A Comparative Study of Lotka-Volterra and System Dynamics Models for Simulation of Technology Industry Dynamics

by

Hakkı Özgür Ünver

Doctor of Philosophy in Mechanical Engineering
Middle East Technical University, 2000

Master of Science in Mechanical Engineering
Middle East Technical University, 1996

Bachelor of Science in Mechanical Engineering
Middle East Technical University, 1993

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management
at the
Massachusetts Institute of Technology
May 2008
[June 2008]

Signature of Author..
Hakkı Özgür Ünver
System Design and Management Program
May 2008

Certified By..
James M. Utterback
David J. McGrath jr (1959) Professor of Management and Innovation
and Professor of Engineering Systems
Thesis Supervisor

Accepted By..
Pat Hale
Director
System Design & Management Program

A Comparative Study of Lotka-Volterra and System Dynamics Models for Simulation of Technology Industry Dynamics

by

Hakki Ozgur Unver

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Engineering and Management

Abstract

Scholars have developed a range of qualitative and quantitative models for generalizing the dynamics of technological innovation and identifying patterns of competition between rivals. This thesis compares two predominant approaches in the quantified modeling of technological innovation and competition. Multi-mode framework, based on the Lotka-Volterra equation barrowed from biological ecology, provide a rich setting for assessing the interaction between two or more technologies. A more recent approach uses System Dynamics to model the dynamics of innovative industries. A System Dynamics approach enables the development of very comprehensive models, which can cover multiple dimensions of innovation, and provides very broad insights for innovative and competitive landscape of an industry.

As well as comparing these theories in detail, a case study is also performed on both of them. The phenomenal competition between two technologies in the consumer photography market; the recent battle between digital and film camera technology, is used as a test case and simulated by both models. Real market data is used as inputs to the simulations. Outputs are compared and interpreted with the realities of the current market conditions and predictions of industry analysts. Conclusions are derived on the strengths and weaknesses of both approaches. Directions for future research on model extensions incorporating other forms of innovation are given, such as collaborative interaction in SME networks.

Thesis Supervisor: James M. Utterback
Title: David J. McGrath jr (1959) Professor of Management and Innovation
and Professor of Engineering Systems

Table of Contents

List of Figures

List of Tables

Acknowledgements

I am grateful to my thesis advisor, Prof. James M. Utterback, for his guidance and support all through this study. It was a privilege and unique experience to learn Technology and Innovation Management from him. I am also deeply thankful to Henry B. Weil, for sharing his ideas, experiences and major work on system dynamics based modeling of innovation.

My deep appreciation goes to all SDM staff, particularly, Pat Hale, Director of SDM, and Helen Trimble, Career Development Director, for their constant efforts and support for my career advancement and success in Systems and Technology leadership. I am also thankful to Mr. John Masciola, V.P. of Instrument R&D, who provided leverage and flexibility during my study, and other co-workers for their support at Caliper Life Sciences, Hopkinton MA.

Finally, I would like to thank to my wife, Nilgun, and my family whose encouragement have sustained me and to all my friends, who shared my experience and joy over the course of my fellowship in the Systems and Technology Management field at MIT, Cambridge MA.

To my family

1. Introduction

Technological innovation has been the most powerful thrust behind economic growth and rising standards in our quality of life. In the last century industrial growth and GDP of many nations has been rising at an unprecedented pace, especially in industrialized and emerging nations, which were successful in adopting open-market and free-trade policies and practices. In open markets, firms compete with their products and services depending on their superiority and attributes such as quality, performance, flexibility, cost, or timing. Innovation activities, both inside and outside of firms, are significant determinants of these attributes, and the success or failure of firms [Suarez 2003]. Recently, examining these activities and modeling the dynamics of innovation, both qualitatively and quantitatively, has received significant attention by many scholars, and institutional researchers. As research in this area reveals more about the dynamics and determinants of success or failure in open markets, the findings will have significant impact on developing better policies, and setting the course for sustainable growth by regulators of established markets and new adopters, and accumulating a valuable knowledge base for the guidance and betterment of players in the open market arenas [Dosi 1982].

This thesis' focus is the comparison of two methodologies, *Lotka-Volterra* and *System Dynamics*, used in the quantified modeling of technology industry dynamics. It builds on decades of research and the work of Abernathy, Clark, Pistorius, Utterback and Weil. The framework for multi-mode interaction among the technologies of Pistorius and Utterback not only identifies different forms of technological battles between competing technologies, it also provides a numerical solution model based on differential Lotka-Volterra equations for n-numbers of technologies [Pisterious and Utterback 1997]. Their unique framework captures the reality that interaction between technologies is not always confrontational. In fact this interaction can manifest itself reciprocally when one technology may either enhance or inhibit another technology's growth. In their work three possible modes of interaction exist, *pure competition* where both technologies inhibit the other's growth rate, *symbiosis* where both technologies enhance the other's growth rate, and *predator-prey* interaction where one technology enhances the other's growth rate, but the second inhibits the growth rate of the first. The multi-mode framework with model formulation for simulation provides one of the richest frameworks for examining the interaction of technologies. Multiple modes, further account for the transitionary effects as the interaction between the technologies transgresses from one mode to another, with time.

Recent work of Weil and Utterback captures and analyzes the fundamental dynamics of innovative industries within a *System Dynamics* model. System dynamics is an approach used to understand the behavior of complex systems over time. It deals with internal feedback loops and time delays affecting the behavior of an entire system. What makes using system dynamics different from other approaches to study complex systems is the use of feedback loops, stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity. In their work, Weil and Utterback selectively reviewed the literature, and identified fundamental dynamics as the sources of innovations and their impacts on firms, markets, and industries, such as entry exit of firms, experimentation and innovation, technology evolution, improvements in cost and performance, emergence of standards and dominant designs, adoption of new technology, network effects, development of a mass market, market growth, market saturation, intensity of competition and commoditization. They created conceptual models capturing these dynamics and then converted them into System Dynamics simulation models representing two competing technologies. The simulation results approximate many actual cases.

In order to provide a common base for comparison, in this thesis we chose two distinct technologies in the photography market, which have been in competition since early 1990s. Digital and film camera technologies excluding camera phones are our choice for this particular case. When Kodak's first digital camera appeared on the market more than a decade ago, it was perceived as more novel than practical for both professional and amateur photographers. Prices were well above the thousands, image resolution and quality was poor, and the cameras were bulky and inconvenient to use. Over time as key performance metrics drastically improved, and many new entrants rushed into emerging market, each year hundreds of new models flooded the mass market, rapidly melting the dominance of film based cameras. After a two decades transition period, many industry analysts agree that the technology transition is over, and the only question remaining is whether film cameras can stay forever in with, may be one or two niches, or will they only be staged in technology museums.

Outline

In the second chapter we summarize key concepts and models in technological innovation. We reviewed the literature and major contributions to the field. Focus areas include, technological innovation, emergence of dominant design, patterns of emergence in disruptive innovations. We overview predominant examples in technology history, such as the evolution of the printing business, and hard disk drive industry. Then we highlight marketing frameworks such as technology diffusion and lead user innovation. We also examine product architecture by relating it to industry structure, and reviewed essential frameworks, developed by world renowned scholars.

In chapter three, we dive into the details of the Lotka-Volterra model, and its formulation. We drive its numerical solution and explain in detail its use in the multi-mode framework of technology competition. Similarly in chapter four we explain the details of the System Dynamics model which is developed for simulating the dynamics of innovative industries. Although we go through the conceptual models in this chapter, the details of simulation model are placed in the Appendix for user's review.

In chapter five, we compare the outputs of both models in detail. First the outputs of System Dynamic model are presented. System dynamics model provides us with a rich portfolio of results in several attributes of technology competition. For the simulation of the Lotka-Volterra model, we go step by step through how the numerical solution of the model is implemented in a spreadsheet and its linear optimization package is used to generate optimal parameters in order to do best curve fitting on the actual data. Later, the model with optimized parameters is used for predicting future dynamics of competition between two technologies.

In chapter six, we discuss two models, and the results of camera market case study. We not only compare the simulation outputs, but also incorporate the findings and research of media, industry articles, and analysis reports of market research companies in order to reflect on real market conditions, in each compared dimension.

In the last chapter, we drive conclusions out of this study and suggest future areas of research.

2. Overview of key concepts and models in technological innovation

Innovation and industrial evolution

The model proposed by Abernathy and Utterback captures the dynamics of the rate of major innovation over time within an industry. This model cuts through two dimensions: 1) the components of product innovation, process innovation, competitive environment and organizations; and 2) the life cycle of the industry, itself.

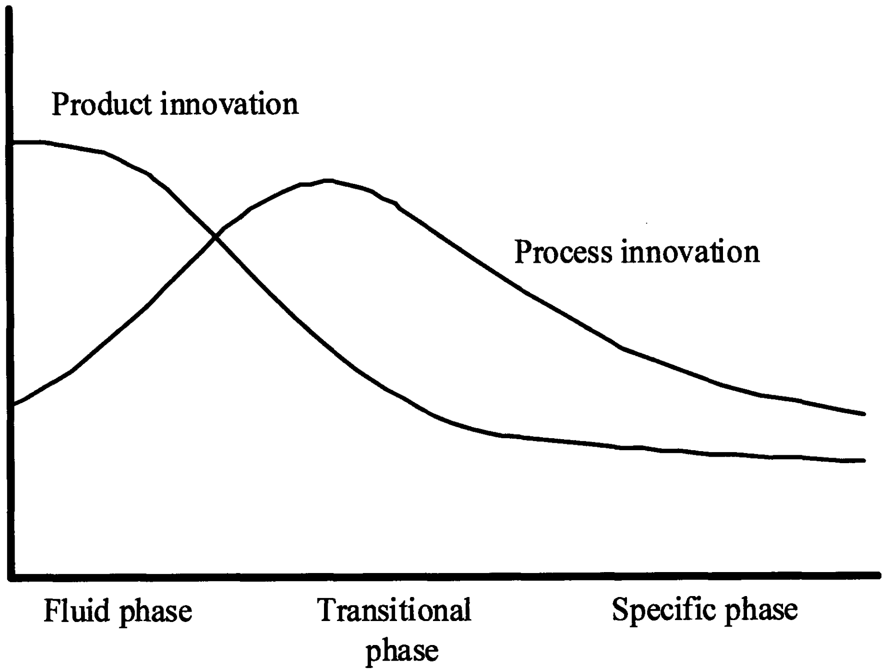
The model characterizes the evolution of an innovative industry in three phases; fluid, transitional, and specific. These three phases are associated both with rate of innovation and the underlying dimensions of the product, process, competition, and organization. The dynamic model of the rate of innovation and the significant characteristics of each phase, as they apply to product, process, competition and organization, are presented in figure 1.

Fluid Phase

In the fluid phase of a technology's evolution, the rate of innovation is very high and rapid. The technologies in the market are usually, crude, expensive, and unreliable. Uncertainty defines user needs and new technologies worked on. Functional product performance is the main basis for competition among competitors in the industry, which usually has an entrepreneurial character. Importance of Intellectual Property is very high as propriety technologies are firms' core resource for capturing and improving market share.

Process innovation takes secondary attention at this stage. Frequent changes in product design, features and characteristic, uncertainty in technologies and market conditions, relatively small and fragmented market sizes, high profit margins caused by proprietary technologies do not provide enough motives for investing in process innovation. Manufacturing requires high flexibility, which can be best attained by a skilled labor force, conducted in small scale plants, and generally located close to the source of the technology.

Organizations are usually smaller in size, informal, and entrepreneurial. Competitors are few but growing in number and size as the market grows. Entry barriers into industry are low and the number of firms rapidly increases as the market signals prospects of growth and profit.



Product	From high variety, to dominant design, to incremental innovation on standardized products
Process	Manufacturing progresses from heavy reliance on skilled labor and general purpose equipment to specialized equipment tended by low-skilled labor
Organization	From entrepreneurial organic firm to hierarchical mechanistic firm with defined tasks and procedures and few rewards for radical innovation
Market	From fragmented and unstable with diverse products and rapid feedback to commodity-like with largely undifferentiated products
Competition	From many small firms with unique products to an oligopoly of firms with similar products

Figure 1 The dynamics of innovation[1]

[1] Utterback, J.M., "Mastering the dynamics of innovation", HBS, p. 91, 1994

Transitional Phase

As the market grows, acceptance of a dominant design by the market will take place. As market characteristics and user needs are better understood, products and innovation start to converge into certain areas, which become more certain.

Concept of dominant design

The term dominant design was first coined by the work of Utterback and Abernathy, to signify the emergence of a dominant technology in an industry.

A dominant design in a product class is the one that wins the allegiance of the marketplace, the one that competitors and innovators must adhere to if they hope to gain significant market share [Utterback 1994]. Usually, the dominant design takes the form of a new product by the fusion of individually technological innovations introduced interdependently during the fluid form of an industry.

During the recent history of computing, the emergence and dominance of the IBM PC is a predominant example of dominant design among all other alternative PC designs manufactured by competitors such as Apple, Tandy, etc. This landmark event in PC industry happened in 1981 by the introduction of IBM PC with a list price of $3000. Although this product did not offer any technological breakthroughs, it was equipped with innovative components, such as Intel 8088 microprocessor, floppy disk, CRT monitor, standard QWERTY keyboard, and fused by open architecture and standards. By betting on an open architecture strategy, IBM leveraged many suppliers such as Intel and Microsoft, which helped the development of the IBM PC in less than 18 months. It also became the center of gravity for many hardware and software manufacturers in the industry who wanted to be "IBM compatible" and command a market share in the industry.

In this phase the product and process innovations are more tightly linked. Designs require more consideration from manufacturing technologies and the cost efficiency of production. Expensive equipment brought into manufacturing and islands of automation began to appear the in shop floor. The growing rigidity in manufacturing and operations mean that design changes slows down and becomes more costly.

Specific Phase

In specific phase, the objective of the firms remaining in the industry is to produce specific products at a very high level of efficiency. At this time, basis of competition turns from innovative products and new features to the value ratio of quality to cost. The link between product and process are very close. Manufacturing equipment used is highly specialized, automated, expensive, and geared towards highly efficient, low unit cost production of highly specified products. Therefore the cost of changing designs and implementing radical innovations in products are extremely high and disruptive to manufacturing systems of the organizations.

Organizationally, firms are more structured, managed by rigid rules and goals. Inventors are replaced by managers who monitor and control the smooth working of production systems. Competitors are few, with stable market shares. Entry barriers into industry are high, caused by saturated markets and high capital and technology investments of the existing firms.

Dominant design and industry landscape

James Utterback studied the business of printing covering four major innovation cycles in the industry. Mechanical typewriters, electrical typewriters, word processors, and personal computers have one fundamental objective: to put words on paper neatly and efficiently. The reader should refer to Prof. Utterback's *Mastering the Dynamics of Innovation* for the breathtaking story of this industry and its evolution over a period of more than a century. Figure 2 presents the ecology of business succession by graphing the total number of firms in this industry. It must be noted that each time technology shifted, new dominant firms emerged and their predecessors usually exited the industry if they failed to adopt the new technology and standards. During 1900 Underwood, Remington, Royal, and L.C. Smith & Brothers were supposed to dominate the American market. During the electric typewriter era, IBM controlled 60 percent of the market. During early 1970s, dedicated word processors began to appear and replace typewriters. New companies emerged such as Wang, Olivetti, Xerox and led the market along with IBM. In the age of PCs, Apple, Tandy, Commodore emerged as the innovators, until IBM entered the market and changed the industry structure from vertical to horizontal by its open-architecture and aggressive outsourcing strategy. During this structural shift in the PC industry, new players such as Compaq and Dell emerged where the old leaders Tandy and Commodore struggled and finally exited the industry.

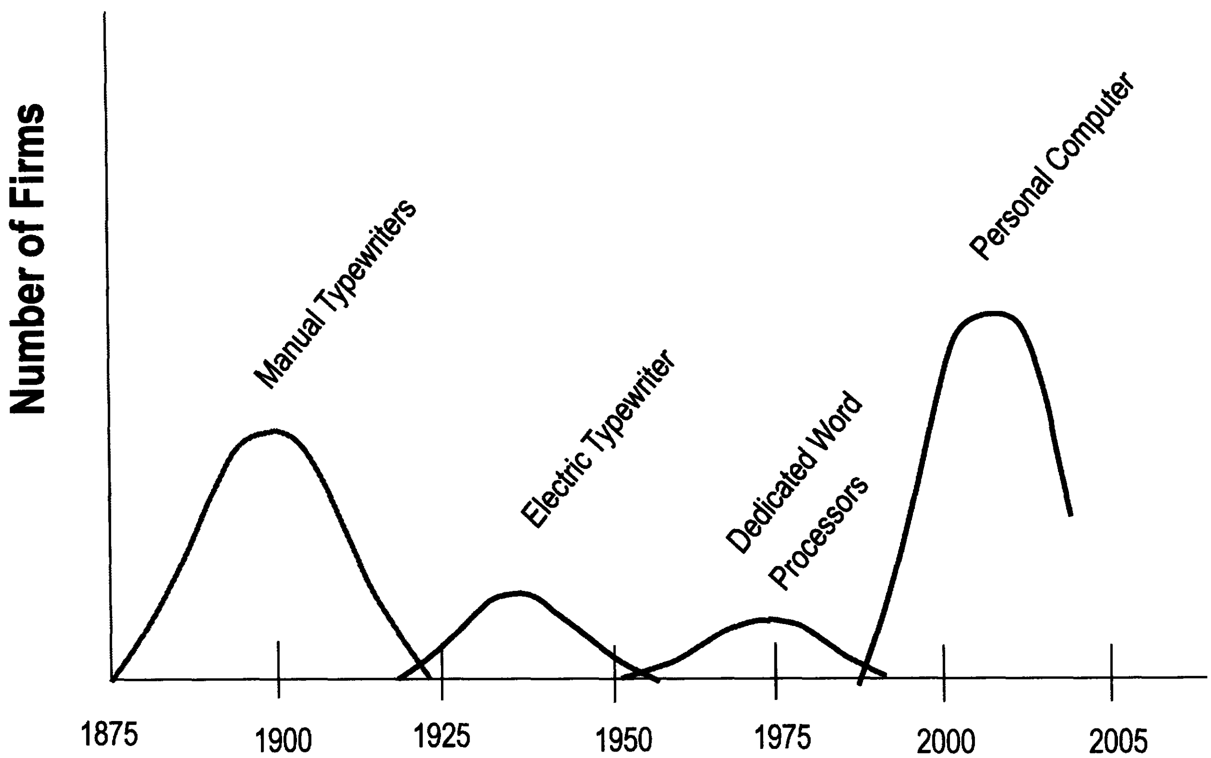


Figure 2 Ecology of business succession[2]

If chapters in the printing industry are examined in more detail, the common pattern of number of firms and its relation with dominant design would become clearer. Figure 3 depicts the number of entries, exits, and total number of firms in U.S. market of typewriter industry over a course of six decades. Initially the growth was rather slow and the peak level in the industry took almost three decades. In early 19th century there were over 30 firms in U.S. market and until that time typewriter manufacturers offered products with few standardized characteristics. Underwood introduced its Model 5 in 1899. This was the first typewriter allowing the typist to see what he or she actually typed as the keys struck the page. It was also the first to have a tabulator which makes columnar presentations much simpler, and it was able to cut stencils and make good copies. These features helped the Model 5 to grasp the dominant share of the market quickly, and it formed users expectations of what an ideal typewriter should look like.

