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A UNIFIED APPROACH TO R&D MANAGEMENT †

by

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ABSTRACT

The objective of this paper is to provide a conceptual framework for unifying various aspects of the R&D process and decisions that have been considered in such diverse disciplines as operations research, engineering management and economics. The proposed framework and the synthesis of the existing literature within this framework are intended to serve two purposes. Firstly, the analysis is meant to provide scholars with a comprehensive basis for understanding the interrelationships within the existing literature and for developing new models that integrate various facets of the R&D process and the resource allocation decisions. Its second purpose is to enhance managers' understanding of the R&D process as a whole, so that better decisions that take into account the dynamic and uncertain nature of various phases of the total R&D process can be made.

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I. INTRODUCTION

In recent years, problems related to the nature and conduct of industrial research and development have been considered in such diverse disciplines as economics, engineering management and operations research. At the macro level, economists have studied the effect of the firm size and the industrial market structure on the innovative activity, in terms of the resulting inducements to invent, accept and utilize new products and processes. Such studies are exemplified by Mansfield [41, 42, 43], Nelson, Peck and Kalachek [52] and Arrow [3], while Kamien and Schwartz [34] have recently provided a comprehensive survey of this area. Given the market environment, the problems that have been considered at the level of the firm may be braodly classified into (a) R&D project selection and capital budgeting, and (b) determination of resource allocation strategies for the selected projects. Although specific contributions will be indicated later, the surveys by Baker and Pound [8], Cetron, Marino and Roepcke [13], Clarke [15], Weingartner [66] and Baker and Freeland [7] illustrate the former class of problems, while the latter class is typified by the essays in Dean [17] and Marshak, Glennan and Summers [44], and Gittins [28]. Most of the theoretical models as well as the empirical studies reported in the literature at the micro as well as the macro level focus on specific aspects of the total R&D process and decisions, depending upon the author's professional bias and the the limitations of the existing techniques available for their analysis.

The objective of this paper is to provide a conceptual framework for unifying and synthesizing various aspects of the R&D process and resource allocation decisions that have been considered in the literature at the micro level. It is hoped that the proposed framework and the literature overview will (a) enhance the practicing managers' perspective of the total R&D process and the existing literature, thereby facilitating better decision-making and (b) provide scholars with a synthesis and a broader basis for understanding the interrelationships within the existing literature, and identifying the possibilities for developing new models that would integrate different facets of R&D resource allocation decisions.

We will concentrate mainly on studying an industrial R&D process aimed at developing new products or processes of economic value and the resource allocation problems facing the manager in charge. Our emphasis will be on identifying the general characteristics of different phases of the process and the associated decision problems, rather than on precise mathematical details, (although mathematical nomenclature and symbols will be used for compact representations.) The analysis of each phase of the R&D process will include a general formulation of the associated decision problem and will be illustrated by representative existing literature. Since the dual purpose of this paper is to present a unified framework and an overview of the relevant literature within a limited space, no attempt will be made to provide an exhaustive survey of the R&D literature. As indicated before, many excellent comprehensive surveys already exist in the literature.

The most distinguishing feature of research and development, as compared to other investment and productive activities, is the significant amount of uncertainty associated with its conduct. This uncertainty and the corresponding environmental sources may be said to consist of natural, technological and market components and are described in Section 2. In Section 3, the research and development activities are described, respectively, as those involving utilization of the available technology for reducing the natural uncertainty about the true state of nature and application of this knowledge to development of new products or processes of economic value. These activities require selection of capital and human resource allocation strategies in face of the technological uncertainty regarding their effectiveness and the market uncertainty regarding the economic value of the output. The static and dynamic problems of R&D project selection and resource allocation considered in the literature are then identified as speical cases. In Section 4, we consider the problem of optimally controlling the market uncertainty and its relation with R&D resource allocation, thereby pointing out the need for integrating the marketing and the R&D activites and decisions that are usually analyzed separately in the literature. An R&D project is then defined as consisting of the required research, development and marketing activities that involve resource expenditures in face of natural, technological and market uncertainties. The identification problem considered in Section 5 is concerned with observing, testing and estimating these uncertainties and the effectiveness of resource allocations in their control, thereby yielding an R&D project definition. Such a description of the project identification activity unifies, summarizes and illustrates the literature on R&D project evaluation and approach selection problems. The final section integrates these identification, research, development and marketing activities along with the associated resource allocation strategies, thereby defining the entire R&D process and managerial decisions involved in its planning and control. The general conclusion of the paper is that such a unified approach for visualizing the R&D process and decisions not only provides a better perspective for understanding the existing diverse literature but also enables one to identify potential areas of future research.

2. THE ENVIRONMENT AND UNCERTAINTIES

The environment of an industrial R&D process may be broadly described as consisting of natural, technological and economic components. The natural environment of the R&D process refers to those aspects of nature that are relevant to the development of the contemplated new products or processes. The true state of relevant natural environment will be symbolically denoted by s. As an example, s may be the true tensile strength of an alloy to be used in a new machine or it may represent the chemical composition of an organic compound to be used in developing a new drug.

