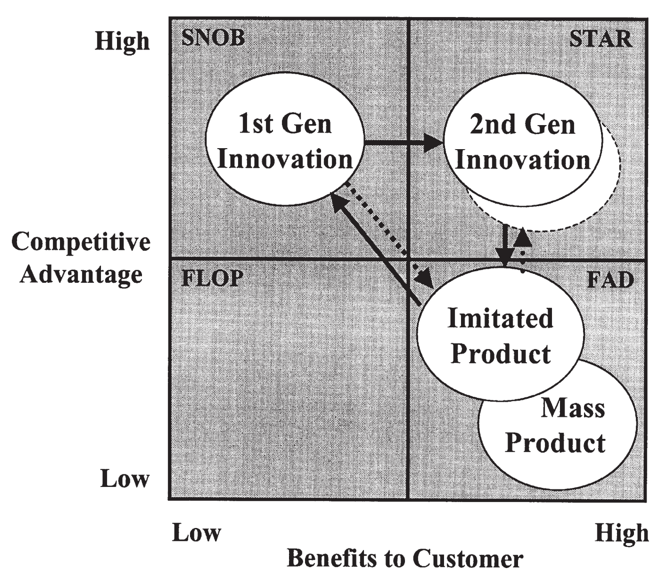

Fig. 2. Dynamics of innovation and imitation.

infrastructure, and not perceived as being worth the investment by the consumers.

When competitive advantages are lost through internal inefficiencies, current strategy must be revised. Are inefficiencies caused by long commercialization lead time? Can production costs be reduced by design-for-assembly (DFA) and design-for-manufacturability (DFM) through the use of standard components? If development lead time needs to be improved, should the firm hire more technical personnel? How should the technical knowledge pool be managed? Sometimes, in answering such questions, firms may decide to get into partnership with other firms to share some of the inherent risks. Other firms practice concurrent engineering and benchmarking of innovations with the hope of shortening the gap between its development and production lead times and the launch of such innovations into the market place.

4.1. Sustaining STARS

Pressure from competition and market demands make it difficult for STARs to stay on top for a long period of time. They should continuously advance and strengthen competitive advantages and benefits to customers. As Teece (1986, p. 290) describes: "…the best initial design concepts often turn out to be hopelessly wrong, but if the innovator possesses an impenetrable thicket of patents, or has technology which is simply difficult to copy, then the market may well afford the innovator the necessary time to ascertain the right design before being eclipsed by imitators." Enduring the STAR position can be very tough and costly, at times. In order to hold such status, STARs must have persistence in subsequent, continuous product innovation and improvement generations through reputational ties, persistent learning-by-doing advantages in production, the ability to improve existing products at lower cost than competitors (Scherer, 1992).

4.2. FAD–STAR transformation

FADs (e.g., imitated products or mass produced products) can become STARs (e.g., second generation innovations) by strengthening their weak competitive advantage without compromising current value perceived by customers. The FAD–STAR transformation can occur if there are significant improvements in the performance of the product it imitated, such as reduction in size and weight of the product, more appealing aesthetic features, lower price tag via manufacturing processes, better services, etc. In any case, the changes and improvement attempted should be visible in the eyes of the customers. If not managed properly, FADs can become FLOPs when they can no longer satisfy customers' needs, nor achieve improvement in product development and manufacturing. Managers, in making strategic decisions, must ask the following questions: Have sufficient advances been made in the technology under consideration? Can advantages be gained through improving product features and/or manufacturing capabilities? How much improvement and changes in technical personnel are needed, and to what extent? Is pursuing radical product design a better alternative? Occasionally, in trying to improve competitive advantage through technology innovations, FADs end up becoming SNOBs. This happens when projects under evaluation take the current degree of customer value provided for granted, and too much emphasis is given to the improvement of technical aspects of the project.