[2] Utterback, J.M., Disruptive Technologies lecture notes, Sloan school of management, MIT, 2006

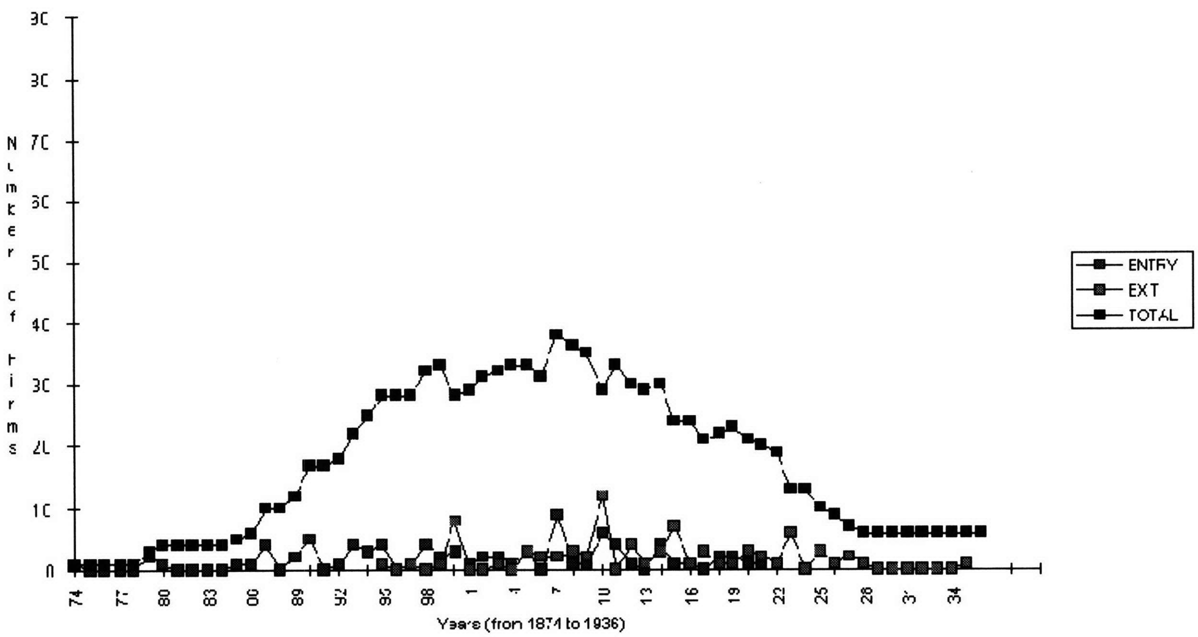


Figure 3 Number of firms in the U.S. typewriter industry[3]

After Underwood's Model 5 became the dominant design, the irreversible decline in the industry started in 1907. By 1940, only five manufacturers had a share in the market; Remington, Royal, Smith and Underwood, each having 20% market share and IBM with 10% share. After its peak time, more than 90% of the firms entered the industry either bankrupted or exited the industry [Utterback 1994].

Many scholars studied a variety of industries; automobiles, televisions, transistors, integrated circuits, etc. The pattern presented in figure 3, can be similarly recognized in all of these industries, although not always as close to a bell shape curve as in typewriter industry.

Patterns in the emergence of disruptive innovations

S-curve

The recurring phenomenon in every industry is the dynamics between an established product and an invading product having a radical technological innovation. This generalized pattern, also known as an *S-*

[3] Utterback, J.M., "Mastering the dynamics of innovation", HBS, p.33, 1994

curve model, can be seen in many product markets as periods of continuity, when the rate of innovation is incremental and infrequent, and periods of discontinuity when product or process changes occur. Radical innovation creates new businesses and destroys existing ones, just as ice maker machines destroyed the New England ice-harvesting industry, personal computers killed mini computers, and digital cameras conquered almost all of the photography market analog cameras once had [Utterback 1994].

An invading technology has the potential for delivering radically better product performance or lower production costs, or both. In the fluid phase of an industry, the performance of a particular product improves rapidly as many different design approaches are tried. After a dominant design emerges and major advances have been made, a period of incremental innovation and infrequent change sets in. At this stage, when invading technology appears, the established technology offers better performance or cost than its challenger. However if invading technology has real merit, it typically enters a period of rapid development, as mature technology enters a stage of slow improvements with descending speed (Figure 4).

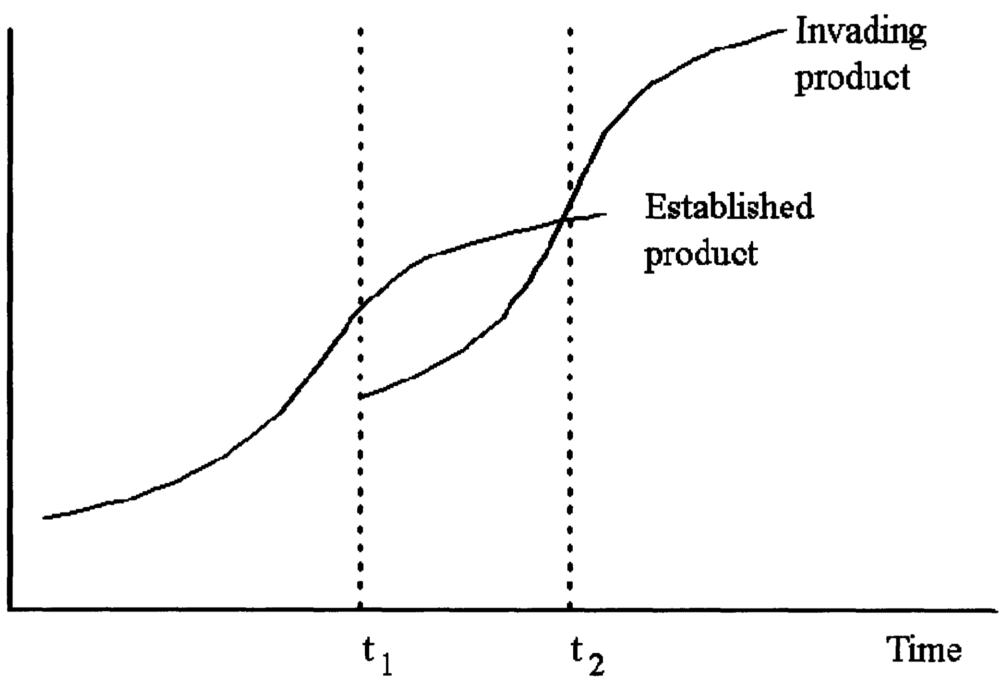


Figure 4 Performance dynamics of an established and an invading product[4]

[4] Utterback, J.M., "Mastering the dynamics of innovation", HBS,p.159, 1994

In such scenarios, the established players do not always sit back and relax. Most of them fight back. The burst of improvement from the established player in figure 5, symbolizes this behavior. The established player briefly enjoys this burst of improvement, however eventually performance of invading products surpass the established product, which has the improvement becoming marginal over time.

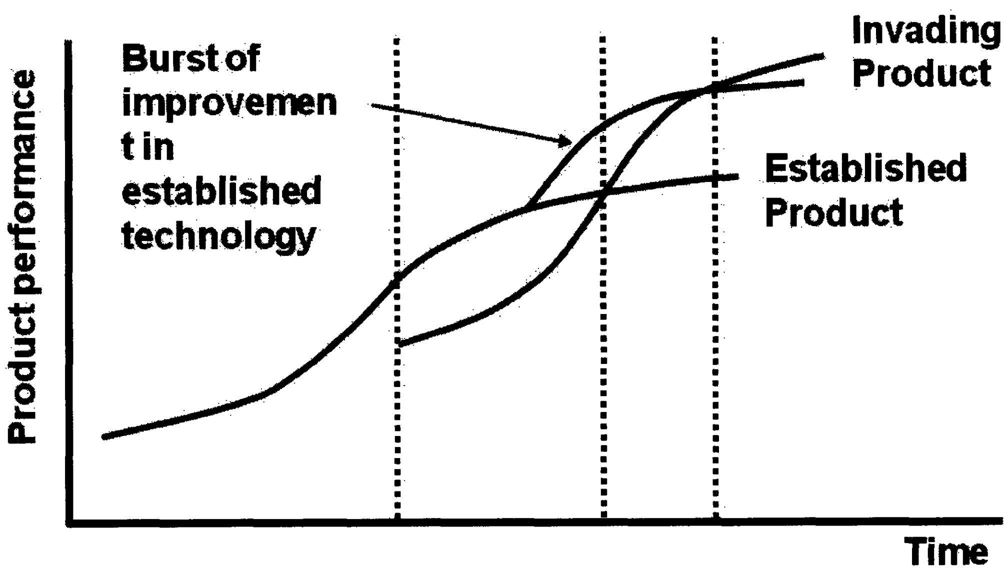


Figure 5 Burst of improvement in challenged product[5]

Manager's dilemma: to listen or not to listen to the customer?

Among many patterns identified by scholars in technology industries, Clayton Christensen's framework on Disruptive Technologies is one of the most stunning. Christensen investigates why many successful companies in their industries fail suddenly, and defeated by a small and entrepreneurial, new entrant to the industry, which they ignored.

Many established and well managed companies try to solve rationale questions in order to stay competitive and increase their market performance. When they are working on a new technology product, they ask whether their mainstream customers will want it? Is the market big enough that, their investments for the technology are justifiable? In answering all these questions, they unknowingly find

[5] Utterback, J.M., "Mastering the dynamics of innovation", HBS, p.160, 1994

themselves in the heart of a management paradox. For many established companies staying close only listening to mainstream customers and being ignorant to emerging markets were lethal.

Research proves that most well managed companies consistently deliver new technologies and products, as long as those technologies address the next generation performance needs of their mainstream customers. However, these very same companies rarely show interest in technology appealing to only a small or emerging market, having no affiliation with their mainstream customers. Christensen identified this pattern repeatedly in many industries that confronted technological change. In each instance, the companies listened to their prime customers, delivered them the products they needed, and in the end disrupted by those technologies their customers led them to ignore.

The history of the hard disk drive industry reflects this disruptive pattern multiple times. The managers of established hard disk companies stumbled at each instance of technology change, when the diameter of disk drives shrank from 14 inches to 8 inches to 5.25 inches then to 3.5 inches and finally to 1.8 inches. Each new architecture, which essentially had dimensional and weight merit, initially offered the market substantially less storage capacity than its predecessor. As an example, the first 8 inch drives offered 20 MB when it was first introduced, while 14 inch drives were offering about 200 MB at the time. The leading mainframe manufacturers rejected 8 inch architecture at first. As a result hard disk manufacturers shelved their projects for developing 8 inch architectures and focused all their best resources to improve the capacity of 14 inch drives. The pattern was repeated with 5.25, 3.5, and 1.8 inch disk drives; established computer manufacturers rejected the new drives as their capacity was inadequate for their customers and so did disk-drive suppliers.

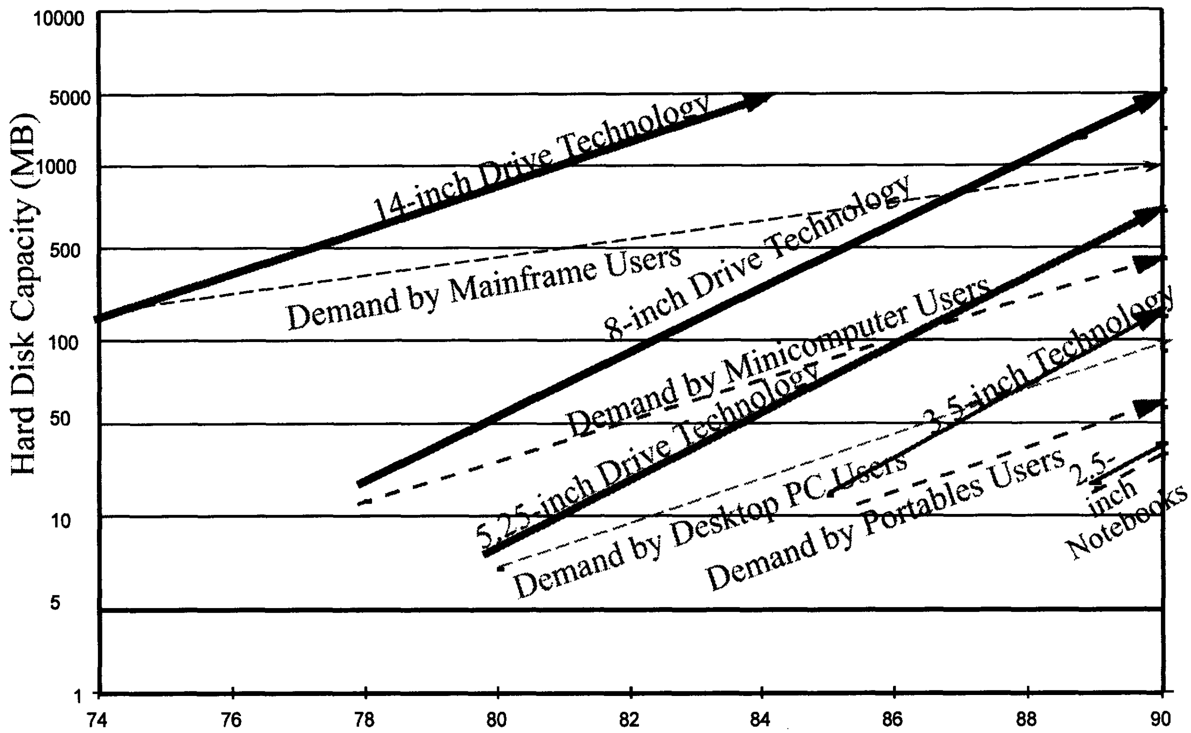


Figure 6 Capacity demanded vs. capacity supplied in Hard Disks[6]

To explain the reasons behind these events, the concept of performance trajectories, the rate which the performance of a product has improved, and is expected to improve, can be used. It is possible to identify a critical *performance metric* in almost every industry. In digital photography, it is the resolution of pictures (measured in Mega Pixels), in microprocessor industry it is speed of execution of mathematical operations (nowadays measured in Giga Hertz range), or in the hard disk industry it is the storage capacity (which reached Giga Byte levels early 90s). Figure 6 portrays the performance trajectories of each disk drive architecture, from 14 inch to 2.5 inch over approximately two decades. Two observations can be made from this figure. First, *sustaining technologies* tend to maintain a rate of improvement and give customers better performance in the attributes they already have. For instance, thin-film components in drives, which replaced conventional ferrite heads and oxide disks between 1982 and 1990, enabled capacity increase. Second, disruptive technologies introduce a very different package of attributes from the one mainstream customers have and they usually perform a lot worse in the attributes that mainstream customer value. When the first 8 inch drive was introduced its capacity was

[6] Bower, J.L, Christensen, C.M., "Disruptive Technologies: Catching the Wave", Harvard Business Review, Jan-Feb, p. 46, 1995

less than the average capacity of 14 inch disks by 1/50. However in physical dimensions and weight, it was considerably smaller than 14 inch. Unfortunately, these were attributes mainframe users did not value much, and nor did manufacturers. Indeed, while offering less capacity, the disruptive architectures created other new attributes as well as smaller sizes; internal power suppliers(8 inch drives), low cost stepper motors(5.25 inch drives), ruggedness, light weight, and low power consumption (3.5 inch drives). The disruptive architectures in disk drives made possible the emergence of new markets which created minicomputers, desk top PCs, and portable computers, respectively [Christensen 2002].

How to identify a disruptive technology?

The pattern of disruptive technologies can be generalized as in figure 7. Proven in many cases, it is noticeable that once the disruptive technology became established in their new markets, sustaining innovations raises its performance so steep that, it soon reaches the performance trajectory the market needs. At this point, the defended technology might have a performance well above what the marketplace can absorb. This state actually makes the defended technology vulnerable in marketplace [Bower and Christensen 1995].

Further, Christensen suggests a method to spot and cultivate disruptive technologies. The first step in identifying a disruptive technology is to examine internal disagreements over the development of new products and technologies. Usually financial and marketing managers rarely support a disruptive technology because they will have a very tiny managerial or financial incentive. On the other hand, technical groups often persist in the disruptive technology and the market it will create. The next step is to ask the right questions to the right people. Managers generally ask questions and assess a new technology for their mainstream customers and hoping to get good feedback. Generally these customers will be pushing the product performance higher to stay ahead of the game and they will be accurate when they are assessing the potential of a sustaining technology. However they will be the wrong people to ask when assessing the potential of a disruptive technology.

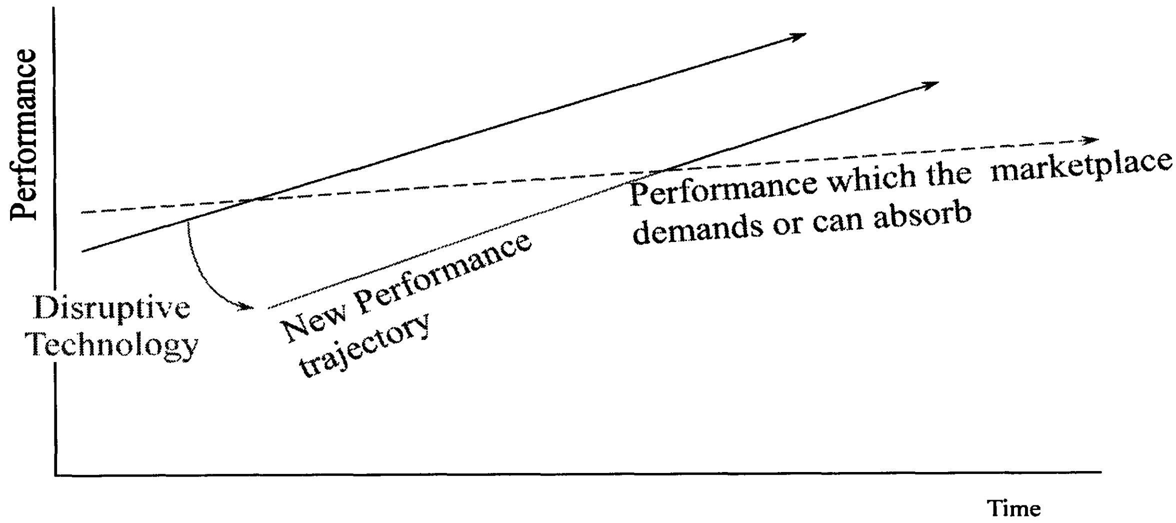


Figure 7 Pattern of the disruptive technology[7]

Once managers have determined a technology is disruptive, the next step is to locate the initial markets for that technology. Usually traditional market research techniques fail, as there may not even be a concrete market, for the disruptive technology. Under this condition, managers should create information about emerging markets, such as, who could be potential customers, and what are the segments, use context, valuable features, and price points. The best way to create this type of information is to experiment with rapid new releases of a product line. It is easier for small and entrepreneurial companies to experiment like this, but for established companies which are strict with processes and managerial hierarchy, it is very difficult. Often, the best choice for them is to keep an eye on small and agile companies and acquire the technology when it becomes sufficiently proven and the market shows sign of expansion. If an established company decides to develop a disruptive technology organically, creating a separate organization is necessary; with the conditions that disruptive technology has a lower profit margin than the mainstream business, and should serve the unique needs of a new set of customers.

A manager can spot and either incubate or acquire a disruptive technology, by utilizing the techniques briefly described above, but one should differentiate between recognizing the pattern and breaking the pattern, they are very different. Generally, disruptive technologies are financially very unattractive to established companies. The potential revenues from the emerging markets are very small, or even nonexistent. Hence, managers typically find themselves in a dilemma when making a decision. One

[7] Utterback, J.M., Disruptive Technologies lecture notes, Sloan school of management, MIT, 2006

option is going *down market* with the disruptive technology, accepting the smaller markets and lower profit margins. The other is to go *up market* with sustaining technologies and enter market segments, which has attractive and large market sizes and lucrative profit margins. In most well managed companies, latter choice is the rational path to take in order to reduce risk and advance careers.

Technology adoption, lead user innovation and communities

Diffusion of Innovations

Before moving into lead user innovation, it is necessary to briefly examine the technology adoption lifecycle model first proposed by Everett Rogers, in his famous book *Diffusion of Innovations*.