The technological environment, to be referred to by t, consists of relevant aspects of the technology that are currently available for researching, developing and marketing the contemplated invention. These include the available scientific and engineering skills and equipment, the current state of knowledge, available information processing facilities (e.g. computers), and diffusion channels for marketing the innovations (e.g. television and other advertising media).

Finally, the economic environment, to be represented by e, may be described by the organizational structure of the firm (e.g. the degree of decentralization), the industrial market structure (e.g. the degree of competitiveness), governmental regulations affecting appropriability of new inventions (e.g. the patent system) and other economic factors affecting the profitability of marketing new products or processes (e.g. consumer tastes and prices).

The conduct of an R&D process operating within this environment involves considerable amount of uncertainty. This uncertainty may be decomposed into the three components resulting from the corresponding enviornmental sources described above. The natural uncertainty corresponds to an absence of perfect knowledge about the true state s of the natural environment, a reduction in the natural uncertainty being achieved through the research activity. This natural uncertainty may be represented by the researcher's prior probability distribution $P(\cdot)$ of s (summarizing his beliefs, knowledge and the state of information regarding true s), and may be thought of as an input to the research activity. For example, as in Glennan in [44], his information about the true tensile strength s of the alloy may be summarized by, say, the normal distribution with mean $\bar{s}$ and a certain variance. More knowledge about the true tensile strength, (corresponding to a less uncertainty about s) may be represented by a smaller variance and would expedite the development of a more durable engine using this alloy.

With the natural uncertainty summarized in $P(\cdot)$ as an input, the research and development activities require a resource allocation, to be denoted by a, to reduce this uncertainty and apply the resulting knowledge to develop a new product or process. The final outcome of the R&D activities may be symbolically denoted by Q. For example, Q may represent some quality attribute (e.g. durability) of the developed product (or process) which affects its demand in the market. Due to the intrinsically uncertain nature of the R&D activities, Q is usually random. The technological uncertainty represents the internal uncertainty regarding the effectiveness of an R&D resource allocation a in processing the initial knowledge $P(\cdot)$ into the final outcome Q with the use of the available technology. Symbolically, this uncertainty may be represented by the conditional probability distribution $\mathcal{P}(\cdot|P(\cdot), a)$ of the final outcome Q. Thus, typically, a more favorable technological environment (e.g. availability of faster computers and better qualified scientists) results in a superior product with a higher probability, for the same resource expenditures.

The economic value of a given outcome Q of the R&D activities to the firm may be denoted by R, and corresponds to the return obtainable from diffusing the innovation into the economic environment. Usually, R is a random variable due to such uncertain economic factors as changes in consumer tastes and competing products and may be partially controlled by the marketing expenditures (e.g. on advertising), to be denoted by a_m. The market uncertainty regarding the economic value R of the innovation Q with the marketing expenditures a_m may then be summarized by the conditional probability distribution $\mathcal{M}(\cdot|Q, a_m)$

of R. Such a distinction between the technological and market uncertainties has been made by Kamien and Schwartz [32] and others.

Thus, a description of an R&D process naturally requires a consideration of the natural $P(\cdot)$, the technological $\mathscr{P}(\cdot|P(\cdot), a)$ and the market $\mathscr{M}(\cdot|Q, a_m)$ uncertainties, depending upon the corresponding natural, technological and economic components, s, t and e of the environment.

3. THE RESEARCH AND DEVELOPMENT ACTIVITIES

The R&D activity taking place in presence of the above uncertainties has been defined by Arrow [3] as consisting of production and application of knowledge and may be roughly decomposed into the research activity of producing knowledge and the development activity of applying it. For instance, an R&D program aimed at nuclear power generation may be divided into the required basic research in nuclear physics, which may use observed data about the properties of uranium isotopes so as to yield plausible theories regarding their atomic structures, on one hand, and the development of a commercially viable atomic power reactor based on these theories. Although in reality the distinction between research and development activities is often rather hazy and their conduct often nonsequential, such a distinction nevertheless seems to be a natural and convenient approximation and as such has been employed by Brandenburg and Stedry [11] and others.

Various theories regarding generation of new knowledge through research have been proposed, particularly in the philosophy of science literature; for example, see Carnap [12], Churchman [14] and Popper [54]. However, for our purposes, the research activity may be adequately described as an activity that reduces the natural uncertainty about the true state of nature s by an application of capital and human resources. This uncertainty reduction is achieved through experimentation, observation, data processing and formulation and verification of theories and models about true s. For example, conducting tests on the previously mentioned alloy may reduce the variance of the distribution of its strength, yielding a better estimate of its true value; see Glennan in [44] for a further discussion of this interpretation. In general, the research activity may be defined as that of modifying the prior knowledge $P(\cdot)$ regarding true s by making experimental observations and processing them in the Bayesian fashion to yield the posterior probability distribution to be denoted by $P'(\cdot)$. The amount of reduction in the natural uncertainty $P(\cdot)$ achieved through the research activity depends upon the technological uncertainty that is partially controlled by the research expenditures a_r. Thus, employing better qualified scientists or using measuring instruments of greater precision costs more but also provides a better understanding of the various physical properties of the alloy that determine its tensile strength, thereby yielding a better estimate of its true value. The output $P'(\cdot)$ of the research process is therefore a result of the stochastic transformation, which may be denoted by $\mathcal{R}(\cdot \mid P(\cdot), a_r)$. The informational value of the output $P'(\cdot)$ of the research process depends upon the manner in which it is utilized in the subsequent development process that culminates in a concrete new product or a process of economic worth.