How the Japanese conquered the solid-state color television market in the US during the 1970s is an example of how FADs can become STARs. Although US manufacturers were the leaders in the design and development of both monochrome and color television with the application of transistor technology, they failed to implement this technology into their main product offerings. The Radio Corporation of America (RCA) was the pioneer in developing black-and-white television as well as the patent holder of its color television technology. Because both technologies were available to the newcomers through licensing, only modest investment in R&D was required. This situation had opened many doors with huge opportunities for other competitors, especially the Japanese who also licensed the technology. However, the Japanese went a step further by reducing the costs and improving the quality of the solid-state color television sets. This gave them a competitive advantage over the Americans. By 1976, the Japanese had gained such a strong technological and market presence that it was too difficult for US producers to catch up (Scherer, 1992).

4.3. FLOP–STAR transformation

Reviving FLOPs can be a difficult task. Because they often do not bring enough revenue, little attention is paid to them. There is usually a limited amount of capital allocated to such projects. Thus, it is less gruesome for companies to either improve technical aspects of the product or to improve its perceived customer value, but not simultaneously. Attempts to accomplish both tasks at the same time are almost an impossible mission, often leading the FLOPs to be abandoned from the portfolio at once. The only visible value contributed by FLOPs is the overall learning and knowledge gained by the organization during the process of managing such projects.

4.4. A balanced portfolio in the context of the R&D Project Portfolio Matrix

As mentioned, a balanced portfolio should contain an assortment of projects that enables a company to achieve the growth and profit objectives associated with its corporate strategy without exposing the company to undue risk (Hill and Jones, 1992). In the R&D Project Portfolio Matrix, a balanced portfolio should contain STARs, FADs, SNOBs, and sometimes FLOPs. These projects are related to each other in a dynamic fashion. FADs are important because they can remain highly profitable. Since FADs are often based on imitation of existing products, risks associated with first movers can be minimized. In other words, let the innovator be exposed to all possible risks, and FADs may be able to benchmark relevant elements to their benefits. Thus, FADs may be able to produce similar products with more value added elements and benefits visible to the customers by providing better services, more efficient and capable manufacturing processes, and better R&D management.

SNOBs are equally important as FADs because they possess the technological know-how of innovations and products that may provide breakthrough platforms for firms, especially for those engaged in high-tech industries. They need to be nurtured properly and patiently for they may require vast amount of investment. However, when SNOBs do become STARs, they will bring revenues as well as strengthen core capabilities and competencies that are difficult to be matched by the competitors.

5. The case of batteries for Electric Vehicles (EVs)

The main mission of Zero Emission Vehicles[8] (ZEVs) and Hybrid Electric Vehicles[9] (HEVs) is to eliminate tailpipe emissions that would get rid of full-cycle carbon dioxide emissions leading to improved local and global air quality. Results from ongoing experiments have shown that while EVs eliminate tailpipe emission of NOx, VOCs and particles, their most dramatic benefit is in lowered carbon dioxide (CO_2) emissions. In order to reduce pollution from automobiles, the California Air Resources Board (CARB)[10] devised regulations demanding the seven largest auto manufacturers to produce the following percentage of ZEVs: 2% by 1998, 5% (2001–2002), and 10% (2003 and beyond). In order to meet clean air regulations, major auto makers are allocating a part of their resources into the research and development of ZEVs (British Columbia Ministry of Environment, Lands and Park, 1995). Historically, the development and commercial acceptance of EVs have been hindered by the lack of suitable batteries (Riezenman, 1998).