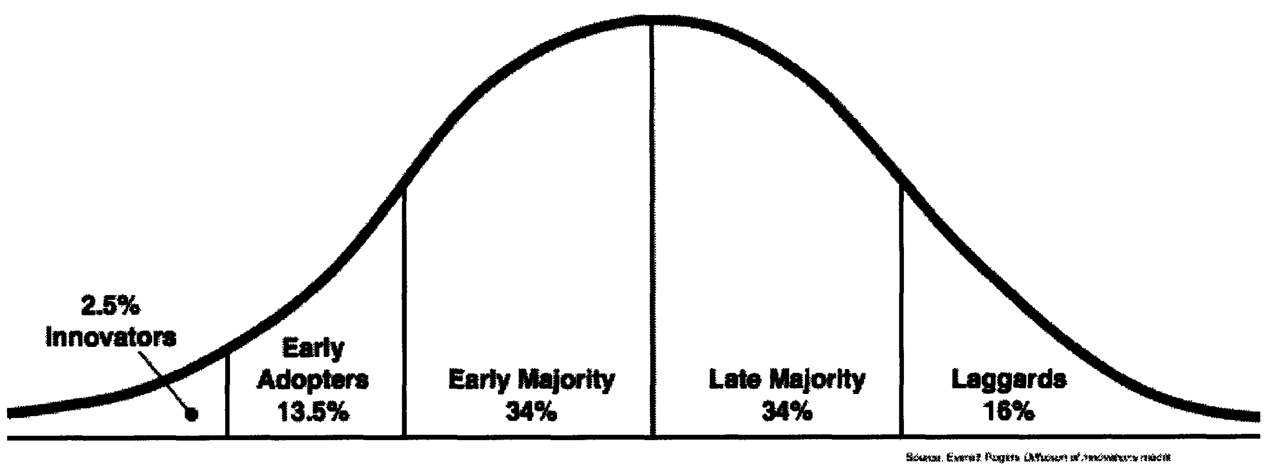


Figure 8 Rogers' technology adoption lifecycle model[8]

The technology adoption lifecycle depicted in figure 8, models adoption of a new innovation or product, according to the demographic and psychological characteristics of defined adopter groups. The process of adoption is illustrated with a bell curve, segmenting adopters in five categories: starting with *innovators, early adopters, early majority, late majority* and finally *laggards*. Rogers' model characterizes these five segments as follows [Rogers 1995]:

1. Innovators – They are venturesome, and educated. These people are eager to take risks for big returns.

[8] Roger, E., "Diffusion of Innovations", Free Press, 1995

2. Early adopters – They are social leaders, popular, and educated. They like to try new ideas but are not techies like innovators.
3. Early majority – They are deliberate and thoughtful people, accepting change more quickly than average. They usually have many informal social contacts.
4. Late majority – They are skeptical, traditional, and a lower socio-economic status. They will use new ideas or products only if the early majority is using it.
5. Laggards –They are traditional, and conservative. They will accept new ideas only when it becomes mainstream or traditional. Neighbors and friends are their main info sources and they are very risk averse.

Further, Geoffrey Moore builds on Rogers' model in his famous 1999 book, *"Crossing the Chasm"*. He argues there is a chasm between the early adopters of the product (the technology enthusiasts and visionaries) and the early majority (the pragmatists). Moore believes visionaries and pragmatists have very different expectations. He attempts to explore those differences and suggest techniques to successfully cross the "chasm," including choosing a target market, understanding the whole product concept, positioning the product, building a marketing strategy, and choosing the most appropriate distribution channel and pricing [Moore 1999].

Lead user innovation

Almost all models about technological innovation and evolution have a common fundamental assumption that innovation is developed by *manufacturers* and delivered to *users* in order to perform one or more functions. On the contrary, the lead user theory assumes that innovation not necessarily always happens by a manufacturer in a manufacturing setting. Instead, the theory suggests most commercially attractive products and product modifications are developed by users with *lead user* characteristics. Eric Von Hippel, world renowned scholar on lead user innovation, claims lead users have two distinguishing characteristics: 1) They are at the leading edge of an important market trend, and experiencing needs that will be experienced by many users in that market, 2) They anticipate high benefits from obtaining a solution to their needs, so they innovate [von Hippel 2005]. As depicted in figure 9, lead users are actually the innovators constituting the first segment of Rogers' innovation adaption curve. However a significant change in the view is that the first segment of lead users innovate to satisfy their own needs, not to adopt an innovation from a manufacturer.

Several scholars studied a variety of industries to find empirical proof, that innovation is done by users and often commercial products are derived from this innovation. Franke and Shah studied user innovation in sports. They studied four communities of sports, canyoning(a popular sports in the Alps), gliding, boardercross (six snowboarders competing in a downhill race), and handicapped cyclists that need improvements in their equipment to accommodate their disabilities. Their research revealed that users' innovations varied a great deal. In the sailplane community, users developed innovations such as a rocket-assisted emergency ejection system. Snowboarders improved their boots and bindings. Canyoners' invented ways to cut loose a trapped rope by using a chemical etchant. They also found that 23% of the innovations were soon produced for sale by a manufacturer [Franke and Shah 2003].

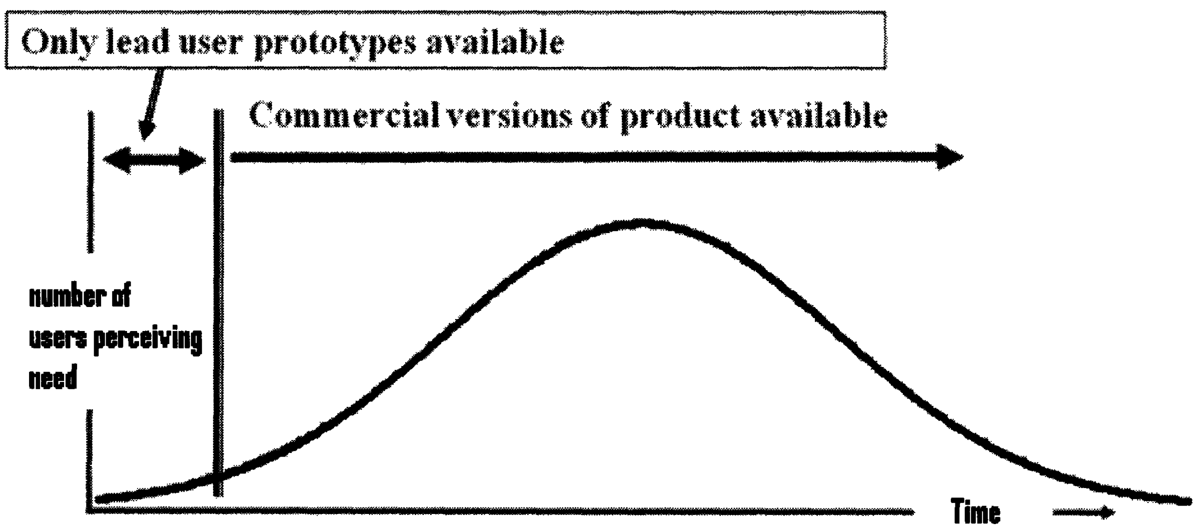


Figure 9 Lead user innovation[9]

The advent of the World Wide-Web and the consequent proliferation of open-source software projects around the world has became a focal point for many researchers from academia on the phenomenon of user innovation communities. A predominant example is the Apache open-source web server. The server software was first developed by Rob McCool, while he was working at the National Center for Supercomputing Applications (NCSA). As he posted his source on the web, a small group of webmasters decided to continue using and developing it. After extensive feedback from many users and modifications, Apache 1.0 was released on Dec. 1, 1995. Four years later, with improvements by many users, Apache became most popular Web server on the internet despite strong competition from Microsoft and Netscape [Von Hippel 2001].

[9] Von Hippel, E., "Democratizing innovation", MIT press, p.134, 2005

Product architecture and platforms

Defining architectural innovation

The types of innovation discussed so far can be grouped into two categories. *Radical innovation* establishes a new dominant design with a new set of design concepts and creates a new set of core design concepts. *Incremental innovation* refines and improves the performance of an established product. In incremental innovation improvement often only occurs in individual components, but the underlying design concepts and links between them stays the same. *Architectural innovation,* a third type occurs when a product's architecture changes but the components and the core design concepts are left unchanged.

The framework of Abernathy and Clark classifying innovation types is given in figure 10. This framework consists of four quadrants representing innovations: Architectural, Niche, Incremental, and Revolutionary. In addition to the three types mentioned, the niche quadrant represents innovation called by Utterback as "sales maximization", in which a stable and specified product is refined and improved so that it will support a new marketing thrust. In figure 10, the market transilience scale is in the vertical dimension, and technology transilience scale in the horizontal. (The term "transilience of innovation" was coined by Abernathy and Clark to indicate the significance of innovation to influence a firm's existing resources, skills, and knowledge) [Abernathy and Clark 1985].

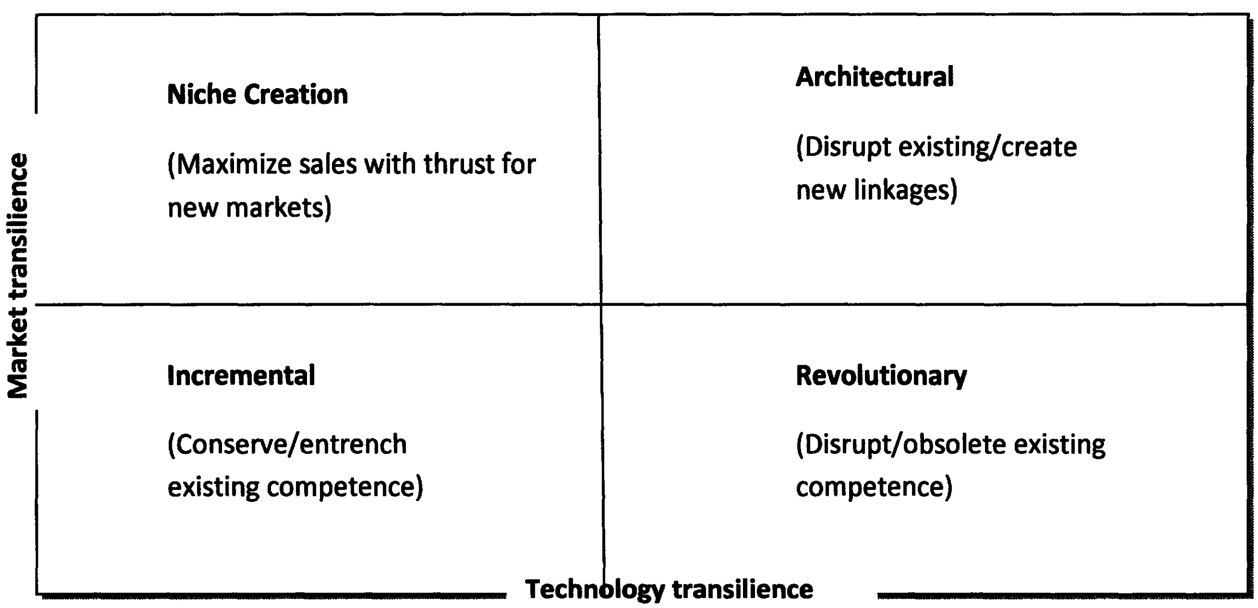


Figure 10 Abernathy and Clark' s framework for innovation types[10]

[10] Adopted from, Abernathy, W.J., Clark, K.B., "Innovation: mapping the winds of creative destruction", Research Policy, 14, 3-22, 1985

Revolutionary innovation is at the heart of Schumpeter's theory of innovation and economic development in which "creative destruction" is the vehicle for growth. These types of innovation, which creates new industries and is often propelled by scientific research, have been extensively reviewed in literature. However, as products become more and more complex with blurred boundaries between software, hardware and services, architectural innovation gains in importance. That is what we shall review here and discuss how it is used as a competitive weapon for superior transilience in markets by established companies.

The essence of architectural innovation is the reconfiguration of an established system to link together existing components in a new way. This does not mean that component technology never changes. Architectural innovation is often triggered by a change in a component, creating new linkages and interactions with other components in the established product. Here is an illustrative example given by Henderson and Clark from the HVAC (Heating Ventilating Air Conditioning) industry: If a room's ceiling air fan is an established technology, improvements in its blade design, or the motor would be incremental innovations. A central air conditioning unit would be a radical innovation, with a completely different set of technology and design. However introduction of a portable fan for the large ceiling fan manufacturers would be an architectural innovation. While the components of the products will be pretty much the same, the architecture of the product would be different [Henderson and Clark 1990].

Product architecture and industry cycles

Every product has architecture. Product architecture is classified in two categories: Integral or modular. In his book *Clockspeed*, Charles Fine explains product architecture types and their relationship with industry dynamics using the recent history of the computer industry.

In the 1970s and early 1980s the computer industry structure was vertical. The three largest companies, IBM, Digital Equipment Corporation and Hewlett-Packard were highly integrated as well as other small players referred to as "BUNCH". In this early stage of the computer industry, products and systems exhibited integral architectures. Almost all of the components of a computer, microprocessors, operating, systems, and peripherals etc. were manufactured in house by the firms in the market. There were no industry standards or interfaces available; hence there was little or no interchangeability across different companies' systems.

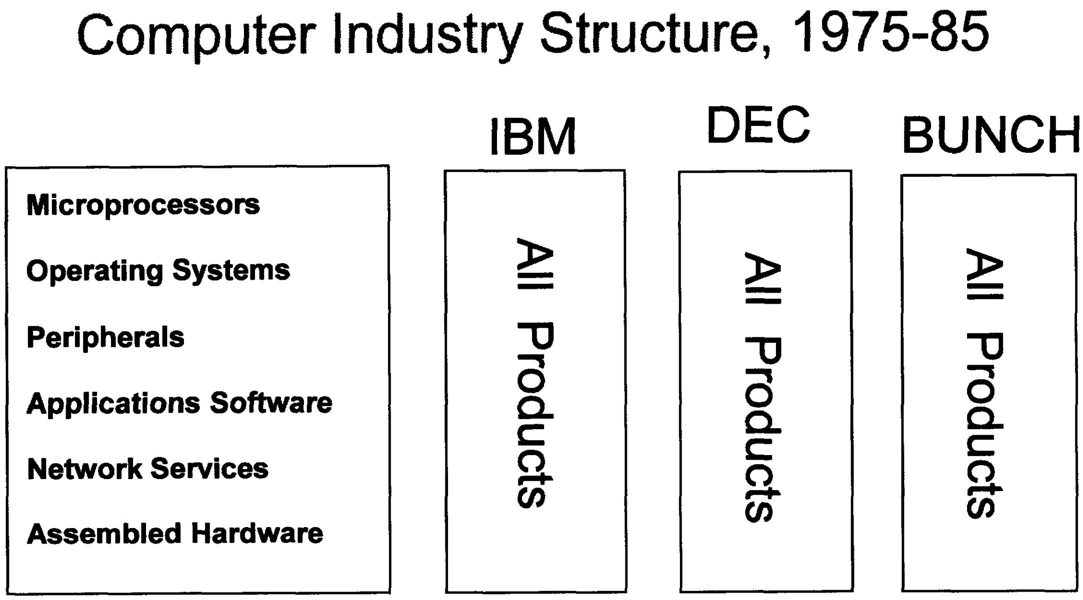


Figure 11 Vertical Industry Structure and Integral Product Architecture in the Computer Industry[11]

During these years, IBM gained significant market power by keeping its integral product architecture close, and holding their existing customers hostage. In the late 1970s, IBM faced fierce competition from Apple with a smaller product called a Personal Computer. In response IBM launched a new business division and a new personal computer of its own.

However for its new PC, IBM chose different product architecture, -modular architecture-, outsourcing almost all major components, such as the microprocessor to Intel and, operating system to Microsoft. The dominant design became an IBM-compatible computer. Many companies entered the industry as subsystem supplies; semiconductors, application software, peripherals, networks, and PC design and assembly. IBM strategy created a shift from a vertical/integral (Figure 11) industry structure to a horizontal/modular one (Figure 12). Within this horizontal structure new companies emerged and competition became very fierce in each supply segment [Fine and Whitney 1996].

[11] Fine, C. H., "ClockSpeed: Winning Industry Control in the age of Temporary Advantage", Perseus Books, p.44, 1998

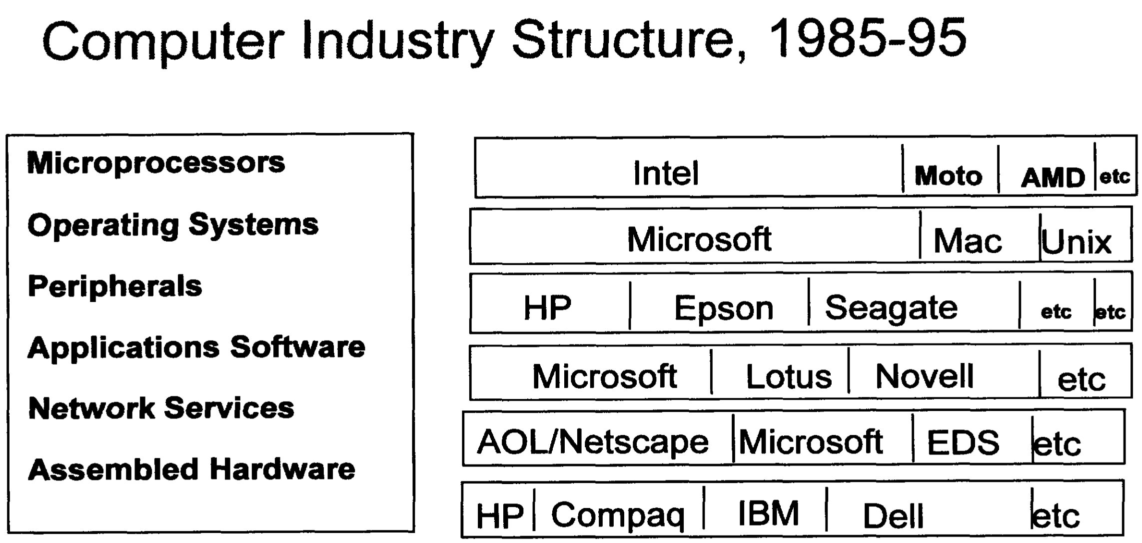


Figure 12 Horizontal Industry Structure and Modular Product Architecture in the Computer Industry[12]

The fierce competition fueled healthy growth in the industry. The IBM-compatible PCs subsystems drastically improved performance curves and delivered product systems which were far more superior to Apple's Macintosh computer. Quite surprisingly, IBM lost about $1 billion in market value after its strategic move, since it was squeezed by assembler like; Compaq, Gateway, Hewlett-Packard, Dell, and many other domestic and international PC assemblers. With a vast amount of supplier options, continuous price-decrease in almost every supplier segment, and an industry wide accepted standard; IBM-compatible entry barriers into PC design and assembly business was almost non-existent.

Fine's Double-Helix model generalizes the behavior of this industry shift from vertical/integral to modular/horizontal. He suggests that the cycle is reciprocal. Horizontal structures are as unstable as vertical structures. Horizontal structures tend to create fierce, commodity competition across layers. When a player in a segment gains power and an edge in costs, quality, and technology, for example, it will drive out weaker competitors. Once a firm finds market power in its row, it will seek opportunities to extend vertically as well. Both Microsoft and Intel, the most powerful players of their respective segments, exhibited this behavior. Microsoft, dominating Operating Systems, entered into application software, network software, multimedia content, and peripheral hardware segments. Intel expanded from microprocessors to the design and assembly of motherboards and, graphics processors. Figure 13

[12] Fine, C. H., "ClockSpeed: Winning Industry Control in the age of Temporary Advantage", Perseus Books, p.46, 1998

illustrates the dynamic cycle modeled as a double helix. When the industry structure is vertical and product architecture is integral, the forces pushing towards a horizontal industry structure and modular product architecture include [Fine 1998]:

1. The entry of niche competitors to pick off discrete industry segments.
2. The challenge of keeping ahead of the competition across many dimensions of technology and products.
3. The organizational rigidities that often constraint established companies for innovation in particular technologies.

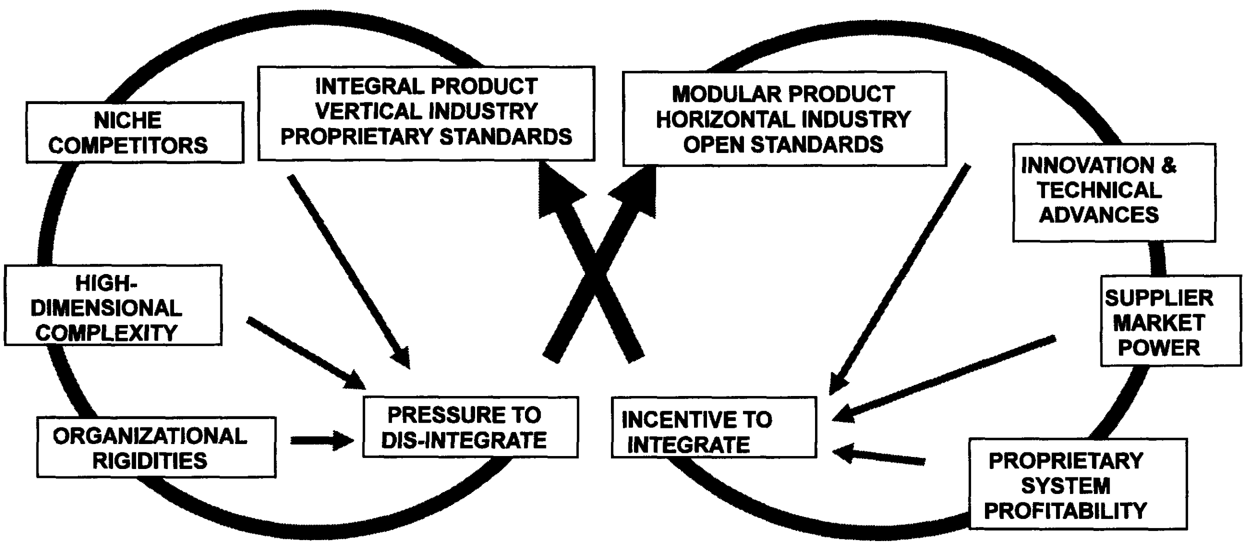


Figure 13 The Double Helix Model[13]

On the other hand, when an industry has a horizontal structure, another set of forces push towards more vertical integration in industry and integral architecture in products. These forces include:

1. Technical advances in one subsystem make the commodity scarce in the chain and the powerful and greedy owner will seek entry into adjacent segments to pick up market share.
2. Market power in one subsystem encourages bundling with other subsystems to increase control and add more value.