The development activity may be broadly described as the activity which translates the research findings into concrete designs or prototypes of new products or processes using engineering techniques. Given the improved knowledge $P'(\cdot)$ about true s, the actual outcome Q of the development activity depends upon the technological uncertainty that is partially controlled by the amount of engineering effort a_d. Although the development activity involves less uncertainty than the research activity (as discussed in Mansfield [41]), effectiveness of the resource allocation a_d in improving the developed product or process can be assessed only probabilistically. Symbolically, the output Q of the development activity is a result of the stochastic transformation $\mathcal{D}(\cdot|P'(\cdot), a_d)$. Nevertheless, it is natural to expect that a greater allocation of development effort a_d, on average, results in a better output product. Thus, given the distribution $P'(\cdot)$ of the tensile strength of the alloy, more elaborate designs and prototype constructions are more likely to yield a more durable (and therefore a more valuable) machine using this alloy, although at a higher cost a_d.

We may now define the composite stochastic transformation $\mathcal{P} = \mathcal{R} \circ \mathcal{D}$, which may be symbolically described by

$$\mathcal{P}(Q|P(\cdot), a_r, a_d) = \int \mathcal{D}(Q|P'(\cdot), a_d)\mathcal{R}(dP'|P(\cdot)a_r),$$

where the resource allocation a_r is required to update the initial prior $P(\cdot)$ into the posterior $P'(\cdot)$ according to the research activity $\mathcal{R}(\cdot|P(\cdot), a_r)$ and the allocation a_d is then used according to the development activity $\mathcal{D}(\cdot|P'(\cdot)a_d)$ to translate $P'(\cdot)$ into a concrete new product or a process Q. Thus, the composite transformation $\mathcal{P}(\cdot|(\cdot), a_r, a_d)$ summarizes the technological uncertainties associated with both the research and development ($\mathcal{R}$ and $\mathcal{D}$) activities that require resource allocations a_r and a_d respectively, to translate the initial knowledge $P(\cdot)$ into the final invention Q. A simple representation of the technological uncertainty $\mathcal{P}$ would be the probability distribution of time required to attain a specified product quality for a given effort. Then it is reasonable to expect that the distribution would shift to the left as the amount of effort is increased, yielding a stochastic analog of the time-cost tradeoff curves studied by Scherer [60] and others in the literature.

In research and development the role of the three types of uncertainties is so pervasive that an <u>R&D activity</u> $\mathcal{A}$ itself may be defined in terms of these uncertainties as $\mathcal{A} = (P(\cdot), \mathcal{P}(\cdot|P(\cdot), \cdot, \cdot), \mathcal{M}(\cdot|\cdot, a_m))$, where a_m is a given marketing expenditure. The resource allocation problem of the manager in charge of such an R&D activity may now be conceptually formulated as that of determining a_r and a_d so as to maximize the expected net return

$$E_{\mathcal{A}}[R-a_r-a_d|a_r, a_d, P(\cdot)] = \iint (R-a_r-a_d)\mathcal{P}(dQ|P(\cdot), a_r, a_d)\mathcal{M}(dR|Q, a_m).$$

In general, the higher the research expenditure a_r the more "accurate" will be the updated knowledge $P'(\cdot)$, thereby increasing the effectiveness of a given development expenditure a_d, as reflected in a more favorable distribution $\mathcal{D}(\cdot|P'(\cdot), a_d)$ of the outcome Q. Thus, conducting more elaborate (and hence more costly) tests on the alloy reduces the variance of its strength; this improved knowledge then permits a more economical use of the alloy in designing a machine part having the desired failure rate, say. However, spending an excessive amount on testing may bring diminishing reductions in uncertainty and also leave less amount for development purposes, ultimately leading to an inferior product. A specific example of such a tradeoff between research and development activities has been considered by Gaver and Srinivasan [24], who consider a simple queueing model in which the uncertainties $\mathcal{P}$ and $\mathcal{M}$ are regarding the completion and the competitor preemption times.