Hence, the success of EV is highly dependent upon the advancement of battery technologies. The ideal battery would satisfy the question posed by Hunt (1998): "What battery technology will give the best combination of performance, life, and cost with adequate safety and minimal environmental impact?" Three main constraints, energy performance, power performance, and lifetime (both in actual time and in charge–discharge time), cannot be simultaneously optimized. That is, improvement in one constraint cannot be achieved without sacrificing other constraints. Other challenges faced by EVs include:

- The need of a widespread charging infrastructure that is safe and convenient, at least comparable to gasoline fuel stations
- Protocol incompatibility with chargers — all manufacturers carry their own proprietary chargers which means a GM EV1 cannot be recharged at a charge station intended for a Ford Ranger EV
- Performance constrained by space and weight
- Energy density has been one of the major concerns for EV batteries. For instance, conventional lead–acid batteries can store about 400 times less energy than gasoline on a weight basis (Hunt, 1998)
- Discharging EV batteries can take hours to days (batteries must be totally discharged before engaged in recharging)
- The impact of the mass market for EVs is difficult to predict. Consumers are inclined to purchase products based first on cost rather than life cycle cost

Tables 2–4 list some characteristics and tradeoffs of three battery technologies: lead–acid, lithium–ion (Li–ion), and nickel–metal hydride (NiMH). Information contained in the tables is extracted from the following sources: Riezenman (1998), Hunt (1998), California Air Resources Board (1999), Toyota (1997), Hermance and Shoichi (1998), Stempel et al. (1998) and Pilkington (1998). The technological performance and tradeoffs between specific energy, energy density, and specific power indicate competitive advantages of these batteries.

The R&D Project Portfolio Matrix analysis of these battery technologies is illustrated in Fig. 3. The competitive advantage is assessed in terms of relative technological advancement of these technologies: specific energy, energy density, specific power, life cycles, and costs (in US$/kWh). Benefits provided to customers are assessed in terms of the relative strengths and challenges posed by the battery technologies. Li–ion batteries show the highest competitive advantage in all three dimensions of performance, followed by NiMH and lead–acid

[8] ZEVs have no tailpipe and evaporative emissions, no emissions from gasoline refining or sales, and no on-board emission control systems that can deteriorate over time (California Air Resources Board, 1999).

[9] HEVs are equipped with a gasoline engine in addition to an electric motor or fuel cells.

[10] For on-going progress reports on ZEV emission regulations visit www.arb.ca.gov.

Table 2
Characteristics and tradeoffs of lead–acid battery technology

COMPETITIVE ADVANTAGE

Specific energy[a] (Wh/kg)	Energy density[b] (Wh/L)	Specific power[c] (W/kg)	Life, full-discharge cycles	Cost (US$/kWh) (in volume production)	Manufacturer, make, model
25–40	70	80–150	300–500	100–150	**EVs** • Dodge Caravan EV • Ford Ranger pickup • GM EV-1 • GM S-10 pick-up • Plymouth Voyager Epic EV **HEVs** • Toyota Coaster

BENEFITS TO CUSTOMERS

Strengths	Challenges
• For on-board energy storage in over 90% of EVs built in US • Wide availability • Low cost • Long historical data • Highly optimized manufacturing techniques • Key electrochemical components (lead and sulfuric acid) are inexpensive	• Driving range: less than 150 km • Poor cycle life in hot climates and at deep discharge levels • Must be discharged completely for hundreds of times over its life • Technological improvements are responsibilities of the industry • Difficulty of accurately determining and maintaining state-of-charge • Large variation of usable capacity with respect to discharge rate and temperature, thus difficult to predict remaining range • Potential environmental problems from lead • Less favorable for HEVs

[a] Specific energy is the amount of energy a battery stores per unit mass at a specified discharge rate; also called gravimetric energy density. It is the main determinant of driving range.
[b] Energy density is the amount of energy a battery stores per unit volume at a specified discharge rate; also called volumetric energy density.
[c] Specific power is the amount of power a battery can deliver per unit mass at a specified state of charge — usually 20%; also called gravimetric power density.

batteries. The size of bubbles represents the relative number of vehicles produced with the respective technology. Gasoline and diesel-powered passenger vehicles are placed in the matrix for comparison purposes. In reality, the overall relative competitive advantages and benefits to customers offered by all EVs and HEVs are compared to gasoline-powered vehicles.