[13] Fine, C. H., "ClockSpeed: Winning Industry Control in the age of Temporary Advantage", Perseus Books, p. 49, 1998

3. Market power in one subsystem encourages engineering integration with other subsystems to develop profitable integral solutions, delivering higher performance in specific attributes.

Product platforms

While architectural innovation is a challenge to companies with rigid organizational structures, many companies were able to use strategies based on product architecture to create business value, conquer new markets, and reach new levels at cost-effectiveness.

A product platform is a set of subsystems and interfaces forming a common structure from which a stream of derivative products can be efficiently developed and produced. A single product's architecture is considered a product platform architecture when it is designed and used as a foundation for the architecture of several other derivative products. When many products share the same product architecture, they are called a product family [Meyer and Utterback 1993]. A general framework for effective use of product families as proposed by Meyer and Utterback is presented in figure 14. This figure represents a single product family (Product family A) starting with initial development of a product platform. Using this platform successive families are followed by major advancements to the core product and process technology of that platform, with derivative products in each generation. Platform family B represents a new generation of products intended to extend the core capabilities of the company to a new market using the very same platform.

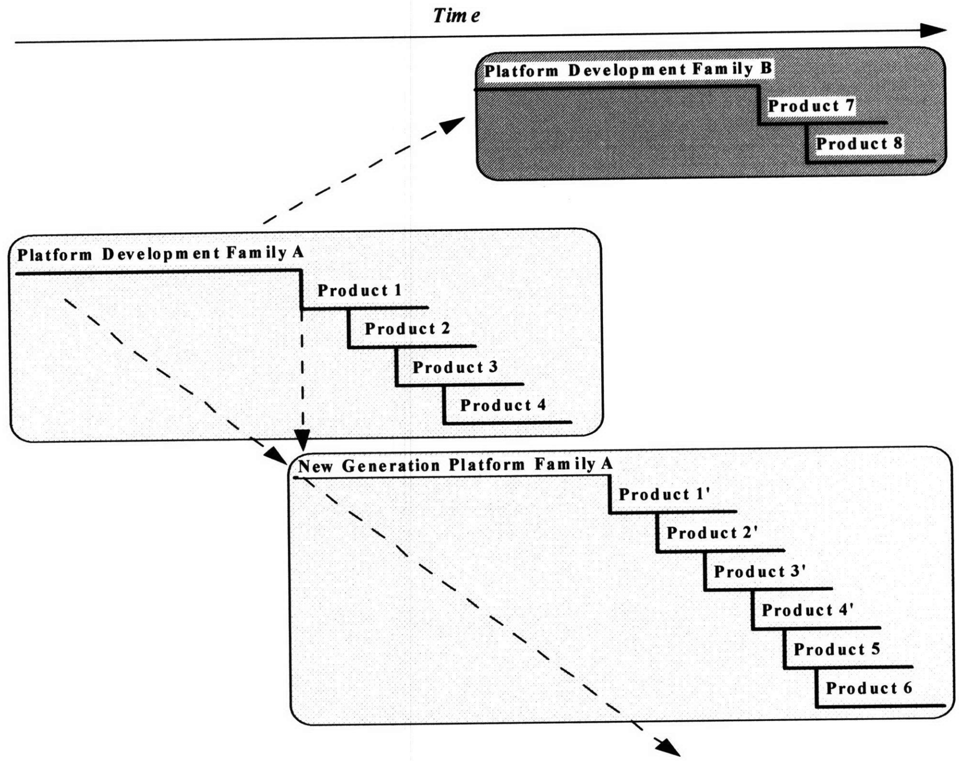


Figure 14 The product family approach to new product development[14]

A product family typically addresses a market segment, while particular products address market niches within that segment. The commonality of technologies and architecture used across multiple product families leads to efficiency and effectiveness in design, manufacturing, distribution, and service, as the firm tailors its core competencies to the specific needs of customer clusters. Black & Decker was one of the pioneers of platform strategy in the U.S. in the early 1970s. The company had dozens of products, jig saws, drills, and sanders using thirty different motors, sixty different motor housings, and dozens of different operation controls. Black & Decker, in order to remain competitive decreased its costs one third by adopting common product platforms across in entire product families. With a budget of $20 million allocated to this effort, engineers designed standard motor housings, controls, and adhesive-bonded armature which can be used in multiple families. Product costs dramatically reduced by 50 percent, and shares soared from 20 percent to dominant pie in most of the product markets that Black and Decker competes in [Meyer and Lehnerd 1997].

[14] Meyer M., H., Utterback, J.M., "The product family and the dynamics of core capability", Sloan Management Review, p.32, Spring 1993

Further, Meyer and Lehnerd identified four different strategies for using Product Platforms. These strategies are depicted in figure 15 on market segmentation grids. In a market segmentation grid, horizontal segments denote cost/performance tiers, "low cost, mid range, high cost", or "low performance, mid range, high performance". Vertical segments denote different business segments that where the company is active.

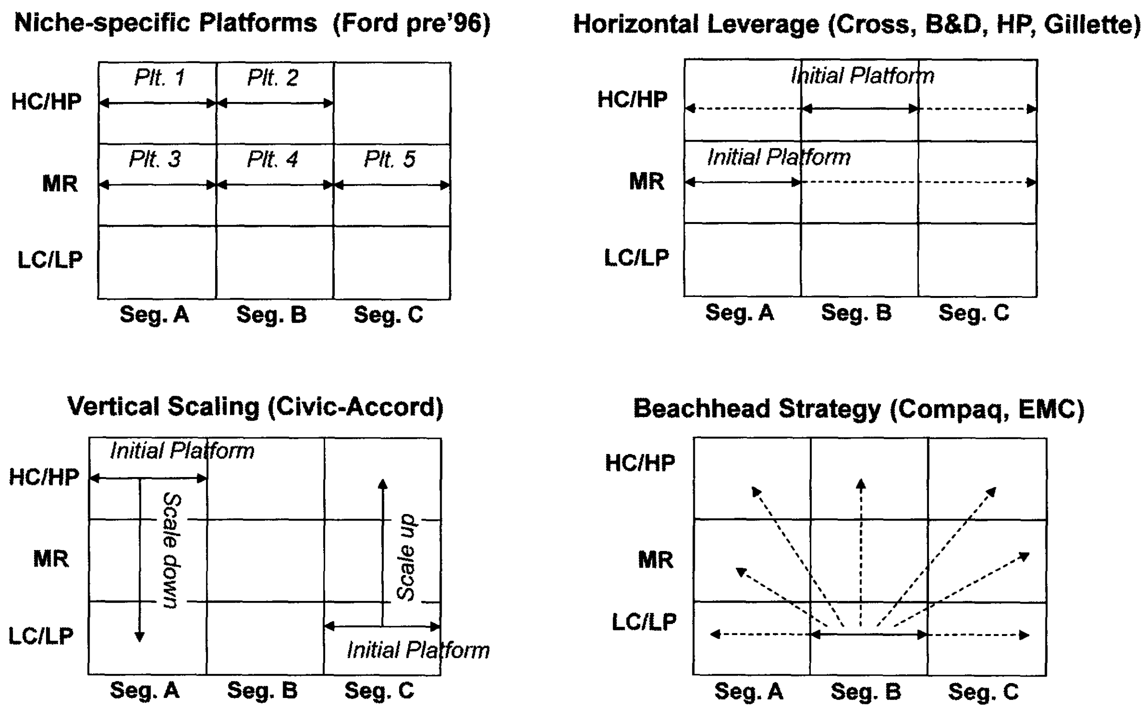


Figure 15 Platform Strategies[15]

Many other well know established companies used platform strategy. For Sony, there has been no greater success than the Walkman. Sony dominated the market, worth $1 billion worldwide, for over a decade and stayed market leader despite fierce competition from world class consumer electronics manufacturers. According to Sanderson and Uzumeri's research, Sony's Walkman strategy was an example of outstanding product family management. Sony followed a disciplined and creative approach to focus its sub-families on clear design goals and target models to distinct market segments.

[15] Utterback, J.M., Disruptive Technologies lecture notes, Sloan school of management, MIT, 2006

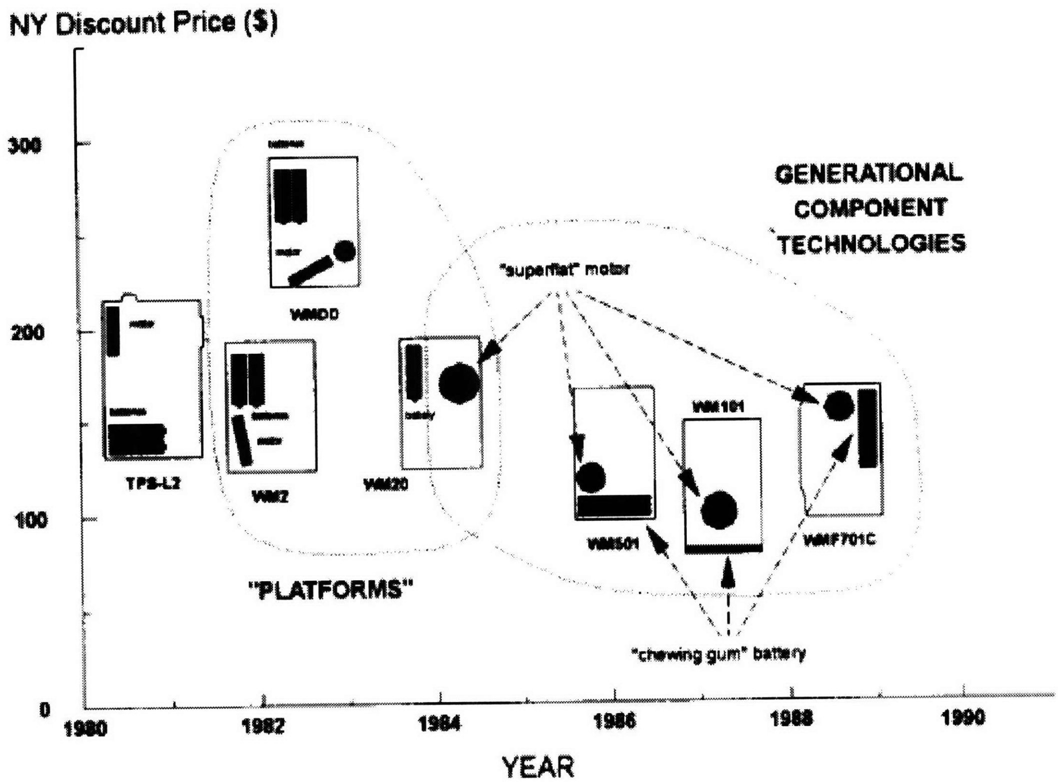


Figure 16 Generational walkman innovations at Sony[16]

Sony offered 20 new models each year and during the 1980s almost 250 models into the US market. From 1980 to 1988, the average market life of a Sony model was 1.97 years. This is twice as long as its competitors. Figure 16 depicts major platforms and two major component technologies developed in Walkman by Sony. Superflat motors enabled dramatic size and weight reduction in Walkman, further augmented by chewing gum batteries, taking advantage of low power consumption of the superflat motors and redesigned electro-mechanics. With platforms as a basis, most of these models were achieved by making small changes in features, packaging and appearance. Sanderson and Uzumeri categorized these non-platform changes into two further categories: incremental and topological innovations. To support the level of variety generated by systematic platform approach and incremental and topological innovations, Sony invested in flexible manufacturing extensively so that it could make many Walkman models on small production runs. By combining industrial design with flexible manufacturing Sony generated designs that had dramatic market impacts and little marginal cost [Sanderson and Uzumeri 1995].

[16] Sanderson S., Uzumeri, M., "Managing product families: The case of Sony walkman", Research Policy, 24, p.768, 1995

For companies like Intel and Microsoft, platform leadership is a very different ball game. These platform leaders drive industry wide innovation for evolving systems (such as PCs), which has pieces separately developed in an industry. As much as these two companies are dependent on each other for innovation and future development of their products, they are also dependent on many *complementor* companies in their industry. Intel considers this situation a challenge, since it cannot be certain that its own key complementors will continue to produce market-expanding innovations as fast as Intel does. Nor can it be sure its target platform, the personal computer, will evolve in compatible ways. For example the platform around the engine may limit the engine, they need to make sure the platform keeps pace on improving, so that the microprocessor can deliver its potential [Cusumano and Gawer 2002].

3. Lotka-Volterra model and dynamics of competition

Multi-mode interaction among technologies

The concept of multi-mode interaction among two or more technologies was first proposed by Pistorous and Utterback. Multi-mode framework suggests three modes of interaction among competing technologies, all are based on the reciprocal enhancement or inhibition of a technologies' growth rate. The concept was introduced by considering four uni-directional modes of interaction; an emerging technology which can have a positive or negative influence on the growth of a mature technology, and a mature technology which can have a positive or negative influence on the growth of an emerging technology.

These four uni-directional modes are combined to yield the three major modes in the multi-mode framework [Pistorious and Utterback 1997]:

- **Pure competition:** An emerging technology has a negative influence on the growth of a mature technology, and the mature technology has a negative influence on the growth of the emerging technology.
- **Symbiosis:** An emerging technology has a positive influence on the growth of a mature technology, and the mature technology has a positive influence on the growth of the emerging technology.
- **Predator-prey:** An emerging technology has a positive influence on the growth of a mature technology, and the mature technology has a negative influence on the growth of the emerging technology, or an emerging technology has a negative influence on the growth of a mature technology, and the mature technology has a positive influence on the growth of the emerging technology.

Table 1Multi mode framework for assessing the interaction among technologies[17]

Multi mode framework for interaction of technology A and B		**Effect of A on B's growth rate**	
		Positive	***Negative***
Effect of B on A's growth rate	***Positive***	Symbiosis	Predator(A) – Prey (B)
	Negative	Predator(B) - Prey (A)	Pure Competition

[17] Pistorius, C.W.I., Utterback, J.M., "Multi-mode interaction among technologies", Research Policy, 26, p.75, 1997

In order to mathematically model the multi-mode framework described above, a system of coupled differential equations with coupling coefficients is required to account for the interaction between them. Lotka-Volterra equations, also known as predator-prey equations, are a pair of first order non-linear, differential equations proposed to describe the dynamics of biological systems in which two species interact, one of them, predator and the other, prey. It was proposed by the American biophysicist Alfred Lotka, and the Italian mathematician Vito Volterra in 1925.

The system of equations describing the interaction can be expressed as [Carroll 1981]:

$$\frac{dN}{dt} = a_n N - b_n N^2 \pm c_{nm} NM \quad \text{Eq}^n\ 1$$

[18]

and

$$\frac{dM}{dt} = a_m M - b_m M^2 \pm c_{mn} MN \quad \text{Eq}^n\ 2$$

[18]

In these equations M and N represent two different technologies competing with each other. The signs of the coefficients indicate the mode of competition. Two positive signs of the coefficients indicate a symbiotic interaction, two negative signs indicate pure competition, and one positive and one negative sign indicates predator-prey interaction.

Solution of Lotka Volterra equations

Several authors in literature stated Lotka-Volterra equations cannot be solved explicitly, but they can be solved numerically. Pielou suggested a numerical solution for the equations in the case of pure competition [Pielou 1969].

$$\frac{dT_i}{dt} = a_i T_i + \sum_{j=1}^{J} s_{ij} c_{ij} T_i T_j \quad \text{Eq}^n\ 3$$

[19]

---

[18] Pistorius, C.W.I., Utterback, J.M., "Multi-mode interaction among technologies", Research Policy, 26, 82, 1997

[19] Pistorius, C.W.I., Utterback, J.M., "A Lotka-Volterra Model for Multi-mode technological interaction: Modeling Competition, Symbiosis and Predator Prey Modes", Proceedings of the Fifth international Conference on Management of technology, Miami, FL, Feb 27 – March 1, 1996

The equation state above, represents *J* technologies interacting in the same market niche. Each technology is expressed as *Ti(t),* where $(2 \leq i \leq J)$. All coefficients are positive and $s_{ii}c_{ii} = -b_i$. Further, if technology *j* has a positive influence on technology *i*'s growth, $s_{ij} = +1$, whereas if technology *j* has a negative influence on technology *i*'s growth, $s_{ij} = -1$.

The numeric form solution for $T_i(t)$ can be found by extending Pielou's solution to the general case:

$$T_i(t+1) = \frac{e^{a_i}T_i(t)}{1 - \sum_{j=1}^{J} \frac{s_{ij}c_{ij}(e^{a_i} - 1)}{a_i} T_j(t)} \quad \text{Eq}^{n}\,4$$ [20]

The formulation above is a general solution for multi-technology, multi-mode interaction. It can be easily implemented into a spread sheet or numerically programmed to model the interaction of any finite number of technologies where the interaction among any pair is either pure competition, predator-prey, or symbiosis.

Pure competition

Pure competition, where each technology exerts a negative influence on the other's growth is a very prevalent case in innovation. Farell, used a model based on Lotka-Volterra equations to investigate pure competition between various technologies, such as lead-free versus soldered food cans, woven versus tufted carpets, fountain versus ball-point pens, and telephone versus telegraph [Farell 1993]. Pure competition is often embodied in substitutes, which is one of the five forces model developed by Porter [Porter 1998]. Substitutes address the same market niche as existing products, they will generally have an inhibiting effect on the existing products growth in the same niche. For example the emergence of LCD (Liquid Crystal Display) monitors as an essential part of laptop computers, as their prices went down, they slowly captured the market of CRT (Cathode Ray Tube) based monitors, acting as a substitute, with better performance in several attributes such as view quality and product dimensions.

Symbiosis

Symbiosis is when each technology has a positive reciprocal effect on one another's growth rate. Symbiosis is the association of two different organisms living attached to each other or one within the other to their mutual advantage. For example, the railroads and the steelmaking industry spurred on each other's development, as did the electric lighting and the telephone. More recent examples of symbiosis can be seen in the computer industry [Girifalco 1991]. Symbiosis between major technologies

[20] Pistorius, C.W.I., Utterback, J.M., "A Lotka-Volterra Model for Multi-mode technological interaction: Modeling Competition, Symbiosis and Predator Prey Modes", Proceedings of the Fifth international Conference on Management of technology, Miami, FL, Feb 27 – March 1, 1996

of PC components, such as operating systems, CPUs, hard disks, and network components enforce each other's growth. The strategic alliance between Microsoft and Intel, which is more closely coupled and co-dependent, is a predominant example from the computer industry.

Predator-prey interaction

A predator-prey relationship may exist between an emerging technology and a mature technology when the emerging technology enters a niche market that is not served by the mature technology. In such a case, the emerging technology will benefit from the presence of the mature technology and the mature technology will exert a positive influence on the emerging technology's growth rate. However, the emerging technology may slowly steal market share from the mature technology, thus having a negative influence on the growth of the mature technology. Hence the predator-prey interaction occurs between them, with the emerging technology, the predator and the mature technology, the prey.

On the other hand, a new technology may trigger a sailing ship effect in the mature technology, resulting in de-maturing and new growth, having a positive influence on the mature technology's growth rate. When this effect occurs simultaneously with one where the mature technology has a negative effect on the growth rate of an emerging technology, a predator-prey relationship results where the mature technology is the predator and emerging technology is the prey.

A well known example of predator-prey competition is the attack of radial-ply tires on bias-ply tires in the USA. During 1970s, when bias-ply was dominating US market, French based Michelin invented radial-ply tire. During its adoption period, sports car drivers who needed high performance started replacing their tires with radial-ply tires. It is argued that initially the competition mode was predator-prey in the sense that radial-ply tires took advantage of existence of bias-ply tires. If automobiles were not using tires at all, a market would not exist and it would be very hard for radial-ply tires to create one. Until a large deal from Lincoln Continentals, radial-ply tires did not threaten the market of bias-ply tires since automotive manufacturers were reluctant to modify the suspension design for radial-ply tires [Foster 1986].

