RESEARCH AND DEVELOPMENT, TECHNOLOGICAL INNOVATIONS AND DIFFUSION

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Contents

Summary

The Chapter describes a comprehensive approach to model the processes of research and development, the introduction of new products, i.e. the stage of innovation, and the process of diffusion of new products in the market place. It emphasizes the importance of an integrated view of the different stages of innovation processes. The aim is to generate insight in the complexity and the dynamics of innovation processes. After a brief discussion of modules to map R&D and innovation diffusion for different market conditions, a model which links the three stages of the innovation processes together is described and analyzed. Since the model views innovation processes from the perspective of the management of a firm, it shows the influence of corporate decision variables like pricing, R&D-budgeting or quality control on the diffusion of innovations and the development of a firm.

1. Importance of Permanent Innovation Activity

Incessant activities of improving and renewing a company's range of products and its production processes are commonly seen as crucial for survival in a competitive environment. However, to improve the competitive position or the competitive advantage, ongoing innovation activity through the development, test and introduction of new products and/or production processes is necessary. This simplified description of the major tasks and objectives during the process of R&D, innovation, and diffusion is faced with highly dynamic and complex problems that have to be solved during the innovation processes by management.

At least since 1970 it could be observed that new and technically more complex and sophisticated products and processes have to be developed in a shorter span of time. Resources have to be allocated to research and development projects which are expected to be economically successful. New products have to be introduced to global markets with stiff competition. Decisions about the adequate time to market and appropriate pricing, advertising, and quality strategies have to be made. The complexity and difficulties to manage innovation activities partly derive from the comprehensiveness of the innovation processes. According to Schumpeter innovation processes can be separated in three stages: (1) invention, the phase where new products are developed, (2) innovation, i.e. introducing new products in the market, and (3) imitation or diffusion, the spreading of new products in the market place (see Figure 1). To be competitive, companies have to be successful in all stages of the innovation process. This becomes obvious when empirically derived new product failure rates and innovation costs are analyzed. Figure 1 illustrates the cascading process of innovation activity and the related innovation costs. Only approximately 40% of all research projects can be seen as successful from a technical point of view. 22% of all R&D projects lead to products that are introduced to the market and 18% are stopped because of the missing economic potential in the market place. From the projects being introduced in the markets, 60% are economic failures and only 40% are economically successful. This means that in total only 8.8% of all R&D projects turn into economic successes and have to earn all resources necessary for the process of innovation activities (*There is a wide range of literature on success rates, with results partly depending on the industry. The numbers in Figure 1 represent average values.*)