Although most of the EVs sold in the market during the late 1990s use lead–acid batteries (over 90% of EVs sold in the US), the numerous technological challenges faced by these batteries with respect to Li–ion and NiMH batteries, will force such batteries to lose competitive advantage. The dilemma with lead–acid batteries is that the total number of EVs produced by year 2010 may actually increase due to the car manufacturers' dependency on this technology. Anyhow, innovations in automotive electronics do not occur overnight. An explanation as to why it is so difficult for radical breakthroughs to take place is due to the system's high interdependency with its subsystems and of linking technologies, which does not permit a single technological configuration to dominate across differing dimensions of merits. Furthermore, technological progress often occurs at the subsystem and system levels of analysis and is shaped by both technical capabilities and by the actions of technical practitioners constrained by suppliers, customers and the larger socioeconomic community (Tushman and Rosenkopf, 1992).

The NiMH battery has the greatest potential for success, both in its competitive advantage in the form of technical performance and benefits to customers. Although not as superior in overall performance as the Li–ion battery, with the support of USABC in addition to being the preferred technology for HEVs, it will gain faster consumer acceptance and adaptation in the near future. Technologically speaking, the Li–ion battery offers the highest performance, but because the technology is still at its infant stage, very little is known regarding its life cycle and high-volume production costs. A significant amount of these batteries will have to be produced in high volume and tested before standards and reliability data can be generated in order to make such technology less risky. So far only the Nissan Altra EV is using this technology.

Table 3
Characteristics and tradeoffs of NiMH battery technology

COMPETITIVE ADVANTAGE					
Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life, full-discharge cycles	Cost (US $/kWh) (in volume production)	Manufacturer, make, model
50–60	175	200	600–1000	300–400	**EVs** • Chevrolet S-10 Electric Pickup • Honda EV Plus • Hyundai Accent EV • Toyota RAV4-EV • Toyota e.com **HEVs** • Toyota Prius

BENEFITS TO CUSTOMERS	
Strengths	Challenges
• Availability for commercial application • Technology of choice in US • Wide application in consumer electronics (e.g., camcorders, laptop computers, cellular phones, etc.) • Driving range: 160 km or more • Better suited for HEVs: excellent power performance able to handle very high rates and short periods of charging • Intrinsic toleration of electrical abuse — there are no net chemical reactions on overcharge or overdischarge • Technology supported by USABC[a]	• Cell size incompatibility with other applications, thus only large auto companies can afford to build production facilities

[a] USABC — US Advanced Battery Consortium, an organization created to pursue the development of advanced batteries specifically for electric vehicles, comprises Chrysler, Ford, and GM, in corporation with the US Department of Energy (DOE) and the Electric Power Research Institute.

Table 4
Characteristics and tradeoffs of Li–ion battery technology[a]

COMPETITIVE ADVANTAGE					
Specific energy (Wh/kg)	Energy density (Wh/L)	Specific power (W/kg)	Life, full-discharge cycles	Cost (US $/kWh) (in volume production)	Manufacturer, make, model
80–90	200	$<$1000	?[b]	?[c]	**EVs** • Nissan Altra EV

BENEFITS TO CUSTOMERS	
Strengths	Challenges
• Superior performance • So far the best long-term hope • Consumer version rules application in lap top computers and cellular applications, thus fast growth in the number of manufacturers • High energy efficiency	• Low tolerance to overcharging, requiring precise charge control

[a] Other less popular battery technologies include nickel–iron, nickel–cadmium, sodium–sulfur, sodium metal–chloride, zinc–air, zinc–bromine, zinc–chlorine, and nickel–zinc.

[b] Battery life is difficult to predict and expensive which is constrained mainly by the configuration of EV batteries, manufacturing variations between cells and cell-to-cell temperature variations during use, and balancing large number of cells over a battery's life (Hunt, 1998).

[c] Production costs cannot be estimated before pilot plants are built and operating. Production costs of such batteries should also be much lower than the batteries built during development programs.