4. System dynamics and innovation modeling

Introduction to modeling with System Dynamics

System dynamics is an approach to understanding the behavior of complex systems over time. It deals with internal feedback loops and time delays affecting the behavior of the entire system. What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity. System dynamics was founded in the late 1950s by Jay W. Forrester of the MIT Sloan School of Management with the establishment of MIT system dynamics group. He began applying what he had learned about systems during his work in electrical engineering to everyday kind of system [Sterman 2000].

System dynamics has been applied to issues ranging from corporate strategy to the dynamics of diabetes, from the cold war arms race between the US and USSR, to the combat between HIV and immune system. System dynamics can be applied to any dynamic system with any time and spatial scale. What system dynamics attempts to do is understand the basic structures of complex socio-technical systems and thus understand the behavior they will produce. Many of these systems analyzed can be built as models on a computer by use of specialized software such as Vensim. As computing power gets better and cheaper, the power of system dynamics is unleashed, as more complicated systems can be modeled and simulated much easier and faster.

The basic elements of system dynamics diagrams are feedbacks, the accumulation of flows into stocks and time delays. By any combination of these elements, a loop which can have a balancing effect or re-enforcing effect on a key variable can be created. A system dynamics model of new product adoption is depicted in figure 17 comprised of two stocks: potential adopters and adopters. The flow from potential adopters to adopters is characterized by the effects of two loops: saturation loop (Balancing) and word of mouth loop (reinforcing). Each link in a diagram has a positive sign if it affects positively from its originator variable to end variable, or has a negative sign if it affects negatively from its originator variable to end variable. In addition to the signs on each link, a complete loop also is given a sign. The sign for a particular loop is determined by counting the number of negative signs on all the links that comprise a loop. A feedback loop is called positive or *reinforcing* loop, if it contains an even number of negative casual links. On the other hand a feedback loop is called negative or *balancing* loop, if it contains an odd number of negative casual links.

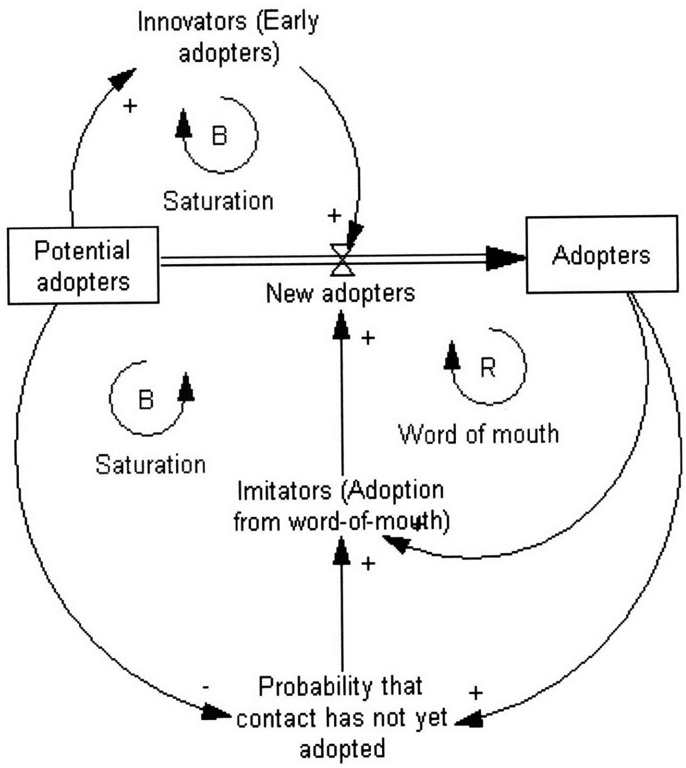


Figure 17 System dynamics model of new product adoption[21]

The real power of system dynamics is unleashed through simulation. The simulation results of the new product adoption model are given in figure 18. Simulation results prove that the adoption curve follows a classical s-curve shape. The increase in adopters is very slow in the beginning, then exponential growth for a period, and finally ends with saturation. As stock of an adopter rises following an S-curve, potential adopters stock reduces following a reverse s-curve trajectory.

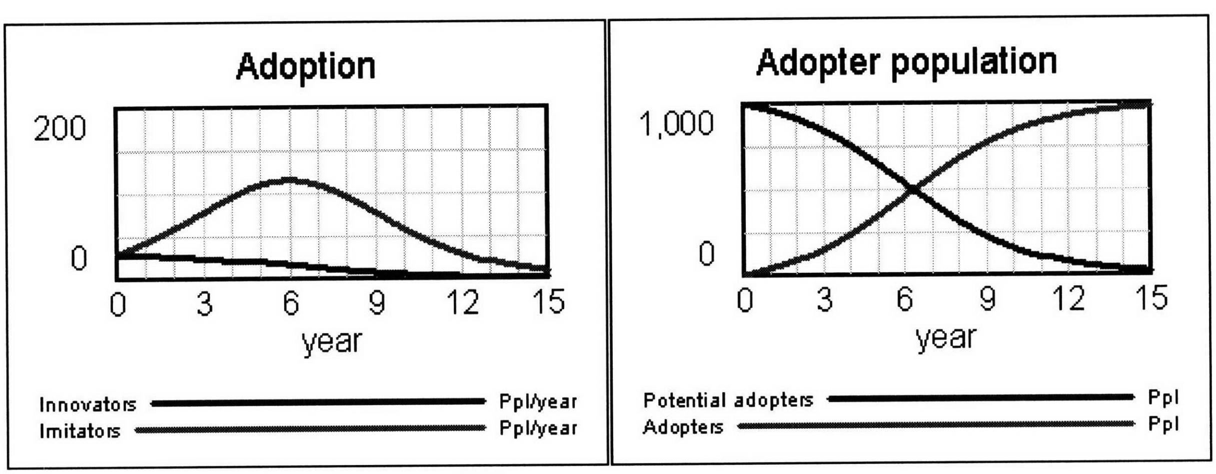


Figure 18 Simulation results of new production adoption model[21]

[21]Morrison, B., System Dynamics, Lecture notes, MIT 2008

Dynamics of Innovation

The literature highlights dynamics that are fundamental to sources of innovation and their impact on firms, markets, and industries. These dynamics are identified by Weil and Utterback as:

- Entry and exit of firms
- Experimentation and innovation
- Technology evolution
- Improvement in cost and performance
- Emergence of standards and dominant designs
- Adoption of new technology
- Network effects
- Development, growth, saturation of a mass market
- Intensity of competition and commoditization

Weil and Utterback captured the fundamental dynamics of innovation in technology industries within a System Dynamics model. This integrated conceptual model is depicted in figure 19. The model connects the number of companies in the market, technology evolution, adoption of new technology, and the profitability of companies. Other fundamental dynamics of innovation are represented; entry and exit of firms, improvements in cost and performance, market growth, intensity of competition, and commoditization [Weil and Utterback 2005].

A more detailed casual loop diagram for modeling a number of companies is given in figure 20. In the fluid phase of an industry usually a "lemming effect" occurs, where there is an inflow of entrants to the industry by companies which are attracted by the potential of the new industry. In a short amount of time there will be high number of firms, generating a high level of experimentation and innovation. Continuous innovation, feature, and performance characterize competition among products. As diversity of designs and products increase, the need for more standardization grows and dominant design emerges. After the emergence of a dominant design, innovation based competition gives way to process based competition which aims to reduce cost and improve quality. As industry stabilizes entry rate slows and many companies exit, bankrupt or acquired. Remaining companies who own dominant designs continue to grow and dominate the industry.

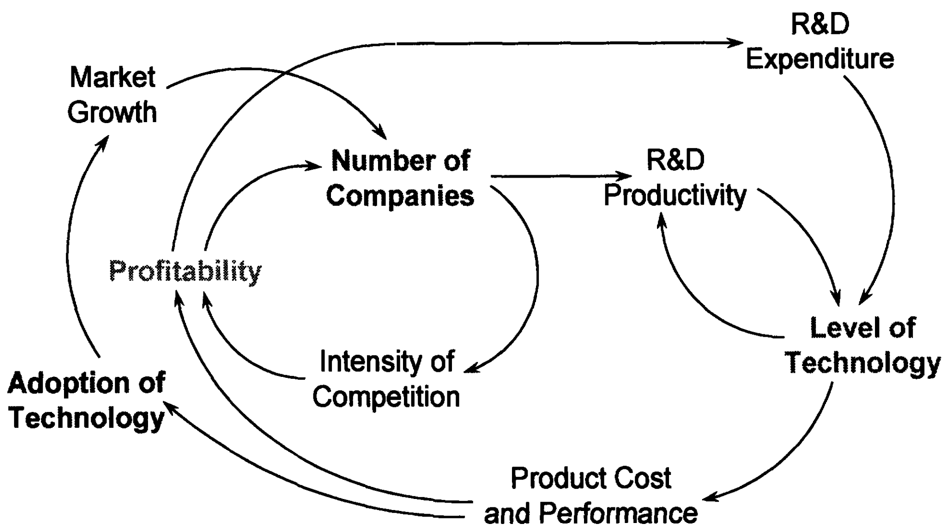


Figure 19 Integrated conceptual model for dynamics of innovation[22]

The dynamics of technology adoption encompass both objective and emotional factors, i.e., price/performance, network effects, and perceived risks (Figure 21). By the emergence of a dominant design, the industry consolidates, leading to a few companies which can realize substantial economies of scale. During this transition, incremental improvements continue to enhance performance while process innovations improve productivity and quality. The decline in unit costs and improvement in quality as a function of cumulative unit production is called "learning effect".

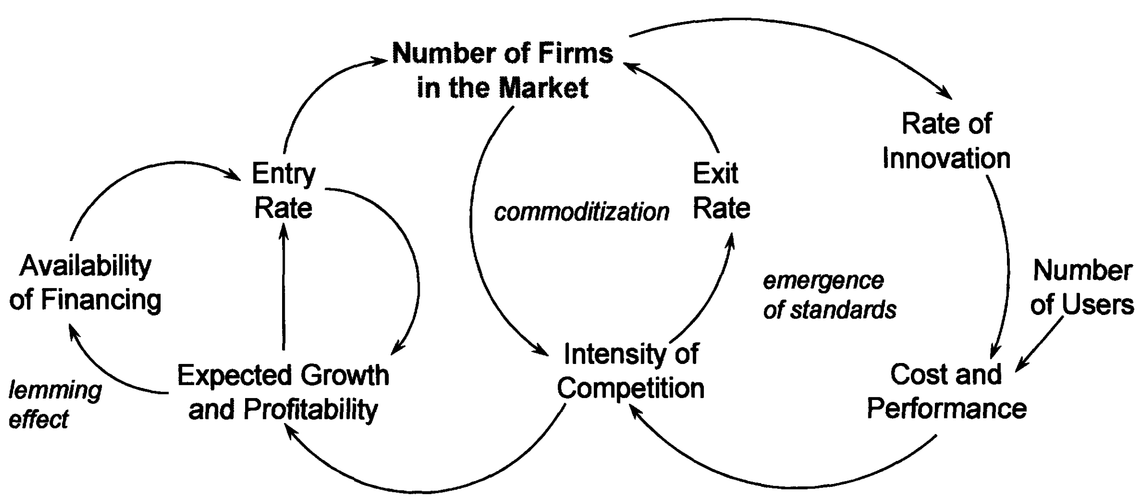


Figure 20 Number of firms in the market[22]

[22] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

When an industry is new and uncertain, perceived risks of a new technology are high, as they are unproven. As the number of users increase, skepticism among users turns into confidence in the technology. Highly respected "reference users" and increasing user masses, make the new technology legitimate and easier to justify. As the new technology becomes more fashionable as a product or service, the risk of not adopting is perceived as "becoming a dinosaur" or "not getting it".

The conceptual model based on causal loop diagrams is simple and generic. It can be applied to a broad range of products and services; assembled or process-based, complex and simple, analog or digital, business or consumer. In many variations and combinations, most industries can be modeled and dynamics can be simulated using key parameters about the industry.

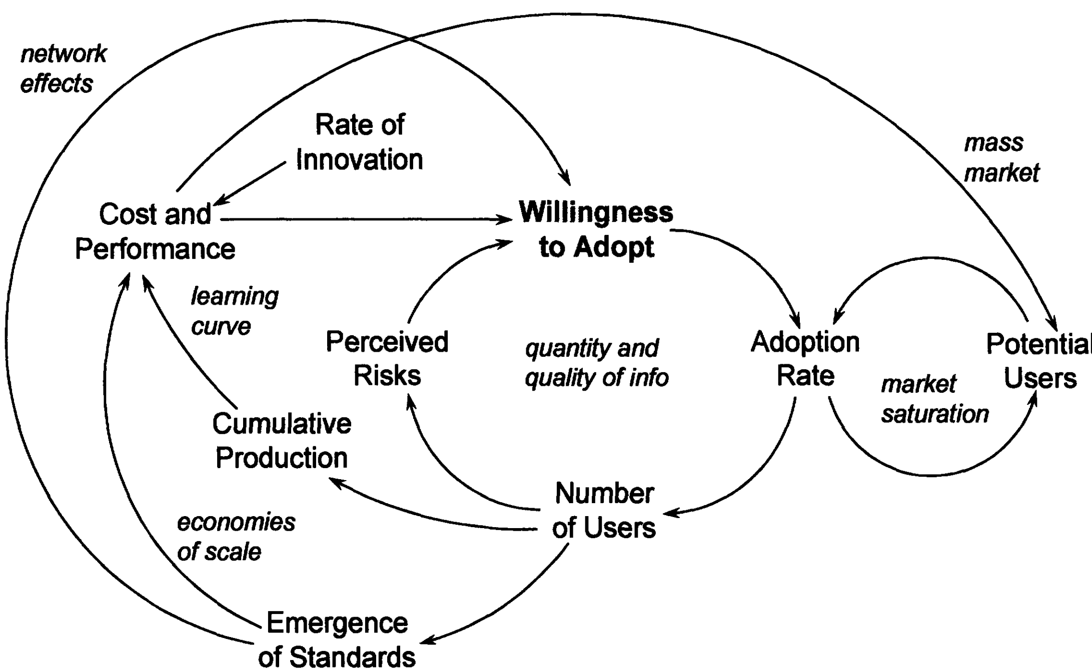


Figure 21 Willingness to adopt new technology[23]

[23] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

5. Comparison of L&V model and SD in modeling innovation dynamics using a Case Study

Both of the models, reviewed in the previous chapters in detail, can be applied to a broad range of industries; assembled and process-based, complex or simple, physical or digital, business or consumer. However in order to show a good contrast between two simulation methods, choosing an industry where competition between "old" and "new" technology is intense, is important. During the last decade in the photography market, strong competition has been taking place between the "old" and "new" technologies.

Our main objective is to compare the characteristics and performance of Lotka-Volterra modeling vs. System Dynamics approach in innovation dynamics. It is important to review which characteristics of innovation dynamics can be simulated by two models and those that can be simulated by both of them. First we will simulate the essential variables incorporated in a System Dynamics model. These are a lot more than the Lotka-Volterra model can offer. Then we will simulate Lotka- Volterra model and contrast the results.

Simulation by System Dynamics model

The simulation of competition dynamics by film and digital cameras is limited to the U.S. market only and we excluded digital cameras in cell phones. It presents results for products based on two generations of technology, labeled as "old" and 'new". Simulations run from 1990 to 2020. The new technology was launched in 1990. Market upper limit is bounded by the assumption that 90% household in U.S. would have cameras [Weil and Utterback 2005].

The first simulation is the number of companies entering and exiting both markets separately, and the total number. The entry and exit of firms into a market are central to the dynamics of innovation. In the early stage of a new market or generation of a new technology the perceived opportunity by established firms and entrepreneurs is large. As technology matures a dominant design emerges and first entry rate peaks and drops. As entries drop and exit from the industry increases and peaks, lagging the peak of entry rates usually couple of years.

This classical behavior of firm entry-exit dynamics is observed as the result of our simulation. The entry rate into the digital camera market sharply increased during 1990s and reached its peak at 1998. The trend in exit rates peaked in 2000 and started to decline after. If we examine the actual number of companies for digital camera, there was sharp increase during 1990s, hitting its peak at 54 in 1999, and then started declining continuously, were it reached levels of a few remaining in market at 2020 (Figure 22).

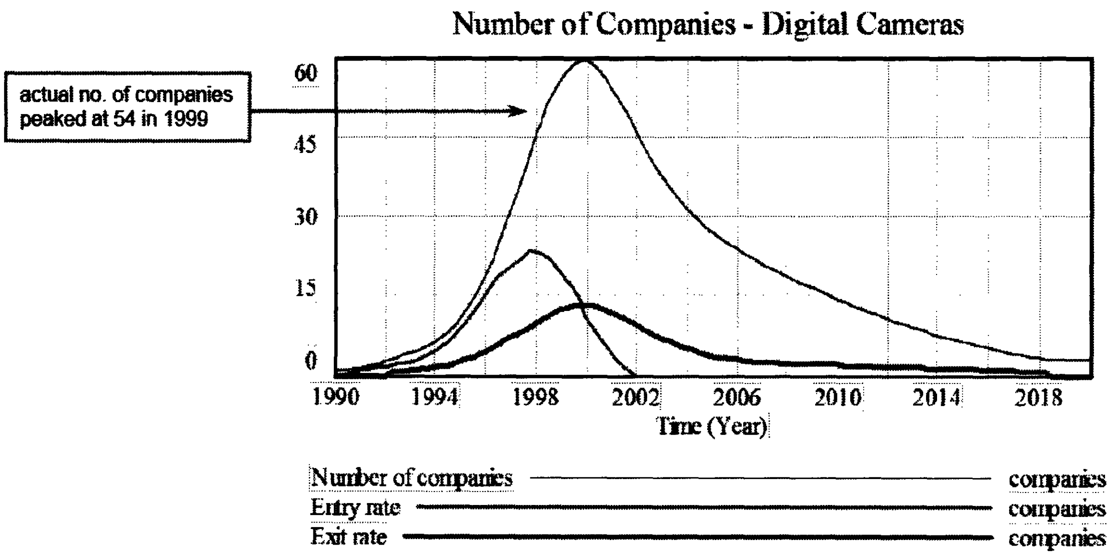


Figure 22 Dynamics of entry-exit of firms into digital camera market[24]

Price/cost is another leading indicator of competition dynamics. In the early phase of a new technology both cost and price are at its peak. There are not enough economies of scale yet to reduce the costs and for firms with their unique technologies protected by IP rights and a mostly vertically integrated structure, profit margins tend to be high. As dominant design or standards emerge and production volume increases, costs start to decline. Industry structure converts to horizontal and the market matures. The product or service becomes "commoditized", where product differentiation is difficult, customer loyalty and brand values are low, and profit margins gets very thin. The only sustainable advantage comes from cost leadership. Commoditization is more aggravated by excess capacity. Margins are highly sensitive to capacity utilization and product innovation slows or stops, although process innovation continues in pursuit of a better cost advantage.

[24] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

Figure 23 shows the price dynamics for both film and digital cameras. Early digital camera prices were far more than average film camera prices. The market was small, costs were higher, and fluid technologies possessed by entrants were protected by IP laws. As the market grew and was flooded with incumbents and start-ups, competition intensified, economies of scale increased, thus continuously decreasing the average costs and price. As unit costs declines, quality improves as a function of cumulative production. This is also known as the "learning curve" effect. After the emergence of a dominant design triggers industry consolidation, only a few leading suppliers can remain in market. As a mass market forms, they now have the advantage of realizing substantial economies of scale contingent on high levels of capacity utilization. In 2004 the average cost of digital cameras equaled film cameras and continued to decline thereafter, whereas the price of film cameras was hanging around their commodity pricing levels.