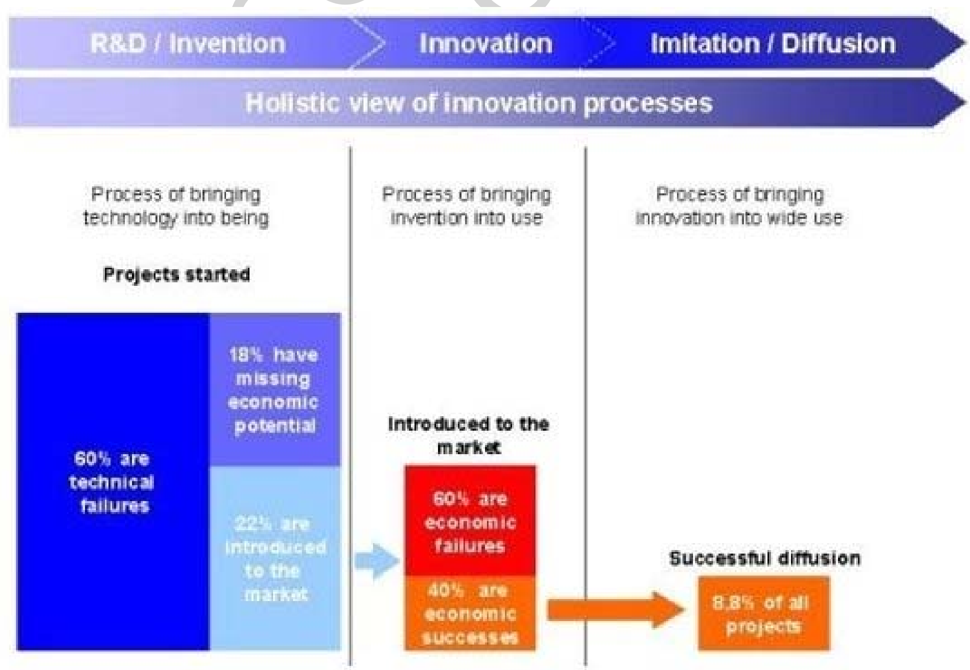

Figure 1. Outcome of innovation activities

Many concepts to support the management of innovation processes only consider the distinct and separate stages of the whole innovation process. Some authors used the System Dynamics approach to investigate the dynamics of R&D projects in search for levers for an effective management of R&D projects. Others investigate the dynamics of new product development projects and the interactions between the different stages and tasks of these projects. Several basic research articles discuss different approaches to model the diffusion of innovations over time. This article will briefly examine these models and show that they are insufficient to improve the understanding of the structures and forces driving the processes of R&D, innovation and diffusion, but its main focus are the interactions between the three Schumpeterian stages of the innovation process.

Figure 2 shows in a causal loop diagram mutual influences of corporate decision variables (marked with hexagons) on technical capability and demand of the products. It also shows how corporate decisions are interconnected through several feedback structures. Although the figure does not show all potential feedback relations, it gives an impression of the complexity of a comprehensive innovation process model.

