Modeling the Dynamics of Technological Ramp-Up within Firms

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ABSTRACT

This paper uses the system dynamics methodology to integrate the dynamics of technological innovation into a formal model of business strategy. This model—known as the Technology Ramp-Up Simulator (TRUSIM)—specifically focuses on the evolution of technological performance and competitive structure. TRUSIM links existing firm management system dynamics structures to new modules representing the dynamics of innovation and that of technological capability. This model will be used to explore several typical scenarios of industrial evolution, such as technological lock-in and first-mover disadvantage

1. Purpose

Technological innovation is arguably the most powerful determinant of our economic future. The improvement in the Western standard of living during the past three centuries would not have been possible without it (Solow 1957). However, formal dynamic models of technological innovation are relatively underdeveloped. Existing models are typically quite aggregate and do not separate product from process innovation. There is a clear need for a dynamic model of innovation to reflect firm- and industry-level causal factors, and provide insights into how to manage innovations effectively.

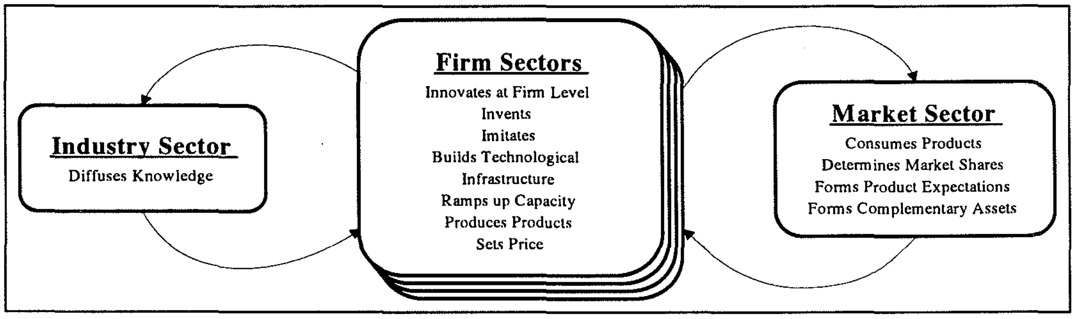

Figure 1: TRUSIM Sector Diagram

An overall schematic of a model, called the Technology Ramp-Up Simulator (TRUSIM), is presented in Figure 1. A complete description and listing of the model is available in Anderson and Joglekar (1995). In this model two new system dynamic modules formalizing the dynamics of innovation and technological infrastructure have been integrated with "classic" system dynamic modules for market behavior, capacity, production, and investment. The innovation module is based on the Abernathy-Utterback (Utterback 1994) descriptive model of product and process innovation and Von Hippel's (1988) work on sources of innovation. The technological infrastructure module is based on work by Fine and Joglekar.

2. Theory

There are two specific bodies of theory outside the common system dynamics literature that are used to build this model. The first is the theory of innovation. Most formal innovation models fall into one of two groups. Some are quite simple, often confounding many variables (Berndt 1991). Others are of the black-box nature typical of forecasting models (Young 1993). There also exist several industrial evolution models, notably Nelson and Winters (1982) and Levinthal and March (1988). These models are extremely stylized and their use as a policy tool is problematic. In the realm of system dynamics,

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many informative models examine innovation at the macro level, which is too aggregate for the present purposes (Graham and Senge 1980). The remainder, while set at an appropriate scale, do not separate product from process. (See Homer 1981, Davidsen 1989, or Kreutzer 1989 for examples.) Packer (1964) has created the model most similar to TRUSIM by differentiating the dynamics of capacity from professional capability, but he also does not differentiate product from process investment.