More generally, the problem of optimally distributing a given budget B among several (possibly interrelated) R&D activities $\mathcal{A}_1, \ldots \mathcal{A}_n$ may be formulated in the above notation as that of maximizing

$$E\left[\sum_{i=1}^{n} R_i \,\middle|\, (a_r^1, a_d^1), \cdots (a_r^n, a_d^n)\right]$$

subject to

$$\sum_{i=1}^{n} (a_r^i + a_d^i) \le B$$

$$a_r^i, a_d^i \ge 0, \; i=1,2,\cdots n.$$

In case the R&D activities are independent, the objective function simplifies to

$$\sum_{i=1}^{n} E_{\mathcal{a}_i} [R_i | a_r^i, a_d^i].$$

Specific versions of this problem (without distinguishing between the research and the development phases) have been extensively studied in the literature under the general heading of <u>R&D project selection problem</u>, an R&D project being what we have called an R&D activity. Typically, the desired outcome Q_i (corresponding to the success target) of each R&D activity $\mathcal{a}_i$ is prespecified. The technological uncertainty $\mathcal{P}_i$ is then aggregated into the probability of achieving this success $\mathcal{P}_i(a_i)$ as a function of the allocation a_i, while the market uncertainty $\mathcal{M}_i$ is summarized by the expected value $\bar{R}_i$ (and sometimes the variance) of the return R_i from the i^{th} activity. The static project selection problem is then that of selecting a subset of the n given projects, so as to maximize $\sum_{i=1}^{n} [\mathcal{P}_i(a_i)\bar{R}_i - a_i]$ subject to $\sum_{i=1}^{n} a_i \leq B$. The capital budgeting formulation has been considered by Disman [20], who applies the net present value method for its solution. Asher [5], Freeman [22], Beged-Dov[9], Hamberg [30], Bell and Read [10], Souder [62] and others provide integer linear programming formulations, while Minkes and Samuels [47] also include, in addition to the budget constraint, a constraint on the level of risk of the portfolio of selected projects. Models that take into account various uncertainties in a more elaborate fashion than just expected values use stochastic programming and and stochastic networks. The former approach considers probabilistic objective functions and constraints and is summarized by Gear, Lockett and Pearson [26] and Freeman and Gear [23], while the latter is represented by Dean [16], Gear and Lockett [25], Lockett and Gear [38] and Lockett and Freeman [37]. Finally, Weingartner [66] has provided a survey of the methods of selection among interrelated projects along similar lines.

The above problem formulation and the models described are largely static in that only one shot resource allocation decisions are considered. However, most R&D activities evolve over a period of time, during which the resource allocation decisions can be modified on the basis of the updated information regarding their current status. Such a <u>dynamic resource allocation</u> strategy would take into account the effects of past allocations when making decisions regarding current allocations, thereby providing a degree of flexibility in the management of R&D activities over time. Given an R&D activity $\mathcal{A}$ that evolves through time, with the initial input $P(\cdot)$ and the final market uncertainty $\mathcal{M}(\cdot|Q, a_m)$, the total technological uncertainty $\mathcal{P}(\cdot|P(\cdot), \cdot)$ regarding its output Q may be considered to be a composition of a series of intermediate stochastic transformations that are controlled by resource allocations through time. To consider a general formulation of the dynamic resource allocation problem, suppose, for the simplicity of exposition, that our R&D activity consists of the development phase alone and suppose that the progress of the R&D activity is reviewed at discrete points in time $t=0,1,2,\ldots$. Let Q_0 denote the initial product (or process) on hand, and for $t=1,2,\ldots$ let Q_t denote the product developed by date t, summarizing the activity status on that date. For example, Q_t may be a certain measure of efficiency of the engine developed by date t. Also let a_t denote the amount of resources allocated to the R&D activity in period t, and $\{Q_t,a_t\} = \{Q_o,a_o \ldots Q_t,a_t\}$ be the history to date t. Suppose that, given the activity history $\{Q_t,a_t\}$, $p(\cdot|\{Q_t, a_t\})$ represents the probability distribution of Q_{t+1}, summarizing the one stage technological uncertainty in period t. Typically, one would expect that higher expenditures and more promising status histories would lead to more favorable values of Q_{t+1}, on average. Let T be the (random) stopping time at which the R&D activity is terminated, yielding the final outcome Q_T (a random variable), whose economic worth will be, as before, determined according to the market uncertainty $\mathcal{m}(\cdot|Q_T, a_m)$. Thus the overall technological uncertainty $\mathcal{P}(\cdot|Q_o, \sum_{t=0}^{T} a_t)$ is composed of one period transformations, $p(\cdot|\{Q_t,a_t\})$ t=0,...T. Then the dynamic R&D resource allocation problem is to select the stopping rule T and the resource allocations $a_0, a_1, \ldots a_T$, so as to maximize the expected net return symbolized by

$$\int \ldots\ldots \int\int (R- \sum_{t=0}^{T} a_t)\mathcal{m}(dR|Q_T, a_m)p(dQ_T|Q_{T-1}, a_{T-1})\ldots\ldots p(dQ_1|Q_o,a_o).$$