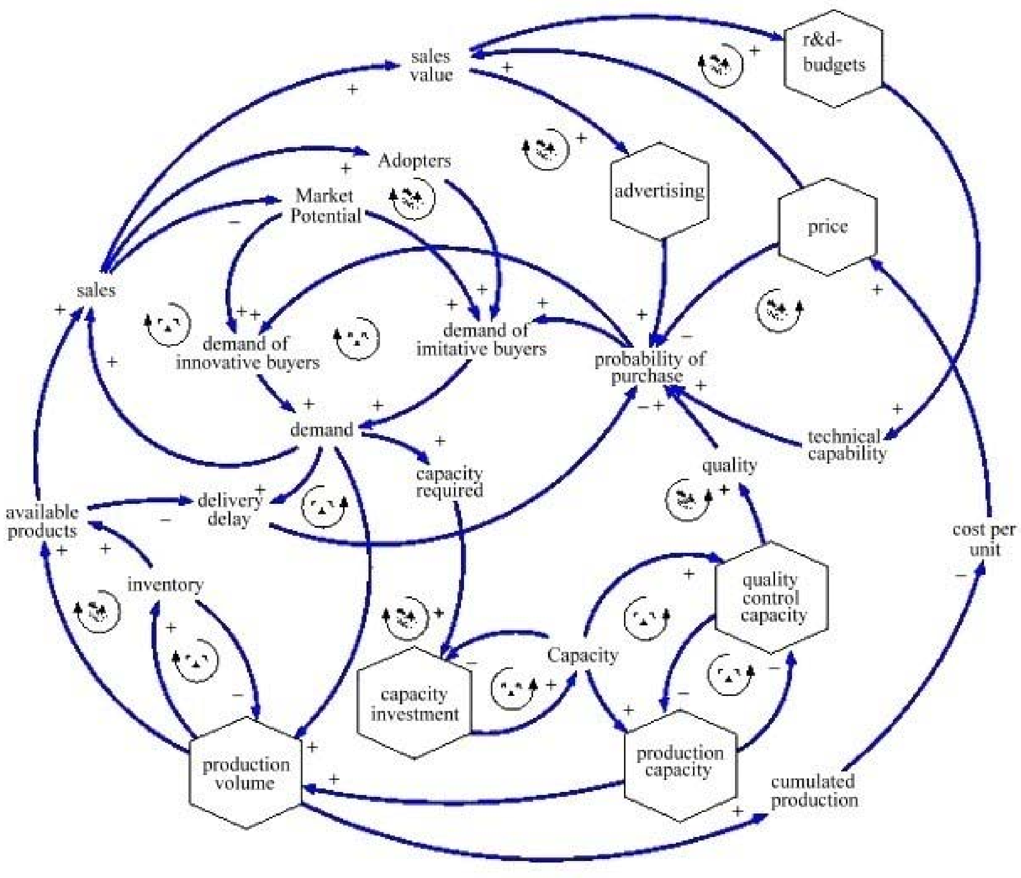

Figure 2. Feedback structures driving innovation processes

Decision variables like pricing or advertising show a direct impact on the probability of a purchase. The higher the advertising budgets and the lower the price, the higher will be demand for the products of a company. There are also indirect or delayed effects, which slow down or speed up the spread of a new product in the market. The actual sales of a product may be limited by insufficient production and inventory, which increase the delivery delays perceived by the potential customers and therefore result in decreasing probability of demand and purchase. Growing demand motivates the company to expand its capacity and to increase the volume of production. This leads to higher cumulated production and through experience curve effects to decreasing costs per unit, lower prices, and therefore to still further increased demand.

Since total capacity has to be used partly to ensure the quality of the output, a certain percentage of capacity has to be allocated to quality control—either end of pipe or during the production process. Quality control will improve product quality, which directly affects demand.

For an improved understanding of the dynamics generated by the feedback structures, the System Dynamics approach is highly suitable. Models developed in this manner can serve as simulators to analyze the consequences of strategies and to improve understanding of innovation dynamics. It can show e.g., how R&D strategies, pricing strategies, and investment strategies influence each other; it can also show the impact of intensified quality control on production and sales of a period, and therefore can be used to investigate the effects resulting from the links between, R&D and other functional areas as well as the markets of a company (See *System Dynamics: Systemic Feedback Modeling for Policy Analysis*).

2. A System Dynamics Perspective of R&D and Innovation Diffusion Models

The numerous interactions between the different stages of the innovation process require a comprehensive approach. Models which do not consider these interactions must fail if they are used as a tool to evaluate strategies or to generate an improved understanding of innovation processes. This chapter outlines how the different stages can be modeled and which specific aspects have to be considered. It deals with an evolutionary algorithm to model the research and development stage (Section 2.1), discusses different approaches to model the stages of innovation diffusion of a new product or a technological innovation in the market (Section 2.2), and finally links the models of research and development and innovation diffusion under competitive conditions (Section 3).

2.1. Modeling R&D Processes

The stage of research and development deals largely with intangible and at least partly stochastic processes. The uncertain outcome of industrial R&D is commonly observed. In literature many attempts are described to define a production function for research and development similar to that of material goods. These R&D production functions use as input the resources allocated like budget, number of people assigned or laboratory equipment available. As output for example, the number of innovations or patents are used. There are several reasons why these approaches to model R&D processes fail, e.g. the stochastic nature of R&D, and the extremely heterogeneous output, which leads to measurement problems. Most important, however, these models are black box approaches; they are not successful in describing how the various factors influencing the outcome of this stage operate together. They are not suitable to generate insights in the development of technological innovations over time. Here a different approach is suggested. Since the development of new knowledge can be seen as an evolutionary process, an analogy to biological evolution theory defines how new concepts develop by the variation and mutation of existing and known solutions. The results are evaluated on the basis of their viability. If they seem to be superior to previous combinations, they are selected for further development and future evolution; otherwise they are discarded.

Technological knowledge of a company and a product is modeled as binary matrices with the entries “1” and “0” (Figure 3). Each matrix can be interpreted as a basic invention that gives access to the potential of a new technology. The size of the matrix represents the maximum technological potential and expresses the importance of a technology. The element “0” is interpreted as basic knowledge in a specific field of the technology; the element “1” means applied knowledge which will be incorporated in a new product. The number of columns and rows of a matrix is only limited by technical restrictions of the computer system used to run the model. The value of a matrix—and therefore the worth of the technical know-how—is determined by counting the number of elements with the value “1”. It determines the units of technical know-how incorporated in a product. The difference between the maximum possible number of elements which could have the value “1” and the actual number represents the technological potential.