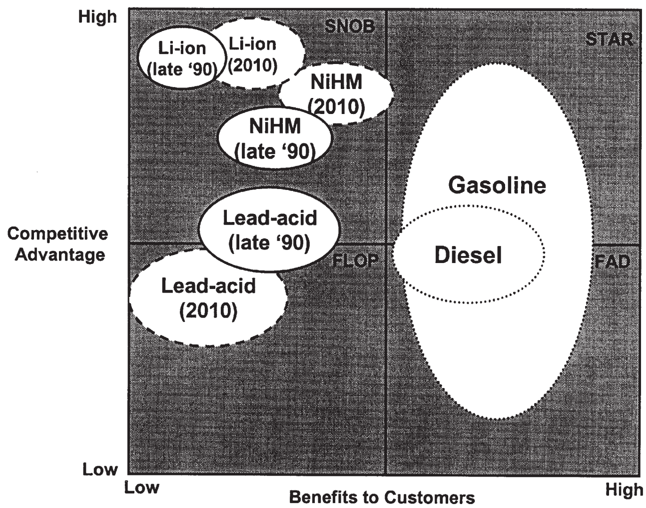

Fig. 3. Batteries for EVs and HEVs.

Depending on the long-term strategy of firms, investment decisions regarding these technologies will vary from firm to firm, hence shaping the content and dynamics of their R&D portfolio. A large firm, such as Toyota, is pursuing lead–acid and NiMH technologies in its battery portfolio. Nissan, on the other hand, concentrates its resources and development efforts in Li–ion technology. American manufacturers, with the support of USABC, have joined forces to advance the development of NiMH technology. It becomes evident that the battery portfolio will dictate how technical knowledge is managed within firms and across industries. In the future, we may observe the convergence of battery know-how between automotive and consumer industries such as laptop computers and cellular applications.

6. Conclusion

The increasing complexity of technologies and new business practices in addition to globalization of markets are forcing many firms to rely on R&D as a source of strategy for long-term growth and sustainability. Firms are also inclined to evaluate their technologies from a portfolio's perspective in which a set or a subset of R&D projects is evaluated together. When projects are evaluated in relation to crucial technologies, technological knowledge management of such projects can be carried out concurrently.

In this paper, the R&D Project Portfolio Matrix was used as a tool to analyze a portfolio of R&D projects by linking competitive advantages of a firm to benefits these projects may provide to customers. The matrix highlighted its special role in systematic R&D project selection, market and technological dynamics of projects, identifying risks and gaps to be fulfilled, and prioritization with respect to investment allocation. The matrix also forces managers to have a long-term perspective of R&D projects by guiding them to evaluate such projects in a balanced-portfolio approach.

Examples of battery technologies (lead–acid, Li–ion, and NiMH) for EVs and HEVs were used to illustrate how such a matrix can be applied, and some of the implications for knowledge and competence management of such projects. In the case EVs and HEVs, advancements in battery technology represent the competitive advantage of a firm. When these batteries are evaluated, with respect to competitive advantages and benefits to customers, and in relation to each other in a graphical form, the implications for innovation management of firms becomes evident.

This paper barely scratched the surface of the complex issue of technology management. One of the intentions of the paper is to highlight the importance of portfolio management of R&D projects, and stress the point that such projects should be evaluated vis-à-vis customers and competitors. Finally, in order to increase the relevance of the R&D Project Portfolio Matrix for technology management and implication for innovation management, an extension of the current research includes the development of sound measurement indicators and methodologies to validate the matrix.

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References

Abell, D.F., Hammond, J.S., 1979. Strategic Market Planning: Problems and Analytical Approaches. Prentice Hall, Englewood Cliffs, NJ.

Abernathy, W.J., Clark, K.B., 1985. Innovation: mapping the winds of creative destruction. In: Tushman, M., Moore, W.L. (Eds.), Readings in the Management of Innovation. Ballinger Publishing Company, pp. 55–78.