In this stochastic control formulation, a dynamic feedback strategy $\alpha(\cdot)$ will specify at any time t, depending upon the activity history $\{Q_t,a_t\}$, (a) whether to stop the R&D activity and market the final outcome Q_t or to continue its further development, and in case of continuation (b) what the current resource allocation a_t should be. A similar continuous time formulation is possible for allowing changes in project status to take place at random points in time, the transition rate of change being $p(1|\{Q_t, a_t\})$. A specific version of this formulation has been analyzed by Deshmukh and Chikte [19], using the semi-Markov decision process methodology. They show that it is best to terminate the project if either it has advanced sufficiently or lagged below a critical level, while in the intermediate region the optimal allocation is increasing in the project status, thus characterizing the optimal strategy $\alpha(\cdot)$. In most of the rest of the literature, the activity target, which may be denoted by 1, is prespecified and the intermediate status Q_t is classified as either successful attainment of the target (i.e. Q_t=1) or not (i.e. Q_t=0), while $p(1|\{Q_t, a_t\})$ = $p(1|0, \int_0^t a_u d_u)$ denotes the (conditional probability of) success rate as a function of the accumlated effort till then. Under different assumptions regarding p, Kamien and Schwartz [32,33] and Lucas [39] have obtained forms of resource expenditure patterns using the Pontryagin's maximum principle, while Aldrich and Morton [2] have obtained similar results using a continuous time dynamic programming models. A typical conclusion is that, if $p(1|0, \int_0^t a_u)$ is increasing in the accumulated effort $\int_0^t a_u d_u$, then the optimal expenditure a_t is increasing in time t. Hess [31] seems to be the first to consider the problem of dynamic resource allocation in an R&D activity, while Rosen and Souder [57] have extended his model to multiple R&D activities; they have considered discrete time dynamic programming models. Gittins [27,28,29] and Laska, Meisner and Siegel [36] have applied variational methods for characterizing optimal allocation strategies for multiple R&D

activities, using models similar to Kamien and Schwartz [32], with criteria such as minimization of the expected time for completing the activities. It is shown that the optimal policy is to pursue the activities sequentially if the success rates are increasing and in parallel if they are decreasing. To consider a general model of several (possibly interrelated) R&D activities $\mathcal{a}_1,\ldots\mathcal{a}_n$ evolving over time, let the vector $(Q_t^1,\ldots Q_t^n)$ represent their status on date t. Then, an application of a dynamic resource allocation strategy would yield the stopping times $(T^1,\ldots T^n)$ and the resource distributions $(a_t^1,\ldots a_t^n)$ of the available budget B_t. An example of such a formulation is provided by the controlled random walk model of Radner and Rothschild [44] who investigate, in a slightly more general setting, implications of following certain plausible behavioral (rather than optimal) rules (e.g. "fire fighting" or "staying with the winner").

This concludes our synthesis of the problem of resource allocation in R&D activities. In summary, the input to each R&D activity is given by the knowledge $P(\cdot)$ regarding the true state of nature, while its output is a product or process of quality Q. The conduct of each R&D activity requires determination of the resource allocation strategies α_r and α_d to research and development, so as to process the initial knowledge $P(\cdot)$ into the improved knowledge $P'(\cdot)$ and translate the latter into the concrete outcome Q. The effectiveness of strategies α_r and α_d in attaining an outcome Q is uncertain due to the technological uncertainty $\mathcal{P}(\cdot|\cdot,\cdot,\cdot)$. The economic worth R of an outcome Q is determined by the market according to the market uncertainty $\mathcal{m}(\cdot|\cdot,a_m)$, where the marketing expenditures a_m have been assumed to be given and fixed throughout this section. The next section considers the problem of optimally choosing a_m along with α_r and α_d, thereby pointing out the interface of the marketing and the R&D activities.

4. THE MARKETING ACTIVITY

The effect of the economic (market) environment has been incorporated into the R&D allocation strategies to a more or less extent by several authors. Thus, for example, Atkinson and Bobis [6] include estimates of sales of the newly developed products into their R&D activity selection and resource allocation model, while in dynamic R&D models, Scherer [61], Kamien and Schwartz [33], Gaver and Srinivasan [24], and Deshmukh and Chikte [19] explicitly include the market uncertainty in the form of the competitors' actions in introducing similar products that affect the demand for the product being developed. Mansfield [41, Chapter IV] summarizes empirical studies of the process of diffusion of new inventions into the economic environment. While the economic environment as an exogenous factor has been extensively studied and modeled in the R&D literature, the subject of altering the economic environment, in terms of bringing about changes in the new product demand through marketing expenditures have been considered in the marketing management literature; see, for example, Kotler [35], Montgomery and Urban [49], Massy, Montgomery and Morrison [46], Rao [56] and references therein.