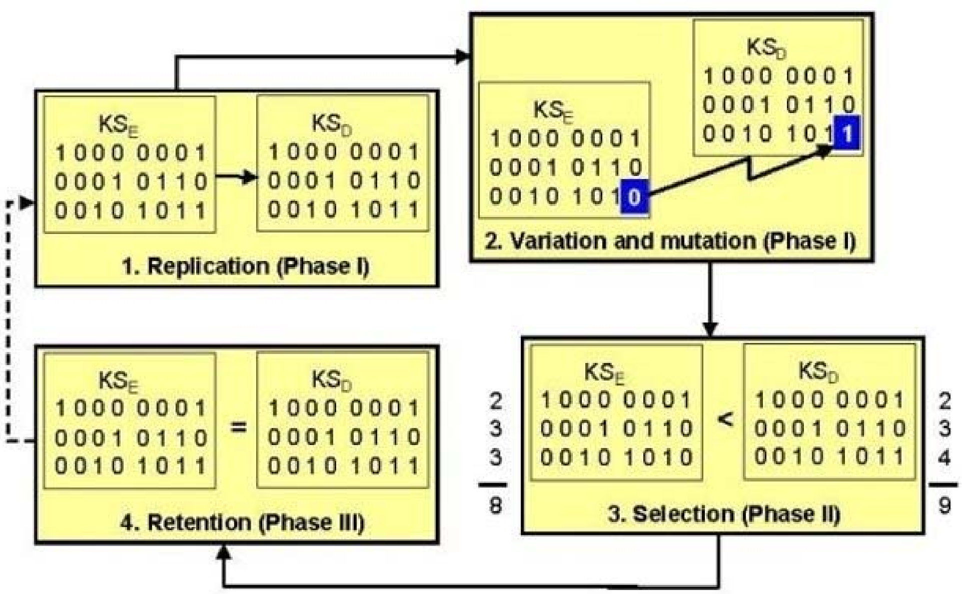

Figure 3. Evolutionary approach to R&D

Figure 3 describes the evolutionary process which is used to map the R&D process. The evolution algorithm—it is written in the programming language C and can be linked to a Vensim-based system dynamics model—follows three phases of evolution. In a first step of phase I (replication) the matrix of a technology, called the knowledge system elder (KS_E) is duplicated to the knowledge system descendant (KS_D). In the second step of phase I (variation and mutation) the algorithm randomly selects an element of the matrix (KS_D) and changes the value of the element from “0” to “1” or vice versa.

In phase II selection takes place. The value of the mutated matrix (KS_D) is compared to the value of the knowledge system (KS_E) by counting the number of elements with the value “1” (selection). If the value of (KS_D) is higher—as in the example of Figure 3—, the new matrix is selected; otherwise—if more elements have been changed from “1” to “0” than from “0” to “1” —, it is rejected. Phase III (retention) realizes the result of the selection. The technological system with the higher number of elements with the value “1” is the superior one and becomes the basis for the next evolutionary step, i.e. the knowledge system (KS_D). The number of variations and mutations of the matrix in each period of time depends on the intensity and the volume of the R&D process. This analogy to biological evolution theory defines how new concepts develop by the variation and mutation of existing and known solutions and the following selection. The respective results are evaluated on the basis of viability. If they are superior to previous combinations they are selected for further development and become the basis for future evolution, otherwise they are discarded.