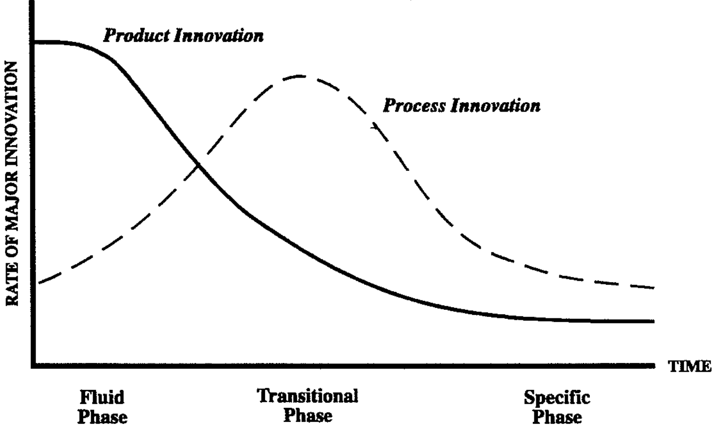


Figure 2: Abernathy-Utterback Model of Innovation Rates

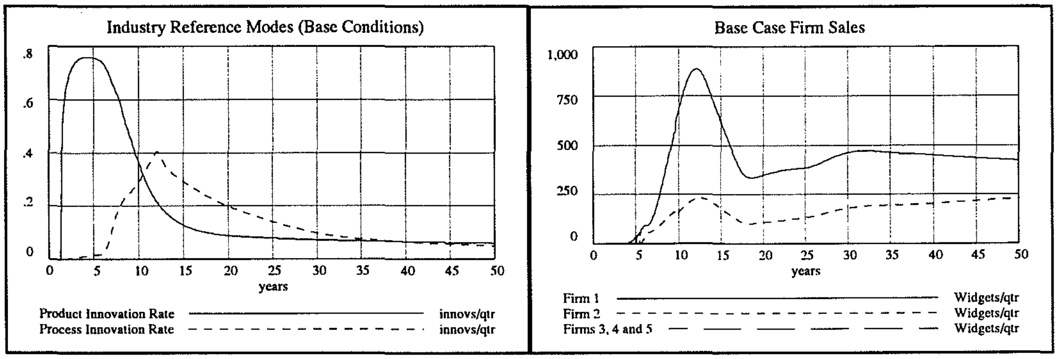
While formal dynamic models of product and process innovation are lacking, there do exist several excellent descriptive models. Of these, probably the best known is the Abernathy-Utterback (AU) model. Presented in Figures 2 is the key reference mode as described by the AU model. It begins with an empirical observation that the rates of product and process development vary not only with time but with each other. At the beginning of a new product's life, product innovation occurs quite rapidly, driven in part by the active participation of lead users. This improvement in product performance is made even more rapid as the innovating firms learn where to focus their energies. The rate of innovation begins to decline after a certain period with the appearance of a dominant design. This period of rapid innovation is termed the "fluid" phase. As product innovation slows down, process innovation accelerates and reaches a peak during the "transitional" phase. This phase coincides with a rapid rise in product demand. Market competition between firms begins to shift from product features to price and quality. During this phase the industry becomes concentrated as surviving firms struggle to take advantage of economies of scale. During the last or "specific" phase, processes are capital intensive, and neither product nor process can be easily changed due to their interdependence. Innovations become ever more incremental. In this environment, change becomes difficult leaving industries vulnerable to breakthroughs that reset the cycle.

The other body of theory is that of technological infrastructure, which is defined as the in-house know-how that evolves as a result of investment in building technological capability. Technological infrastructure is a stock, because it can either be accumulated or depleted over time. This definition of technological infrastructure is congruent with a growing body of literature within the resource-based view of the theory of the firm, which supports the view of knowledge as an asset or a stock (Dierickx and Cool 1989). Technological infrastructure is measured as the accumulated capability of an organization to apply technology to its processes of product development, manufacturing process development, quality improvement, and cost reduction. Accumulation of a firm's internal technology infrastructure is accomplished through individual and particularly organizational learning. Most firms complement their infrastructures with those of suppliers, customers, and other strategic partners. The quality of these link-ups, and the set of organizations with which the firm is linked, form a critical portion of the extended infrastructure (the technology supply chain, see Fine and Whitney 1996). Presence of infrastructure may be positively correlated with increased rates of innovation.