Given a newly developed product of quality Q, the return R from marketing it is uncertain and depends upon the marketing expenditure a_m through $\mathcal{M}(\cdot|Q, a_m)$. The marketing expenditure a_m includes any expenditure (e.g. on advertising), which influences the shape or position of the firm's demand curve of the developed product Q (as in Dorfman and Steiner [21]). To provide a simple general formulation of the static problem of determining the marketing expenditures for a given R&D outcome Q, suppose that z(Q) denotes the profit (i.e. sales price minus production cost) per unit of the new product Q and the market uncertainty $\mathcal{M}(\cdot|Q, a_m)$ represents the distribution of the demand for the product of quality Q when the amount a_m is spent on marketing it. Then the problem is that of choosing a_m within the advertising budget B_m so as to maximize the expected net reward given by

$$E_{\mathcal{M}}[R-a_m|Q,a_m] = \int[z(Q)x-a_m]\mathcal{M}(dx|Q, a_m)$$

A more comprehensive static resource allocation strategy would consider the research, development and marketing activities together. This results in the global optimization problem of selecting a_r, a_d, and a_m simultaneously so as to maximize

$$E[R-a_r-a_d-a_m|a_r,a_d,a_m,P(\cdot)] = \int\int(z(Q)x-a_r-a_d-a_m)\mathcal{P}(dQ|P(\cdot),a_r,a_d)\mathcal{M}(dx|Q,a_m)$$

within the budget restriction $a_r+a_d+a_m \leq B$. Such a formulation would integrate the problems of new product research, development and marketing and identify tradeoffs involved in the resource allocations among these activities. Thus, too much expenditure on an R&D activity would result in the development of a superior product Q; however, it would leave too little a budget for advertising, thereby reducing the expected demand and hence net profits. Similarly, allocating too little to R&D would produce an inferior product, whose demand can not be substantially increased by advertising, however aggressive, due to demand saturation effects. Tradeoffs of this type have been analyzed in a deterministic framework by Dorfman and Steiner [21], who consider a specific problem of joint optimization of product quality, product price and advertising expenditure.

The above static formulation could be extended to take into account the empirically observed fact (see Vidale and Wolfe [65] and Rao [56]) that the effect of advertising on sales persists over a period of time. The resulting stochastic dynamic optimization problem is analogous to the one arising in control of an R&D activity considered in the previous section, except that the reward is obtained continuously during the conduct of the marketing activity rather than just upon its termination. In the literature, only deterministic models of the Vidale-Wolfe type have been considered and the optimal control theory is employed for characterizing optimal advertising policies (e.g. see Nerlove and Arrow [53], Sasieni [58] and Sethi [59].) A general result is that it is optimal to undertake an initial intense advertising until a critical sales level is reached and then continue with just enough expenditure to maintain sales at that level. Given a developed product of quality Q, it would be interesting to obtain a similar characterization of the stochastic control strategy α_m for marketing it. For instance, it is reasonable to expect that a better quality product would require a lesser amount of time and advertising effort to reach the critical sales level and to maintain it there.

In order to integrate the problems of optimally conducting the R&D and the marketing activities, the manager should determine the resource allocation strategies $\alpha_r(\cdot)$, $\alpha_d(\cdot)$ and $\alpha_m(\cdot)$ jointly. Thus, he may first determine, as above, the marketing strategy $\alpha_m(\cdot|Q)$ for each possible outcome Q of the R&D activity, thereby yielding the maximum expected reward R(Q) from the R&D activity. Then he may determine $\alpha=(\alpha_r(\cdot), \alpha_d(\cdot))$, as in the previous section, taking R(Q) as the terminal reward from the R&D activity if Q is the actual outcome. Although in reality, the conduct of research, development and marketing activities is often overlapping through time, the above sequential separation seems to be a reasonable approximation that is necessary for their systematic consideration. A possible integrated model would then correspond to a combination of, for example, the models of Vidale and Wolfe [65] and Kamien and Schwartz [32]. However, such integrated models seem to have received little attention in the literature.

In the previous section an R&D activity was defined to be $\mathcal{A} = (P(\cdot), \mathcal{P}(\cdot|P(\cdot), \cdot,\cdot), \mathcal{M}(\cdot|\cdot, a_m))$ where the marketing expenditures a_m were assumed to be fixed and the problem was that of determining the resource allocation strategies $\alpha_r(\cdot)$ and $\alpha_d(\cdot)$ for controlling the technological uncertainty $\mathcal{P}(\cdot|P(\cdot),\cdot,\cdot)$ in processing the initial input $P(\cdot)$ into a final outcome Q whose value R was determined by the uncontrolled market uncertainty $\mathcal{M}(\cdot|Q,a_m)$. The additional consideration of controlling this market uncertainty through $\alpha_m(\cdot)$, as in this section, may now be used to define the manager's role as that of conducting the <u>R&D Project</u>

$\Pi = (P(\cdot), \mathcal{P}(\cdot|P(\cdot),\cdot,\cdot), \mathcal{M}(\cdot|\cdot,\cdot))$, which may be abbreviated by $\Pi = (P,\mathcal{P},\mathcal{M})$, and which consists of the R&D as well as the marketing activities controlled through strategies $\alpha_r(\cdot)$, $\alpha_d(\cdot)$ and $\alpha_m(\cdot)$. The optimal net return from conducting such a project Π will be denoted by $V(\Pi)$, which may be called as the <u>Project Value</u>. (In general, the R&D manager's problem is that of determining the strategies $\{(\alpha_r^i(\cdot), \alpha_d^i(\cdot), \alpha_m^i(\cdot)): i=1,2,\ldots,n\}$ for conducting n (possibly interrelated) R&D projects $\Pi_1,\ldots,\Pi_n$, so as to maximize $\sum_{i=1}^{n} V(\Pi_i)$).