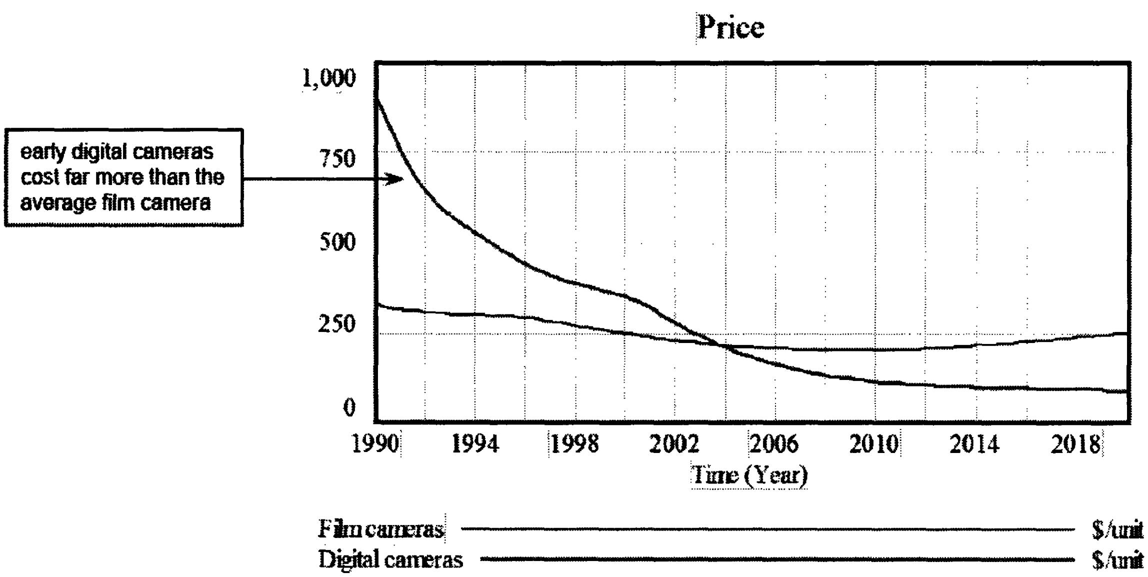


Figure 23 Dynamics of price for film and digital cameras[25]

As competition intensifies in an emerging market, we see drastic improvement in key performance metrics of the products. Increasing performance and stabilization of technology accelerates development of mass market, bolstering attractiveness by consumers and users.

[25] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

There are a few key performance metrics for digital cameras. Resolution is the key parameter that affects the image quality directly. Optical zoom is another important metric for taking quality pictures. Others that can be cited are battery life, size, weight, and ease of photo transfer to other digital media. Here we only simulate the key metric, resolution which is measured in Megapixels. Until 2000, average resolution was less than 1.5 Megapixels. It started to increase sharply after this year maturing at 6 Megapixels at 2020. A significant portion of the performance gain takes place between 2002 and 2010 (Figure 24).

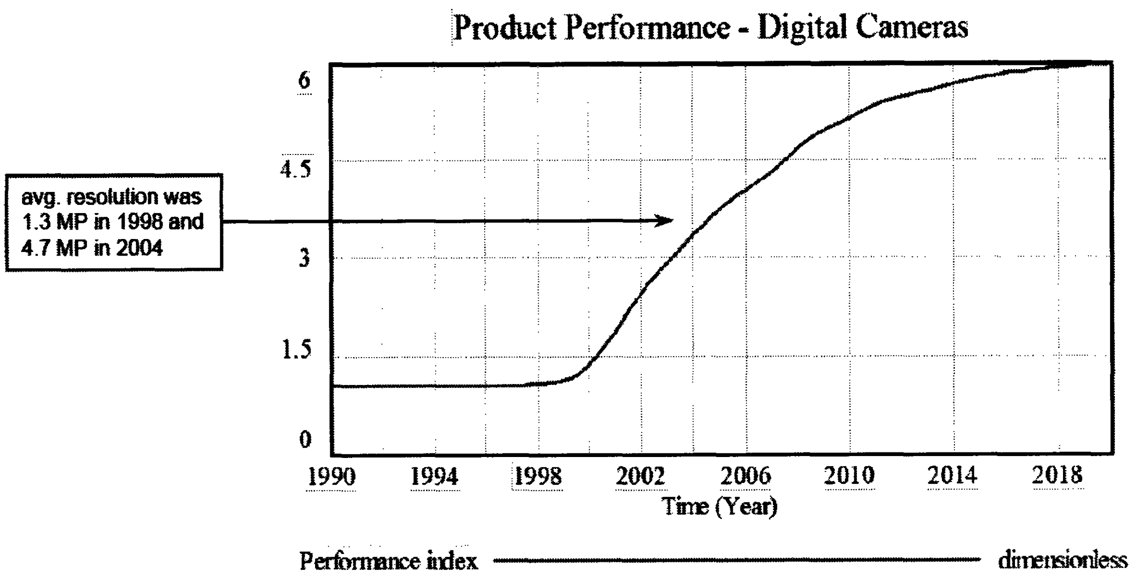


Figure 24 Dynamics of product performance for digital cameras[26]

The perceived risks of an emerging technology are high in its early stage. New technology is unproven, low in key performance metrics compared to the old technology, and potential users have reasons to be skeptical and cautious. Many users who are conscious about technological uncertainties and price wars prefer to wait and see products get more mature and prices drop to reasonable levels. As a market transitions from an emerging market to a mass market, quantity and quality of information about the new technology improves, allowing more confident assessments and decisions by users and buyers. In business markets, highly respected "reference users" legitimize the new technology and enable its selection to be defendable. Then the risk of not adopting it can be seen as "behind the times", or simply

[26] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

“not getting it”. In consumer markets, products or services based on the new technology can become fashionable and a “must have”. Fear of being outdated or lagging in time will start affecting risk adverse consumers and even conservative buyers.

In the simulation output of user willingness to switch to digital cameras, two spikes can be observed. At first, as growth of an installed base ramped up, adoption of early digital cameras accelerated. This was the first reaction to the new technology taking place around 1997 and buyers were mostly early adopters. These users were either amateur or professional photographers (prosumers) who were enthusiastic about the new technology and wanted to start experimenting with it as early as possible. The second spike happened when the price-performance of digital cameras increased significantly. This is the significant indicator of the developing mass market. Around 2005 mass market found a solid ground and the early majority, average consumers in U.S. population, started opting towards digital cameras, instead of buying a new film camera. Finally late majority and laggards adopted the technology, user requirements continued to rise and expectations for key performance metrics became even higher compared to old technology. By 2020 adoption of the technology will be completed and film cameras could only stay in markets for a few niche segments (Figure 25).

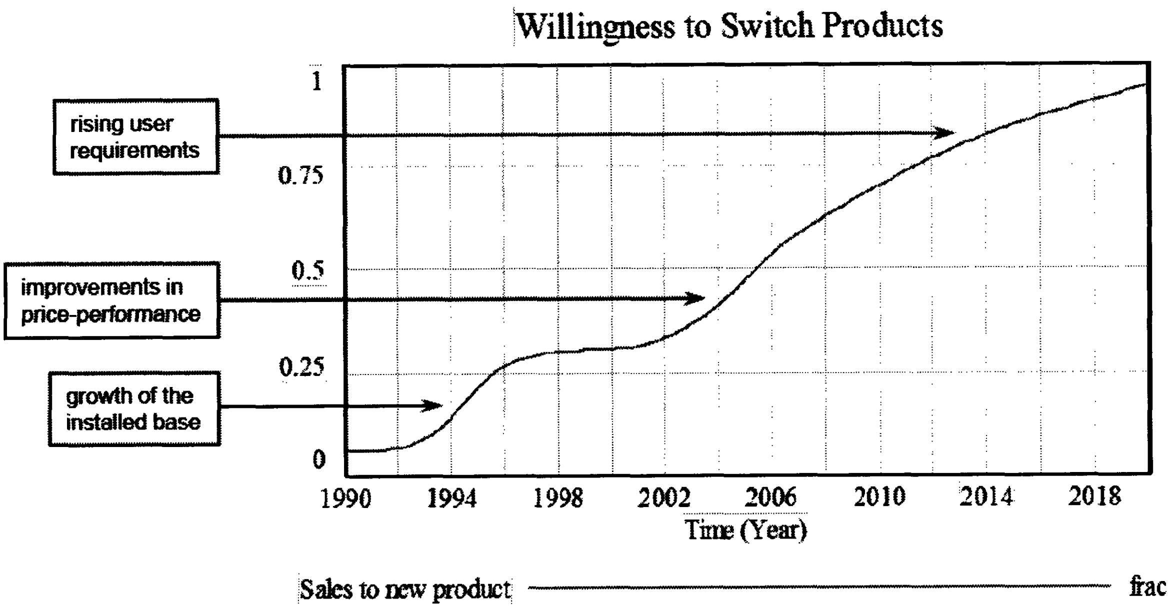


Figure 25 Dynamics of user willingness to switch digital cameras[27]

When a new technology invades a market, it improves its performance in the form of "S-shaped" growth. Decline of the old technology usually depicts a reversed "S-shaped". Most comparable simulations of system dynamics to Lotka-Volterra modeling is unit sales of technologies, which depicts the behavior described. As it can be seen from figure 26, unit sales of the digital camera market continuously increased since 1990 and unit sale of film cameras declined. In 2005 actual sales of digital cameras exceeded those of film cameras. The firms which have a large portion of the market and investments of R&D and production of the old technology usually do not sit back and wait for the new technology to invade the market. They respond with bursts of performance improvements and new functionality to their products in order to keep the declining sales up, along with major marketing campaigns and promotions. The battle here between old and new technology is reflected as waves of units sales in the displayed simulation. It usually continues until unit sales of the new technology exceed those of the old technology, and clearly continues to rise. After this point of no return, established players of the old technology either exit the market rapidly, or develop/acquire competencies with the new technology. The technology battle is completed; there after sales of the new technology improve confidently and the decline of the old technology accelerates.

[27] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

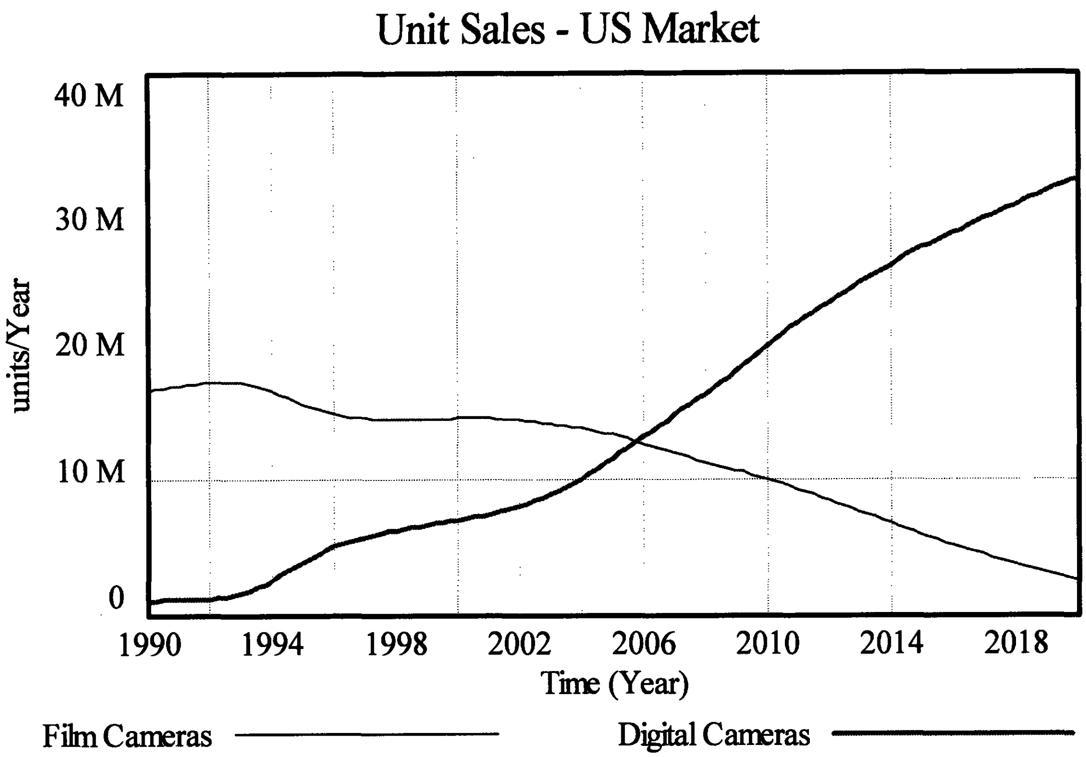


Figure 26 Dynamics of film and digital camera unit sales[28]

Transition of a mass market from an old technology to a new technology takes decades of. In 1991 Kodak released the first digital camera aimed at photojournalists with 1.3 Megapixel sensors. Since then new models and features flooded the market with drastic performance improvements. By many industry experts the conversion of the mass market to digital is accepted as finished in 1998. Even though there are many film camera models on sale today, and many old models still in use, all major cameras makers have stopped their R&D efforts on film cameras. Figure 27 depicts number of units in use for both analog and digital cameras. From the time the first digital cameras appeared on the market in 1990 to the eventual total number of slightly less than 150 M in 2020, took about 20 yrs. During this time the total number of film cameras in the market continuously dropped, and this drop accelerated after number of digital cameras grabs the majority of market share from film cameras in 2009.

[28] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

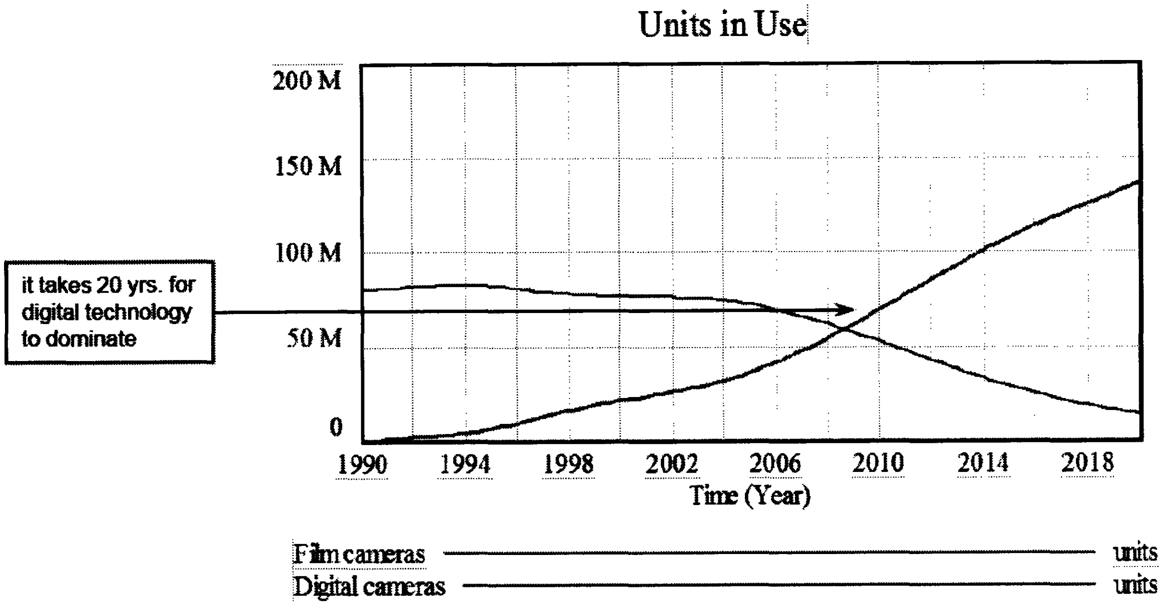


Figure 27 Dynamics of units in use for film and digital cameras[29]

[29] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

Simulation by Lotka and Volterra model

Numeric solution of Lotka and Volterra

Lotka-Volterra equations or predator-prey equations, express the dynamics of multi-mode framework, proposed by Pistorius and Utterback, very well mathematically. The major drawback of this formulation is their coupled differential equation nature, which inhibits an explicit solution. However they can be solved numerically, Pielou has shown that equations can be solved in a numerical form for the case of pure competition [Pisterious and Utterback 1995, 1997]. Pielou's extended solution in Eq^n 4 of chapter 3, considers J number of technologies interacting in the same market niche, incorporating symbiosis, predator-prey scenarios as well as pure competition.

The numeric form solution for $T_i(t)$ can be found by extending Pielou's solution to the general case.

Eq^n 5

$$T_i(t+1) = \frac{e^{a_i} T_i(t)}{1 - \sum_{j=1}^{J} \frac{s_{ij} c_{ij} (e^{a_i} - 1)}{a_i} T_j(t)}$$ [30]

This formulation is a general solution for multi-technology, multi-mode interaction. Researchers can use this model for interaction in a number of technologies where interaction among any pair can be pure competition, symbiosis or predator-prey. One of the advantages of this solution is its ease of implementation of it on a spread sheet. Using simple algorithm tools such as linear optimization and curve fitting, dynamics of competition between two technologies can be simulated and the future can be predicted.

Simulating here the pure competition between film and digital camera technologies, we have two technologies, making J =2. For two technologies that are in pure competition mode, unit sales of each technology will result in the following equation for technology i =1 (digital camera):

Eq^n 6

$$T_1(t+1) = \frac{e^{a_1} T_1(t)}{1 - \frac{s_{11} Cc_{11} (e^{a_1} - 1)}{a_1} T_1(t) - \frac{s_{12} c_{12} (e^{a_1} - 1)}{a_1} T_2(t)}$$

[30] Pistorius, C.W.I., Utterback, J.M., "A Lotka-Volterra Model for Multi-mode technological interaction: Modeling Competition, Symbiosis and Predator Prey Modes", Proceedings of the Fifth international Conference on Management of technology, Miami, FL, Feb 27 – March 1, 1996

And for technology i =2 (film camera):

$$T_2(t+1) = \frac{e^{a_2}T_2(t)}{1 - \frac{s_{21}c_{21}(e^{a_2}-1)}{a_2}T_1(t) - \frac{s_{22}c_{22}(e^{a_2}-1)}{a_2}T_2(t)} \qquad \text{Eq}^n\ 7$$

Use of spread sheet for simulating Lotka- Volterra equations

We have the actual data of film and camera unit sales from 1994 to 2004. What we need to find is the optimal values of a1, a2 and c11, c12, c21, c22, to fit the best curve in data we have at hand. We generate an error function for the difference between the actual and prediction data, and run the Excel™ solver add-on for minimization of this error function. The steps of the approach for simulating the predicted technology dynamics using Microsoft's spread sheet program, Excel™ , are as follows:

1. First, we simply formulate equation 7 and 8 to Excel for columns named "Film Prediction" and "Digital Prediction". These two columns will contain the data which will be simulated, in Figure 28. The variables in equations are given on top of the sheet. Note the gray cells for a1, a2, and c11, c12, c21, and c22. These cells are going to be used by Excel™ solver for the values that need to be optimized for minimizing the error function for the best possible curve fit. It is best to assign initial conditions to "1". Also note that s11, s12, s21, and s22 are all given "-1", as this value represents the pure competition mode of two technologies. Second we assign two more columns for actual film and actual digital camera sales and enter the market data at hand. At this stage we also put maximum limits for film and digital cameras predictions into a green row, in order to bound the upper limit of the market.