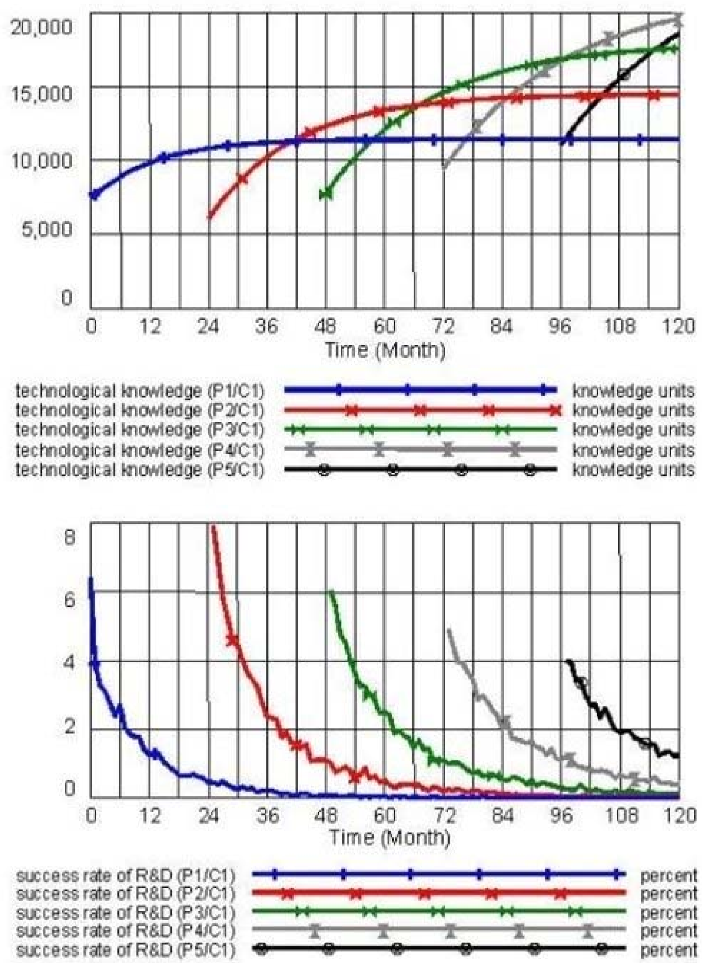

Figure 4. Behavior over time of the evolutionary R&D processes

The evolutionary algorithm generates the time behavior shown in Figure 4. The left part shows the evolution of the technological knowledge for four succeeding technologies of a company. The right part shows the time behavior of the rate of success of R&D and the remaining technological potential as a percentage of the total potential knowledge. The number of evolutionary steps during each period of time depends on the intensity and the volume of R&D, which is held constant during the simulations. In reality it is influenced by the resources a company allocates to R&D. Hence, resources allocated to the process drive the outcome of research and development. The behavior is influenced by stochastic elements since the outcome of variation and mutation depends on the random number picks of the elements of the binary elements of the knowledge matrices.

The evolutionary approach using binary matrices can also be seen in a stock-flow perspective (Figure 5). The number of rows and columns determine the technological potential which is increased by basic research results. This corresponds to the addition of new rows to the binary matrices. The technological potential is decreased by inventions made during the process of R&D. In the evolutionary algorithm this corresponds to the successful variation of an element with the value “0” into an element with the value “1”. The inventions themselves increase the amount of technological knowledge.