Abernathy, W.J., Utterback, J.M., 1988. Patterns of industrial innovation. In: Tushman, M.L., Moore, W.L. (Eds.), Readings in the Management of Innovation. Ballinger Publishing Company, pp. 25–36.

Adler, P.S., Ferdows, K., 1990. The chief technology officer. California Management Review Spring, 55–62.

Altshuler, A., Anderson, M., Jones, D., Roos, D., Womack, J., 1986. The Future of the Automobile: A Report of MIT's International Automobile Program. The MIT Press, Cambridge, MA.

Bessant, J., 1991. Managing Advanced Manufacturing Technology. NCC Blackwell, Manchester, UK.

British Columbia Ministry of Environment, Lands and Park, 1995. BC: A Policy Paper, Clean Vehicles and Fuels for British Columbia. April.

California Air Resources Board, 1999. Website: www.arb.ca.gov.

Capon, N., Glazer, R., 1987. Marketing and technology: a strategic coalignment. Journal of Marketing 51 (July), 1–14.

Christensen, J.F., 1995. Asset profiles for technological innovation. Research Policy 24, 727–745.

Cooper, R.G., Kleinschmidt, E.J., 1993. Major new products: what distinguishes the winners in the chemical industry. Journal of Product Innovation Management 10 (2), 90–111.

Cordero, R., 1991. Managing for speed to avoid product obsolescence: a survey of techniques. Journal of Product Innovation Management 8, 283–294.

Courtney, H., Kirkland, J., Viguerie, P., 1997. Strategy under uncertainty. Harvard Business Review November-December, 67–79.

Day, G., 1977. Diagnosing the product portfolio. Journal of Marketing 41 (2), 29–38.

Fisher, A., 2000. The history of the PC: from floppy disk to laptop. Financial Times, 5 April.

Gomory, R., 1989. From the 'ladder of science' to the product development cycle. Harvard Business Review November-December, 99–105.

Hall, P., 1994. Innovation, Economics & Evolution — Theoretical Perspectives on Changing Technology in Economic Systems. Harvester Wheatsheaf.

Hax, A., 1990. Defining the concept of strategy. In: De Wit, B., Meyer, R. (Eds.), Strategy: Process, Content, Context — An International Perspective. West Publishing Company, pp. 8–12.

Hax, A.C., Majluf, N.S., 1983. The use of the industry attractiveness–business strength matrix in strategic planning. Interfaces 13 (2), 54–71.

Henderson, B.D., 1979. The product portfolio: Growth Share Matrix of the Boston Consulting Group. In: Mintzberg, H., Quinn, J.B. (Eds.), The Strategy Process: Concepts, Contexts, Cases, second ed., pp. 678–680.

Henderson, R.M., Clark, K.B., 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Administrative Science Quarterly 35, 9–30.

Hermance, D., Shoichi, S., 1998. Hybrid electric vehicles take to the streets. IEEE Spectrum November, 48–52.

Hill, C.W., Jones, G.R., 1992. In: Strategic Management: An Integrated Approach. Houghton Mifflin Company, Boston, MA, pp. 274–291.

Hsuan, J., 1998. Capturing Market Access Factors in R&D Management. Licentiate Thesis, Helsinki School of Economics and Business Administration.

Hsuan, J., Vepsäläinen, A.P.J., 1999. Strategisches Portfolio-Management von FuE-Projekten. In: Möhrle, M.G. (Ed.), Der richtige Projekt-Mix: Erfolgsorientiertes Innovations- und FuE-Management. Springer, Berlin, pp. 53–72.

Hsuan, J., Vepsäläinen, A.P.J., 1997. Capturing market access factors in research and development. In:. Managing R&D into the 21st Century — Theory and Practice, The Tools of Trade: Proceedings of the R&D Management Conference, Manchester, UK, July 14–16, vol. 1. R&D Research Unit, Manchester Business School, UK (Chapter 26).

Hunt, G.L., 1998. The great battery search. IEEE Spectrum November, 21–28.