3. Initial Results

3.1 Base Case

This model has been tested using a set of stylized parameters that mimic the rate of innovation allied with product and process development practices observed in the automotive and electronics industries. Initial results of the model are quite promising. Presented in Figure 3 are time-series from a model simulation which replicates the reference modes shown in Figure 2. In general the agreement between the simulation and the reference modes is excellent



Figures 3 and 4: Base Case Reference Modes and Firm Sales

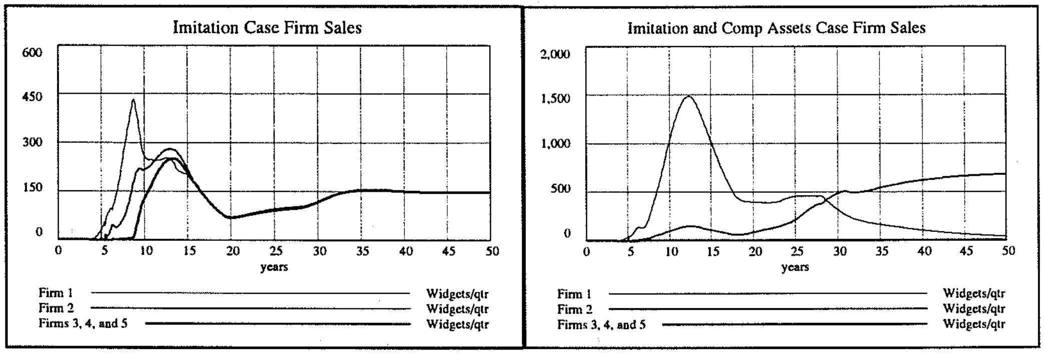
There are five firms in the base simulation, which differ only in their initial number of product and process engineers. Firm 1 has twenty product and twenty process engineers. Firm 2 has ten of each, and Firms 3, 4, and 5, five of each. In the base simulation there is no possibility for product imitation and no complementary assets. The resulting market sales are shown for Firms 1, 2, and 3 in Figure 4. Note the two humps. The first one is the boom-and-bust effect (Paich and Sterman 1994) driven by the launch of a new product. After the bust in year 12, however, capital procurement ceases by all firms. Hence, while process innovation continues, productivity gain is slight. In year 24, enough capital has worn out so that new capital is required to keep up with demand. Firm 2 begins the purchase of the new capital because it overshot the least during the initial boom. Productivity of new capital drives down product cost. Declining cost depresses prices, which leads to rapid influx of a new purchasers. These purchasers create their own very slight boom-and-bust effect from year 24 to year 32. A salient feature of this simulation is the domination of those who begin with the largest resources. This can be described as a first-mover effect.

3.2 Base Case with Imitation

Figure 5 shows the results from the same base parameters when imitation occurs. The most interesting result of the simulation is the elimination of the first mover advantage after year 10. In fact, Firm 2 briefly takes over market leadership until the re-convergence of all firms' sales occurs in year 15. The cause of this market convergence is the converging product performance as the technology matures. All of these results derive from the lesser load of imitation on engineering staffs than that of innovation. This difference allows the followers to create a viable product before they are locked out of the market.

3.3 Base Case with Imitation and Complementary Assets

Successful commercialization of innovation requires that the know-how in question be utilized in conjunction with other capabilities or assets known as complementary assets (Teece 1987). Two examples of these assets are after-sales support and the availability of application software for selling personal computer hardware. This simulation allows both imitation and the presence of complementary assets. Figure 6 shows that complementary assets can, for a while, reestablish the first mover advantage lost through imitation. Firm 1 again dominates the market, this time by translating an earlier product launch into a complementary asset advantage which has a reinforcing effect on scale economies. Only Firm 2 is strong enough to survive the shake-out before year 10. Interestingly, Firm 1 has become so large and bureaucratized that by year 12 its product development efforts fall behind its competitors. Firm 1's complementary assets, however, hinder Firm 2 from capitalizing on its advantage. By year 24, Firm 2 also has a price advantage, but it takes another five years to translate these advantages into market leadership. At this point, Firm 1 is saddled with an inferior product and has too much inertia to easily change its ways, so it loses sales which further erodes its complementary assets. This case has parallels with the computer industry in the 1980s as IBM took control with its dominant PC design, and then lost it to Compaq and others. On the other hand, with a slightly different parameterization one can also generate modes of premature technological lock-in similar to Arthur (1989).



Figures 5 and 6: Firm Sales under Imitation and Complementary Assets

4. Next Steps

The model is being explored to find additional behavior modes. Simultaneously, validation against collected personal computer and automotive electronics data has begun. Finally, simplified models are being developed to capture the essences of strategy under technological innovation.

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