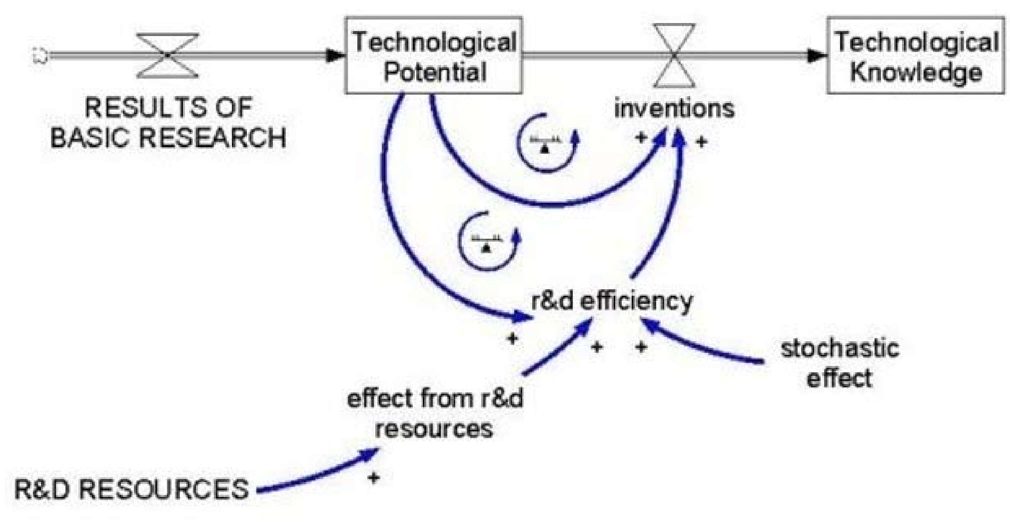

Figure 5. Structure of the R&D process model as stock-flow-diagram

In both, the evolutionary algorithm and the stock-flow structure, the technological knowledge will be incorporated in new products which will be introduced in the market. Then technological knowledge becomes applied technical knowledge. The new product is ready for market introduction, if the technological knowledge exceeds a required value. The market introduction of a new product initiates the phase of innovation and starts the diffusion process. The more successful the product is in the market place, the more resources are generated for allocation to future research and development. This links the R&D process to the market cycles of new products.

2.2. Innovation Diffusion Models

The product life cycle concept is a key framework in business management. It describes the time pattern a product follows through subsequent stages of introduction, growth, maturity, and decline. Although the concept is a powerful heuristic, many models generating the typical behavior over time do not reflect properly the factors causing it. They are based on biological or physical analogies and do not consider e.g., actual economic environment, competition, capital investment, cost and price effects. Purchasing decisions do not follow the same natural laws as the spread of a disease or the dissipation of particles. Innovation diffusion models which do not comprise the relevant decision variables exhibit a significant lack of policy content. They do not explain how structure conditions behavior. They cannot indicate how actions of a firm can promote but also impede innovation diffusion.

Besides the decision variables of a company, the aspects of market structure—monopolistic, industry level or competitive—and substitution through successive product generations are important structural elements that have to be considered. These aspects serve as a guideline for the next chapters. First, a model will be discussed, that maps the diffusion of an innovation in a monopolistic situation or which can serve as an industry level model. Secondly, competition between potential and existing companies is introduced. Thirdly, substitution between successive product generations is considered. Each step adds complexity to the model. This approach allows a better understanding of the forces driving the spread of a new product in the market.

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Biographical Sketches

Professor Dr. Peter M. Milling, born 1944, is Professor of Management. He holds the Chair in Business Administration, Industry and Operations Management and is Director of the Institute of Physical and Chemical Technology (Industrieseminar), both at Mannheim University, Germany. Before that he was professor at Constance University and Osnabrueck University.

Professor Milling received his academic education at Mannheim University and the Massachusetts Institute of Technology (MIT). He published numerous articles and several books on systems research and simulation, investigations on innovation dynamics, and manufacturing strategy. He is a winner of the Karin-Islinger-Prize and the Outstanding Scholarly Contribution Award of The International Institute for Advanced Studies in Systems Research and Cybernetics.

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Dr. Frank H. Maier was born 1958 in Bensheim, Germany. He studied Business Administration and Management Science at Mannheim University and received 1986 the degree of a Diplom-Kaufmann from Mannheim University. From 1986 to 1991 he was research assistant at Osnabrück University and collaborator at a research project about the dynamics of R&D and innovation diffusion supported by the Deutsche Forschungsgemeinschaft (DFG). Since 1991 he is lecturer and research assistant at Mannheim University. In 1994, he received the degree of a Dr. rer. pol. from Mannheim University. For his doctoral dissertation he received in 1995 the prize of the Verband der Metallindustrie Baden-Würtemberg e.V.

His current research focuses on success factors in manufacturing in the context of the international research project "World Class Manufacturing". In particular, he investigates aspects of technology and continuous improvement programs and their influence on competitiveness of industrial companies. He has working experience in several national and international industrial companies and is managing partner of SIMCON GmbH, Gesellschaft für Managementsimulation und Consulting, a consulting company concentrating on System Dynamics based management consulting.