Up to this point, we have implicitly assumed that the R&D manager has a complete knowledge of the three uncertainties that define the project Π he is in charge of. However, this is hardly the case in most real world R&D projects. Therefore, before determining $(\alpha_r(\cdot), \alpha_d(\cdot), \alpha_m(\cdot))$ as above, the necessary first step is to evaluate and estimate these uncertainties, thereby defining the project $\Pi=(P, \mathcal{P}, \mathcal{M})$ to be pursued. Such an activity may be called the R&D project identification activity and is considered in the next section.

5. THE R&D PROJECT IDENTIFICATION ACTIVITY

In reality, a research and development task is specified by merely a general qualitative description of its objective and scope along with possible means of attaining it. For example, a general objective of the Energy Research and Development Program of the United States is that of achieving energy self sufficiency, which could be attained in one or more of several possible ways, such as development of nuclear power plants, coal gasification, solar energy development, etc., pros and cons of each being roughly known. The different possible ways or means may be, in general, termed as approaches to achieve an R&D task. As Marschak describes in [44], Chapter 5, an approach corresponds to "the pursuit of a particular kind of design or the use of a particular type of technology or the attempt to reach a particular subregion of the satisfactory part of the performance space." The major conceptual difference between an approach and a project is that, pursuing two or more projects to completion yields the total return equal to the sum of their individual returns, while pursuing two or more approaches (to a task) to completion yields the return equal to only that of the best of these approaches.

Associated with the j^{th} approach is the triple $(P^j, \mathcal{P}^j, \mathcal{M}^j)$, defining the natural, technological and market uncertainties that determine the effectiveness of resource allocation strategies

$(\alpha_r^j, \alpha_d^j, \alpha_m^j)$ in pursuit of that approach. Given n possible approaches to an R&D task, the project identification activity may now be defined as that of estimating the associated uncertainties $\{(P^j, \mathcal{P}^j, \mathcal{M}^j), j=1,2,\ldots n\}$ and selecting one of the approaches, say j^{*th} one, which then defines the project $\Pi = (P^{j*}, \mathcal{P}^{j*}, \mathcal{M}^{j*})$ to be pursued to completion according to the strategies $(\alpha_r^{j*}, \alpha_d^{j*}, \alpha_m^{j*})$ that are determined as in the previous sections. The identification activity essentially consists of translating the qualitative description of an approach to the R&D task into the representation $(P,\mathcal{P},\mathcal{M})$ through activities such as preliminary appraisal, inquiry, observations and estimation of the associated uncertainties. In the literature such estimates have been considered in terms of the expected amount of time and cost required to complete the task (summarizing the technological uncertainty $\mathcal{P}$) and the expected profit obtainable from marketing the innovation (summarizing the market uncertainty $\mathcal{M}$). Let the initial estimate of $(P,\mathcal{P},\mathcal{M})$ be denoted by $(P_0,\mathcal{P}_0,\mathcal{M}_0)$, which is then modified through time by the above mentioned activities requiring an expenditure a_i of resources. As before, we may denote by $\alpha_i(\cdot)$ the strategy for allocating resources $a_i = \sum_{t=0}^{T_i} a_{it}$ to the identification activity, where a_{it} is the amount allocated in period t and T_i is the termination time, following $\alpha_i(\ )$. The final estimate $(P_{T_i}, \mathcal{P}_{T_i}, \mathcal{M}_{T_i})$ is the output of the identification activity and defines the project Π to be pursued.

More generally, given n possible approaches to attaining a research and development objective, we may define the R&D task

$\tau = \{(P_0^j, \mathcal{P}_0^j, \mathcal{M}_0^j): j=1,2,\ldots,n\}$, where $(P_0^j, \mathcal{P}_0^j, \mathcal{M}_0^j)$ is the manager's initial estimate of the uncertainties associated with pursuing the j^{th} approach. Then the identification problem is that of determining $\alpha_i(\cdot)$ for allocating estimation efforts $\{(a_{i0}^j, a_{i1}^j, \ldots a_{iT_i}^j): j=1,2,\ldots n\}$ to each approach and T_i, the identification duration, at the end of which one of the approaches, say j^{*th} one is chosen on the basis of the final estimates $\{(P_{T_i}^j, \mathcal{P}_{T_i}^j, \mathcal{M}_{T_i}^j): j=1,2,\ldots n\}$, yielding the project $\Pi = (P_{T_i}^{j*}, \mathcal{P}_{T_i}^{j*}, \mathcal{M}_{T_i}^{j*})$. However, such a strategy of continuing the identification of all the n approaches for T_i periods before selecting the best one may be uneconomical due to high observation and measurement costs involved. A better strategy would then be one that sequentially eliminates unpromising approaches with unfavorable current estimates as the identification activity proceeds. Such a sequential strategy for identifying and selecting an approach has been proposed and studied by Nelson [51], and Marschak and Yahav [45], who provide conditions under which it is optimal to eliminate approaches with unfavorable current estimates of the expected costs and times required to complete the project (summarizing the associated technological uncertainty) following those approaches. MacQueen [40] considers, in a related context, the problem of sequentially evaluating, testing and selecting an approach based on estimates of its expected terminal return (summarizing the market uncertainty), using the optimal stopping theory. He shows that, under certain conditions, it is optimal to eliminate an approach with estimate lower than a critical value, accept if it is above some other critical value and collect more information for intermediate estimates. Sometimes, the evaluation of approaches is accomplished by their actual implementation (e.g. see Abernathy and Rosenbloom [1].)