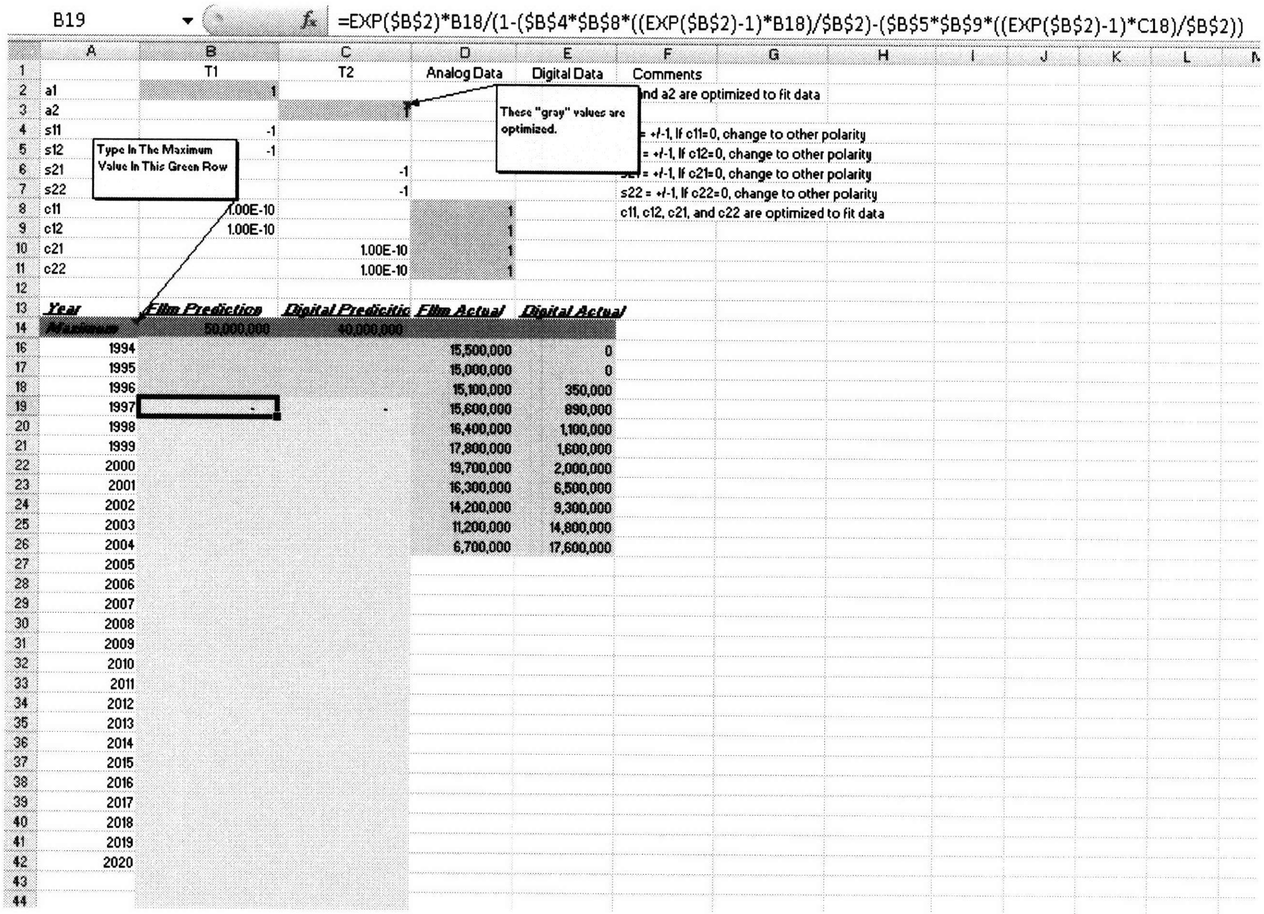


Figure 28 Formulation of Lotka- Volterra equations in excel sheet

2. In order to employ a curve fitting to the actual data by the equations we use, we need to define an error function. For each year, the following error function can be used for the best possible fit:

$$Error(t) = \sqrt{\left|T_1(t)_{prediction} - T_1(t)_{actual}\right|^2 + \left|T_1(t)_{prediction} - T_1(t)_{actual}\right|^2} \quad \text{Eq}^n\,8$$

Next we enter error function above as a separate column, and also allocate weight column to improve the fit for any time point. Then we sum all errors at the bottom to one cell as Total Error. The total Error cell will be used as the *target cell* by the solver for the objective of minimization (Figure 29).

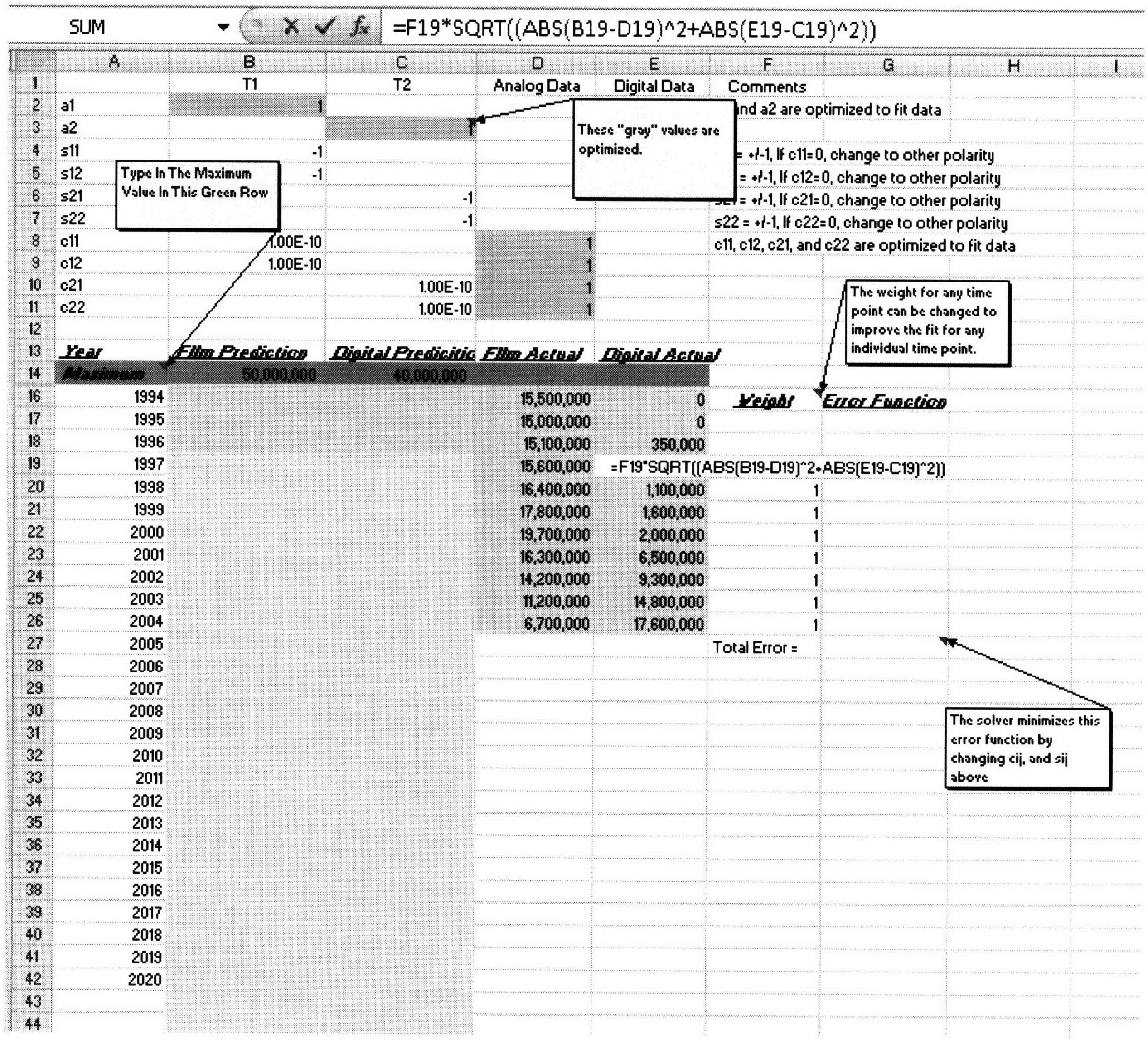


Figure 29 Formulation of error function for curve fitting

3. Then we run the Excel™ solver add-on for performing a linear optimization to find the best values for a1, a2, and c11, c12, c21, c22 variables. We define these as changing cells and we define the Total Error cell as the *target cell*. Further, as constraints we define that any predicted value cannot be larger than the values we provided in the green row. By this constraint we can put an upper limit to market size (Figure 30).

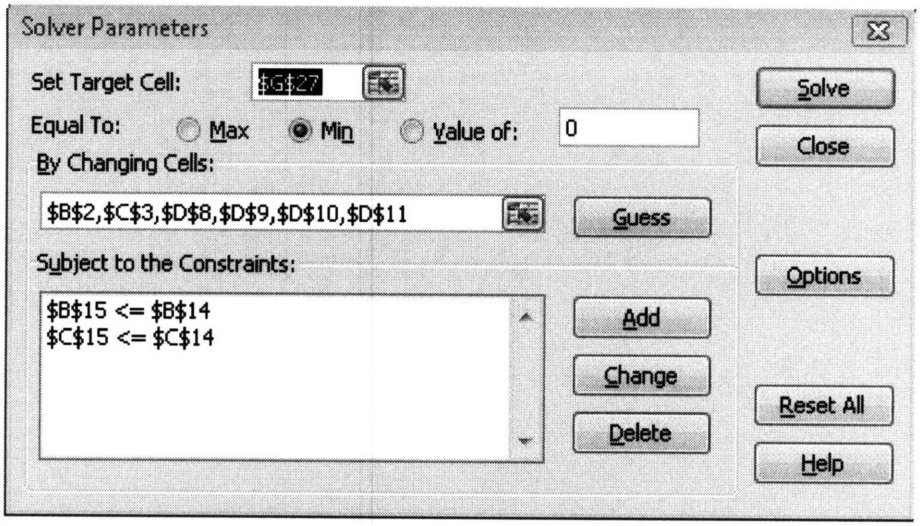


Figure 30 Use of solver add-on for optimizing equation parameters

4. When the solver is able to converge and find the least possible Total Error, we have the best fit values for film prediction and actual prediction and all the parameters for equations are optimized (Figure 31). The model parameters which Excel™ solver evaluated for best prediction curve of digital and film camera case, given the supplied market data, are given below:

a1 = -0.274739451699818

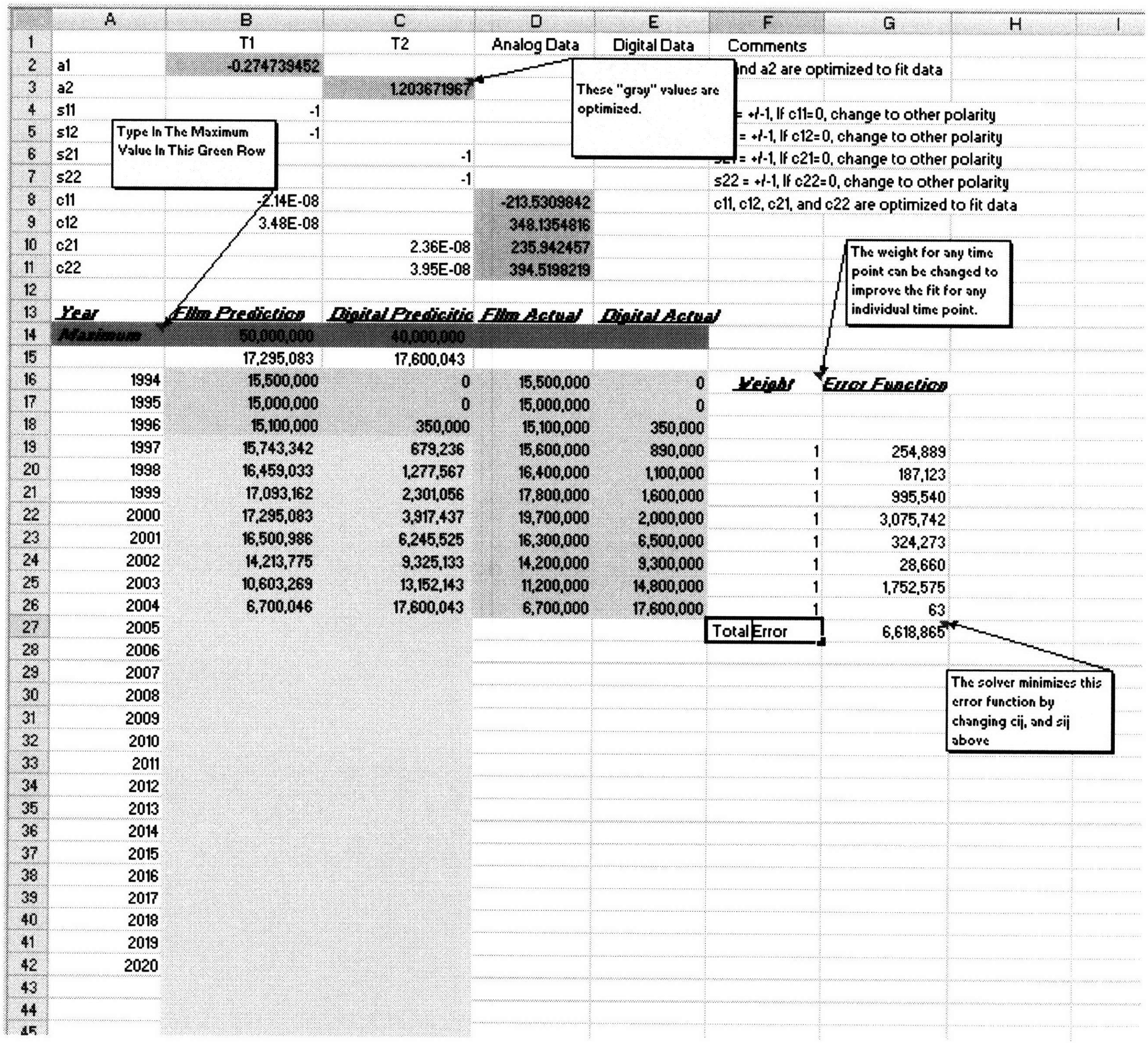
a2 = 1.20367196656898

c11 = -2.14E-08

c12 = 3.48E-08

c21 = 2.36E-08

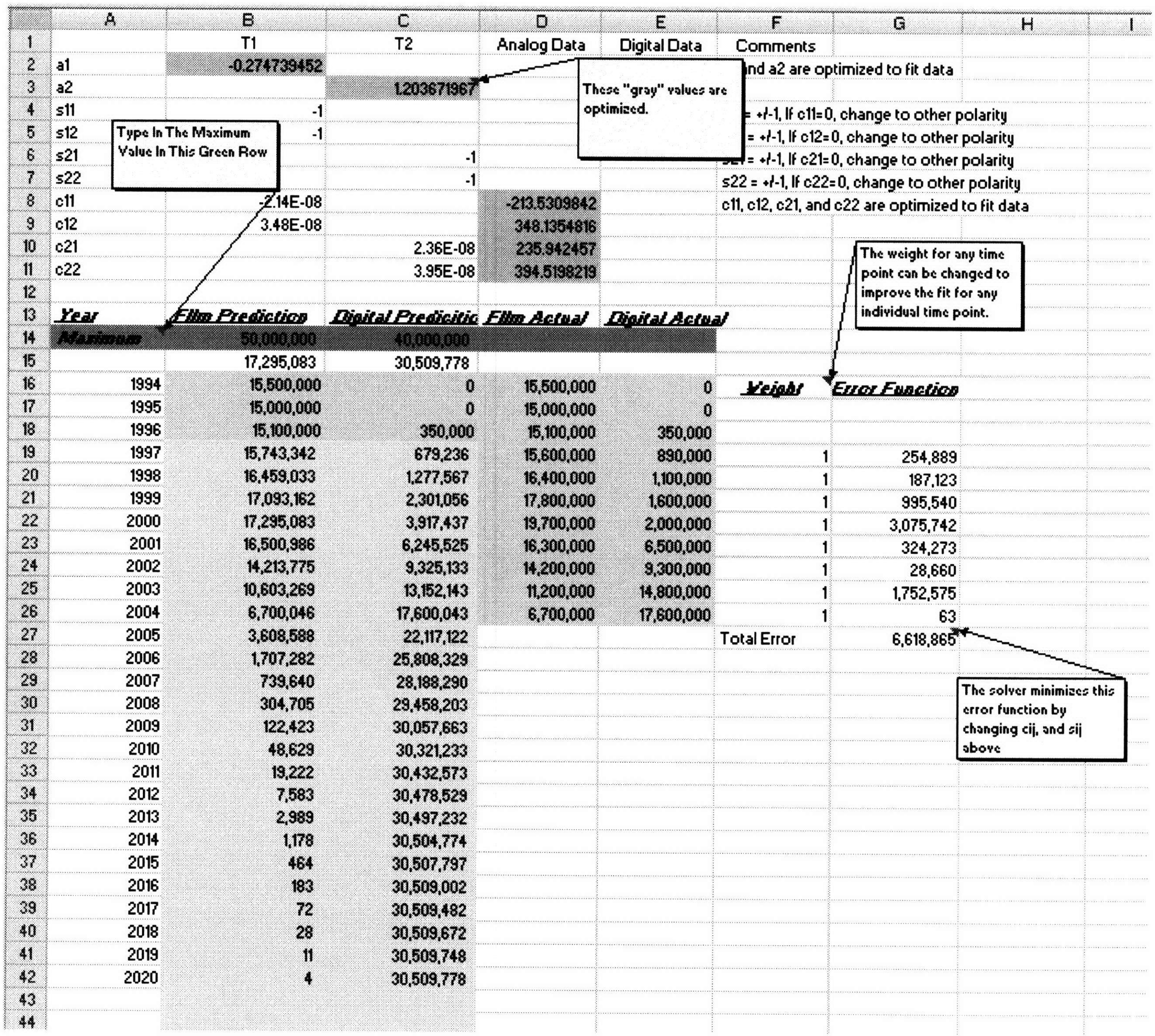
c22 = 3.95E-08



	A	B	C	D	E	F	G
1		T1	T2	Analog Data	Digital Data	Comments	
2	a1	-0.274739452				nd a2 are optimized to fit data	
3	a2		1.203671967				
4	s11	-1				= +/-1, If c11=0, change to other polarity	
5	s12	-1				= +/-1, If c12=0, change to other polarity	
6	s21		-1			= +/-1, If c21=0, change to other polarity	
7	s22		-1			s22 = +/-1, If c22=0, change to other polarity	
8	c11	-2.14E-08		-213.5309842		c11, c12, c21, and c22 are optimized to fit data	
9	c12	3.48E-08		348.1354816			
10	c21		2.36E-08	235.942457			
11	c22		3.95E-08	394.5198219			
12							
13	Year	Film Prediction	Digital Predicitic	Film Actual	Digital Actual		
14	Maximum	50,000,000	40,000,000				
15		17,295,083	17,600,043				
16	1994	15,500,000	0	15,500,000	0	Weight	Error Function
17	1995	15,000,000	0	15,000,000	0		
18	1996	15,100,000	350,000	15,100,000	350,000		
19	1997	15,743,342	679,236	15,600,000	890,000	1	254,889
20	1998	16,459,033	1,277,567	16,400,000	1,100,000	1	187,123
21	1999	17,093,162	2,301,056	17,800,000	1,600,000	1	995,540
22	2000	17,295,083	3,917,437	19,700,000	2,000,000	1	3,075,742
23	2001	16,500,986	6,245,525	16,300,000	6,500,000	1	324,273
24	2002	14,213,775	9,325,133	14,200,000	9,300,000	1	28,660
25	2003	10,603,269	13,152,143	11,200,000	14,800,000	1	1,752,575
26	2004	6,700,046	17,600,043	6,700,000	17,600,000	1	63
27	2005					Total Error	6,618,865
28	2006						
29	2007						
30	2008						
31	2009						
32	2010						
33	2011						
34	2012						
35	2013						
36	2014						
37	2015						
38	2016						
39	2017						
40	2018						
41	2019						
42	2020						

Figure 31 Optimized parameters as solver converges to a solution

5. In order to complete the unit sale numbers, we need to simply extend the equations through the years, we do not have actual values and generate predictions for these years. Since we have optimized the parameters for best curve fit in the simulation of Lotka-Volterra, all we need to do is select and extend the last year calculated through the years we want to predict (Figure 32).



	A	B	C	D	E	F	G
1		T1	T2	Analog Data	Digital Data	Comments	
2	a1	-0.274739452				nd a2 are optimized to fit data	
3	a2		1.203671967				
4	s11	-1				= +/-1, If c11=0, change to other polarity	
5	s12	-1				= +/-1, If c12=0, change to other polarity	
6	s21		-1			= +/-1, If c21=0, change to other polarity	
7	s22		-1			s22 = +/-1, If c22=0, change to other polarity	
8	c11	-2.14E-08		-213.5309842		c11, c12, c21, and c22 are optimized to fit data	
9	c12	3.48E-08		348.1354816			
10	c21		2.36E-08	235.942457			
11	c22		3.95E-08	394.5198219			
12							
13	Year	Film Prediction	Digital Predicitic	Film Actual	Digital Actual		
14	Maximum	50,000,000	40,000,000				
15		17,295,083	30,509,778				
16	1994	15,500,000	0	15,500,000	0	Weight	Error Function
17	1995	15,000,000	0	15,000,000	0		
18	1996	15,100,000	350,000	15,100,000	350,000		
19	1997	15,743,342	679,236	15,600,000	890,000	1	254,889
20	1998	16,459,033	1,277,567	16,400,000	1,100,000	1	187,123
21	1999	17,093,162	2,301,056	17,800,000	1,600,000	1	995,540
22	2000	17,295,083	3,917,437	19,700,000	2,000,000	1	3,075,742
23	2001	16,500,986	6,245,525	16,300,000	6,500,000	1	324,273
24	2002	14,213,775	9,325,133	14,200,000	9,300,000	1	28,660
25	2003	10,603,269	13,152,143	11,200,000	14,800,000	1	1,752,575
26	2004	6,700,046	17,600,043	6,700,000	17,600,000	1	63
27	2005	3,608,588	22,117,122			Total Error	6,618,865
28	2006	1,707,282	25,808,329				
29	2007	739,640	28,188,290				
30	2008	304,705	29,458,203				
31	2009	122,423	30,057,663				
32	2010	48,629	30,321,233				
33	2011	19,222	30,432,573				
34	2012	7,583	30,478,529				
35	2013	2,989	30,497,232				
36	2014	1,178	30,504,774				
37	2015	464	30,507,797				
38	2016	183	30,509,002				
39	2017	72	30,509,482				
40	2018	28	30,509,672				
41	2019	11	30,509,748				
42	2020	4	30,509,778				
43							
44							

Figure 32 Predicted values for film and digital sales based on solver's optimization

6. Last, we can select film prediction and digital prediction columns and generate a line graph, presenting the dynamics of battle between film and digital cameras between 1994 and 2020 (Figure 33). According to the estimation of the model by year 2010, digital camera unit sales is slightly above 30 million units and film camera unit sales drop to 48,000 units. As digital camera sales remain pretty much flat until year 2020, film cameras continue to drop and cannot sustain any market presence.