Itami, H., Numagami, T., 1992. Dynamic interaction between strategy and technology. Strategic Management Journal 13, 119–135.

Kanter, R.M., 1989. Swimming in newstreams: mastering innovation dilemmas. California Management Review Summer, 45–69.

Lauro, G.L., Vepsäläinen, A.P.J., 1986. Assessing technology portfolios for contract competition: an analytic hierarchy process approach. Socio-Economic Planning Science 20 (6), 407–415.

Nixon, B. and Innes, J., 1997. Research and development performance measurement: a case study. Paper presented at the 1997 R&D Management Conference, Manchester, July 14–16.

Noori, H., 1990. Managing the Dynamics of New Technology: Issues in Manufacturing Management. Prentice Hall, Englewood Cliffs, NJ.

Pavitt, K., 1990. What we know about the strategic management of technology. California Management Review Spring, 17–26.

Pavitt, K., Robson, M., Townsend, J., 1989. Accumulation, diversification and organisation of technological activities in UK companies, 1945–83. In: Dogson, M. (Ed.), Technology Strategy and the Firm: Management and Public Policy. Longman Group UK Limited, pp. 38–67 (Chapter 4).

Pilkington, A., 1998. The fit and misfit of technological capability: responses to vehicle emission regulation in the US. Technology Analysis & Strategic Management 10 (2), 211–224.

Riezenman, M.J., 1998. Engineering the EV future. IEEE Spectrum November, 19–20.

Roussel, P.A., Saad, K.N., Erickson, T.J., 1991. Third Generation R&D — Managing the Link to Corporate Strategy. Arthur D. Little, Inc.

Scherer, F.M., 1992. International High-Technology Competition. Harvard University Press, Cambridge, MA.

Segev, E., 1995. Corporate Strategy, Portfolio Models. International Thomson Publishing, London.

Slatter, S., 1980. Common pitfalls in using the BCG Portfolio Matrix. London Business School Journal Winter, 18–22.

Stempel, R.C., Ovshinsky, S.R., Gifford, P.R., Corrigan, D.A., 1998. Nickel–metal hydride: ready to serve. IEEE Spectrum November, 29–34.

Teece, D.J., 1986. Profiting from technological innovation: Implications for integration, collaboration, licensing and public policy. Research Policy 15, 285–305.

Toyota, 1997. Care for the Earth — Toyota Automotive Eco-Technologies. Toyota Motor Corporation, Japan (November).

Tushman, M.L., Rosenkopf, L., 1992. Organizational determinants of technological change: toward a sociology of technological evolution. In: Research in Organizational Behavior. JAI Press, Greenwich, CT, pp. 311–347.

Tushman, M.L., Anderson, P.C., O'Reilly, C., 1997. Technology cycles, innovation streams, and ambidextrous organizations: organization renewal through innovation streams and strategic change. In: Tushman, M.L., Anderson, P.C. (Eds.), Managing Strategic Innovation and Change. Oxford University Press, pp. 3–23.

Utterback, J.M., 1994. Mastering the Dynamics of Innovation. Harvard Business School Press, Boston, MA.

Vepsäläinen, A.P.J., Lauro, G., 1988. Analysis of R&D portfolio strategies for contract competition. IEEE Transactions on Engineering Management 35 (3), 181–186.

Von Hippel, E., 1986. Lead users: a source of novel product concepts. In: Tushman, M.L., Moore, W.L. (Eds.), Readings in the Management of Innovation. Ballinger Publishing Company, pp. 352–366.

Wheelwright, S.C., Clark, K.B., 1992a. Creating project plans to focus product development. Harvard Business Review March-April, 70–82.

Wheelwright, S.C., Clark, K.B., 1992b. Revolutionizing Product Development — Quantum Leaps in Speed, Efficiency, and Quality. The Free Press, New York.

Winberg, N., 1996. Good news, bad news man. Forbes January 1, 58–59.

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