The approaches with unpromising (partial) outcomes are then successively abandoned. Even otherwise, it may be optimal to pursue more than one approaches until one of them is successful, (see Scherer [60]). Such a strategy of parallel scheduling of approaches is attractive if the terminal reward or the cost of delaying the project completion is high.

In general R&D management, the strategy $\alpha_i(\cdot)$ for conducting the identification activity must be determined in conjunction with the strategies $(\alpha_r(\cdot), \alpha_d(\cdot), \alpha_m(\cdot))$ for conducting the resulting R&D project. Such a joint determination would take into account the natural tradeoffs between the cost of obtaining improved estimates of various uncertainties involved in an R&D task and the benefits accrued from such better estimates in terms of improved resource allocation strategies. For example, there may be a fixed total budget for search, evaluation and selection of an approach and its implementation, thus providing an interface between the identification and the R&D activities. However, no specific models of this type have been reported in the literature.

Thus, the identification activity takes the R&D task $\tau = \{(P_o^j, \mathcal{P}_o^j, \mathcal{M}_o^j): j=1,2,...n\}$, expressed in terms of the initial estimates of the uncertainties associated with the n possible approaches and applies the sequential resource allocation strategy $\alpha_i(\cdot)$ to improve these estimates and select one of these approaches, thereby yielding the R&D project Π, which is then pursued as in the previous section. We may summarize this <u>identification activity</u> by the stochastic transformation $\mathcal{J}(\cdot|\tau, \alpha_i(\cdot))$ that yields the R&D project Π as a function of the R&D task τ and the strategy $\alpha_i(\cdot)$.

6. INTEGRATION AND REMARKS

To summarize the previous sections, the total research and development process takes place within the natural, technological and economic components (s,t,e) of the environment and the related uncertainties $(P, \mathcal{P}, \mathcal{M})$. The identification activity, $\mathcal{I}$ requires the resource allocation strategy α_i to obtain estimates of these uncertainties for various approaches to the R&D task τ and to select one of the, thereby defining an R&D project Π. The research activity $\mathcal{R}$ then requires an allocation strategy α_r to reduce the natural uncertainty, while the development activity $\mathcal{D}$ applies this improved knowledge P′ about s to provide a new product or process Q, using the allocation strategy α_d. This outcome Q of the R&D activity is finally diffused into the economic environment by the marketing activity $\mathcal{M}$ that requires the allocation strategy α_m in order to collect the return R. Thus, we may define an R&D Process by

$$(\mathcal{I}(\Pi|\tau, \alpha_i), \mathcal{R}(P'|P, \alpha_r), \mathcal{D}(Q|P', \alpha_d), \mathcal{M}(R|Q, \alpha_m)),$$

whose management involves selection of the resource allocation strategies $(\alpha_i, \alpha_r, \alpha_d, \alpha_m)$ for conducting the identification, research, development and marketing activities (see Figure 1). Even more generally, the R&D manager has to conduct multiple such R&D processes simultaneously in practice.

Clearly, the general problem of optimally managing a given R&D process by determining $(\alpha_i, \alpha_r, \alpha_d, \alpha_m)$ simultaneously is of a formidable magnitude. However, such a representation of the total R&D process has integrated its various facets, along with the interrelated resource allocation decisions and provided a broad perspective for viewing the existing literature in a unified fashion, as illustrated at appropropriate places in this paper. Thus, for example, within the context of an R&D process we have identified the interrelationships among such diverse studies as in Arrow [3], Marschak and Yahav [45], Beged-Dov [9], Gittins [27], and Sasieni [58], while some papers apprarently unrelated to our subject matter, such as those by Radner and Rothschild [55] and MacQueen [40], were found to be, in fact, quite relevant. It is hoped that such a total approach and the literature overview has not only provided a better understanding of the decision models in the existing literature but also helped identifying gaps and possible future research topics. Thus, in general, the identification phase seems to have received only a moderate attention and the existing models seem to concentrate on estimating only a single type (i.e. technological or market) uncertainty associated with an R&D task. The literature on resource allocation to the R&D activity itself is extensive, although there are only a few models that consider the process dynamics and the associated uncertainties explicitly or allow for the dependence of R&D resource allocations on the project performance. Finally, the marketing activity has usually been studied independently of the R&D activity and, moreover, without explicity consideration of market uncertainty. In conclusion, we feel that the general framework proposed here has a considerable potential for suggesting new specific R&D resource allocation models that are more comprehensive and at the same time mathematically tractable.