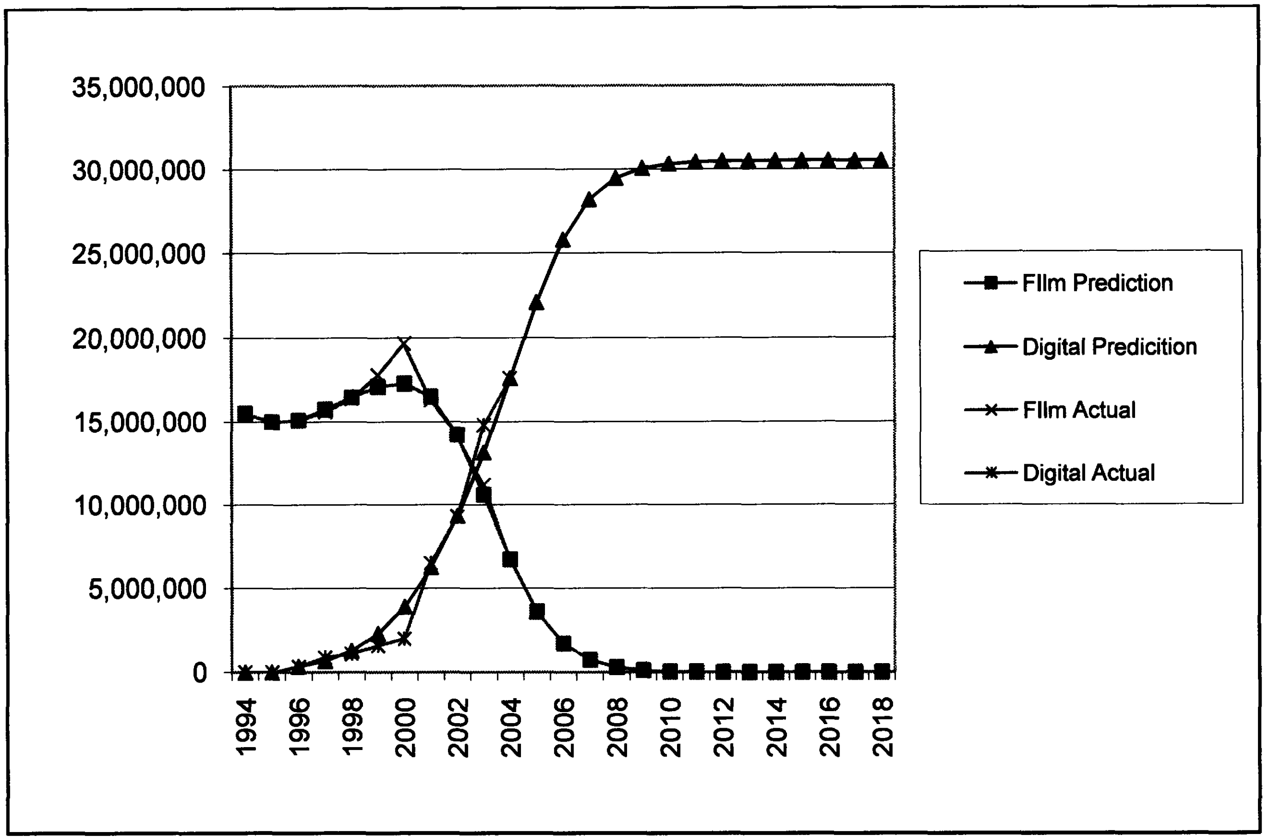
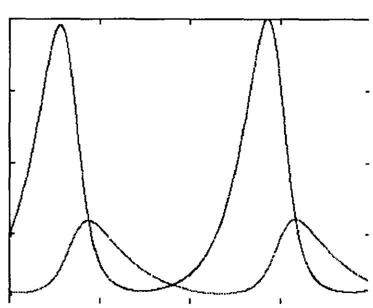


Figure 33 Simulation graph representing technology battle between film and digital cameras

6. Discussion of results

The objective of this chapter is to discuss the results from the simulation of digital and analog camera markets using Lotka-Volterra and System Dynamics models. While we are making a comparison along each key innovation attributes, we will also incorporate market reviews and analyst reports for digital and camera markets, as appropriate. Table 2 is a summarized comparison of Lotka-Volterra model and System Dynamics approach in modeling innovation dynamics, as well as key numerical facts of the simulation results for digital and film camera markets. Further in this chapter, comparisons of the both techniques are made using several key metrics of innovation dynamics with reflections on the status of digital and film camera markets by 2008.

Table 2Lotka-Volterra and System Dynamics compared

	Lotka and Volterra	**System Dynamics**
Model core	Lotka-Volterra equations, also known as the *predator-prey* equations, are a pair of first order, non-linear, differential equations frequently used to describe the dynamics of biological systems in which two species interact, one a predator and one its prey. It was proposed in 1925 by the American biophysicist Alfred Lotka and the Italian mathematician Vito Volterra.	System dynamics is an approach to understanding the behavior of complex systems over time. System dynamics uses feedback loops and stocks and flows for simulating the behavior of complex systems. It deals with internal feedback loops and time delays that affect the behavior of an entire system which can both include technical and social components. It was founded by Jay Forrester at MIT in late 1950s.
Fundamental behavior	Cycling mode between two species i.e: baboons and cheetahs 	Fundamental modes: 1. Exponential growth 2. Goal seeking 3. S-Shaped growth 4. Oscillation 5. Growth with oscillation 6. Overshoot and collapse SD model can generate any output which would cause by superposition of fundamental modes depending on models complexity and configuration

Solution approaches	Lotka-Volterra equations cannot be solved explicitly. Most considerable numerical solutions are as follows: Pielou solved equations for pure competition case (1969). Pistorius and Utterback proposed a numerical solution for multi-technology and multi mode interaction(pure competition, predator-prey or symbiosis) (1996).	Modeling a complex system using System Dynamics approach requires use of sophisticated simulation software, which all components of the system can be modeled as stocks or flows, and their interactions can be modeled as loops, in a system. Commercial software is available for this purpose, such as Vensim.
	Comparisons of simulation results in LV and SD models	
Crossover year	2003	2003
Max number of Digital cameras	30 M in 2008	33 M in 2018
Min number of Film cameras	Below 1 Million by 2007	Below 3 Million by 2020

Landscape of consumer imaging market in 2008

When digital cameras first appeared on the market more than a decade ago, they were perceived as more novel than practical for both professional and amateur photographers. Prices were well above $1,000, image resolution and quality was poor, and the cameras were bulky and inconvenient to use. While they did offer convenience, immediacy of images, and the ability to integrate easily with PCs and the growing online phenomenon, they were mostly ignored by consumers and only the highest quality and most expensive with prices well above $50,000 were embraced by professionals. As the key performance metrics of digital cameras improved very rapidly, the fast adoption of digital cameras took place by consumers in the last five years, portraying an explosive growth.

According to a recent research by industry experts, the installed base has more than doubled in that time period with 65% of consumers purchasing digital cameras, up from 32% in 2002. At the same time, consumers showed a marked decline in ownership of 35mm film cameras, with ownership dropping from 69% in 2002 to only 48% in 2007 (Figure 34). Additionally, it is likely that even consumers who still own 35mm film cameras are using them less. It can be concluded form this data that the mass market transition from film to digital was over by the year 2007 [Gartenberg 2007].

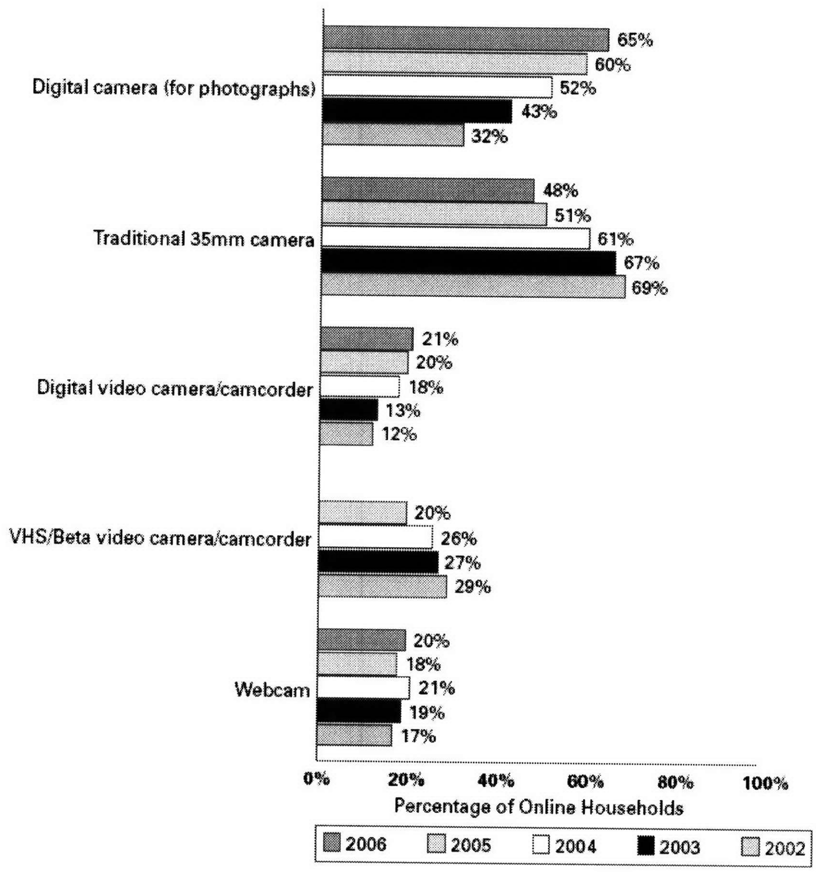


Figure 34 Consumer transition to digital is over[31]

Digital technology offers many advantages to analog in the world of imaging. In addition to the immediacy of capturing and reviewing images, consumers now have the ability to share pictures electronically (via both e-mail and online hosted storage), manipulate, crop, and edit photos. This digital behavior is now mature. In the past, consumers exhibited what is called *analog behavior* in their digital worlds and rarely took advantage of the capabilities that the shift to digital technologies offered them For example it is far more enjoyable to view high-resolution pictures on a high-definition display than it is to view 4x6 print; yet, despite the proliferation of high-resolution screens on both PCs and TVs,

[31] Gartenberg, M., "Digital imaging, uncovering new revenue opportunities in a mature market", Personal Technology, Jupiter Research, Vol 3, p. 2, 2007

consumers still viewed printing as their best way to view and share photos. Most users in the past exchanged pictures with a memory card, printed photos either at home or professionally, and shared them the way they used to do in old film days, ignoring many of the advantages, digital had brought. Today, users are far more engaged in the digital advantage, especially when it comes to sharing their photos. 49% of consumers e-mail pictures and 29% of consumers upload them to the Internet (Figure 35). In addition, consumers across the board are manipulating their images in sophisticated ways and engage in activities including resizing, removing red-eye, and cropping photos. The increasing popularity of photo sharing sites (i.e. www.flickr.com, and www.ofoto.com), or socialization sites (i.e. www.myspace.com, www.facebook.com), where you can share photos in the context of events and blogs, supports this transition in use context of photography [Gartenberg and Wood 2006].

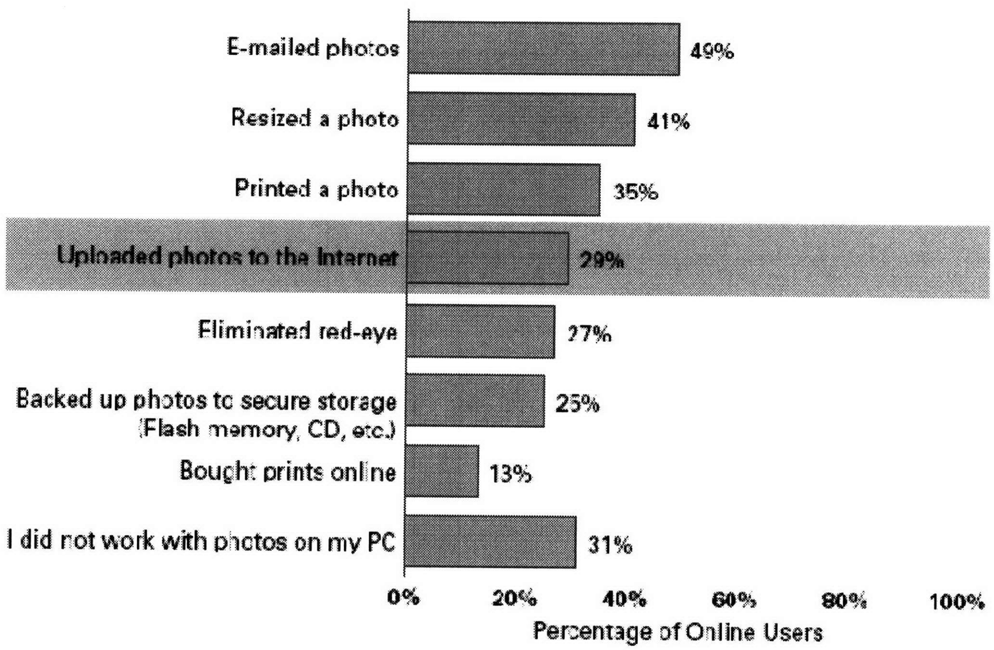


Figure 35 Major post-capture activities of users[32]

Performance characteristics of new technology which drives competition

Performance characteristics of products and their relationship with technology progression and effects on R&D are modeled with System Dynamics. Readers can review the details of part of the model in Appendix A. The model includes several important variables such as R&D productivity, R&D expenditure,

---

[32] Gartenberg, M., "Digital imaging, uncovering new revenue opportunities in a mature market", Personal Technology, Jupiter Research, Vol 3, p.3, 2007

effect of competition on R&D, and effect of profits on R&D. Although multiple performance characteristics are not incorporated, a general performance level is simulated by "level of technology", defined as a stock in the model. It is not possible to model interactions of these variables in Lotka-Volterra model.

In general when consumers are shopping for a camera, there are three categories of features: compulsory, complementary, and luxury. Compulsory features encompass image and lens quality as well as resolution; these features are of the utmost importance to consumer in the selection and purchase of a digital camera. 51% of online consumers said image quality was the most sought-after feature in a new camera while 28% of consumers said resolution was a priority, according to recent research (Figure 36) [Gartenberg 2007]. These requirements are easily met in today's digital camera market. Point and shoot cameras with resolution up to 8 megapixels are available while D-SLRs cameras range up to 21 megapixels. Prices are dropping on both point and shoot cameras and digital D-SLRs, making both accessible to a wide range of consumers. The complementary features include ease of photo transfer to another device, availability of optical zoom, storage, and length of battery life. While these features are not key drivers to purchasing a device, they are important to the capture experience. Without the facility to transfer easily, consumers cannot share photos. The optical zoom feature improves image quality, and no capture device can meet consumer expectations without storage capacity. These are all features that have been available on 35mm cameras for some time, and consumers expect them to be available on a digital camera. Luxury features are the least sought-after features on a digital camera. These features enhance the capture and post-capture experience, but do not impact the general quality of the capture experience. These features include color display and the ability to connect directly to the internet or a TV. Since these features are newer additions to the digital camera, consumers may take some time to adjust to or see value in them.

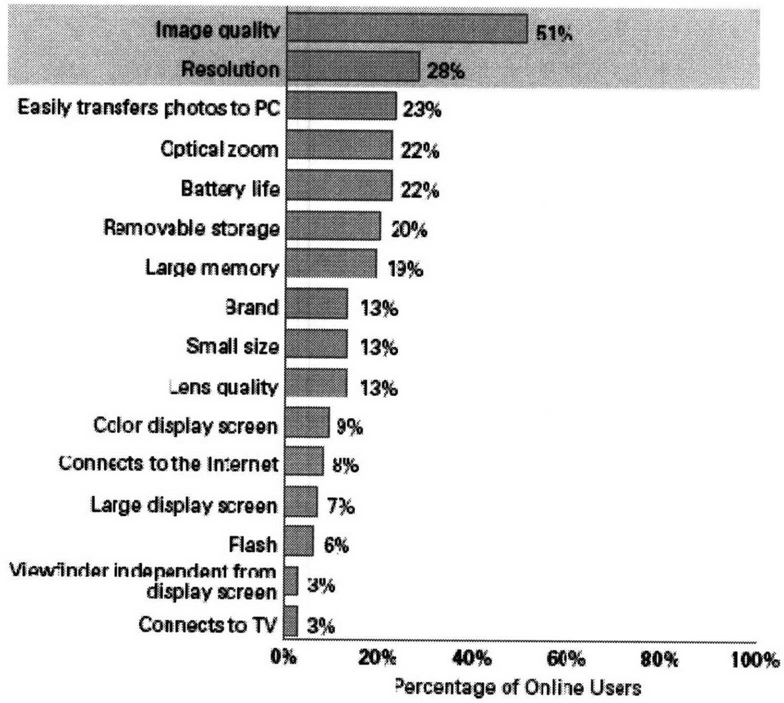


Figure 36 Image quality and resolution are key to digital camera purchase[33]

Limits to growth

Both of the models used, Lotka-Volterra and System Dynamics simulation predicted the maximum unit sales of digital cameras will be in the range of 30 to 40 million units in the year 2020. Lotka-Volterra model reached 30 million in year 2008, far more rapidly than the System Dynamics model which reached the same level in 2018. Lotka-Volterra's rapid increase can be attributed to its algorithm's effort to better fit the sharp ascent of the actual data, provided. In both of these models the upper bound for the market is an adjustable parameter of the system.

Steady growth of the digital camera market continues past the year 2008. Huge price drops and quantum leaps in enhancing the ease-of-use and quality of the medium are expected to translate into major gains for leading manufactures such as Canon, Sony, and Nikon, as they drive to accelerate the use of digital photographic technology in the mass consumer market.

The point and shoot camera type, providing high ease of use, was the initial entry point into the mass market for digital camera manufacturers. The limit of this market is bounded by the total house hold

---

[33] Gartenberg, M., "Digital imaging, uncovering new revenue opportunities in a mature market", Personal Technology, Jupiter Research, Vol 3, p. 6, 2007

numbers in the U.S. market. As the total number of households in U.S. is in the range of 30 million to 40 million, predications of both models is in line with reality. However trends after 2005 and the creation of two new market segments, engage the maturing digital camera market toward another growth trend. The structural change and creation of these new segments will be discussed in the next section.

Structural changes in the market

Although initially digital cameras were mostly the "point-and-shoot" type, recently two new segments were created: Digital-Single Lens Reflex (D-SLR) cameras and camera phones. As these relatively new segments eat up point-and-shoot cameras, a structural change occurs in the digital photography market. Both of the models we used in our study do not incorporate any changes in market structure or segments and assume the analyzed market has only one segment, that is the point and shoot type of digital cameras and 35mm film cameras.

In 2003 Canon, introduced the Digital Rebel, the first digital SLR under $1000 with a lens. It was a well timed move, as image quality and resolution was on a continuous rise and many early point and shoot digital camera buyers were returning to the market for better performance offered with a new generation of point and shoot cameras. Nikon also announced in 2006 that its success with high-margin D-SLR cameras helped account for a 26% increase in third-quarter sales, tripling its profits. Canon ended 2005 with sales up 8.3% and a net revenue increase of 11.9%, performance it attributes largely to its D-SLRs and photo printers. According to Lyra research in Newton, Mass, it is not just the high margins of D-SLR's drawing manufacturers' interest to this segment. The point and shoot camera market is likely to be squeezed further by high quality cameras, introduced into mobile phones and hand held devices (Figure 37) and manufacturers will be most likely to expand their product lines for "prosumers" in the high end D-SLR segment[Austen 2006].

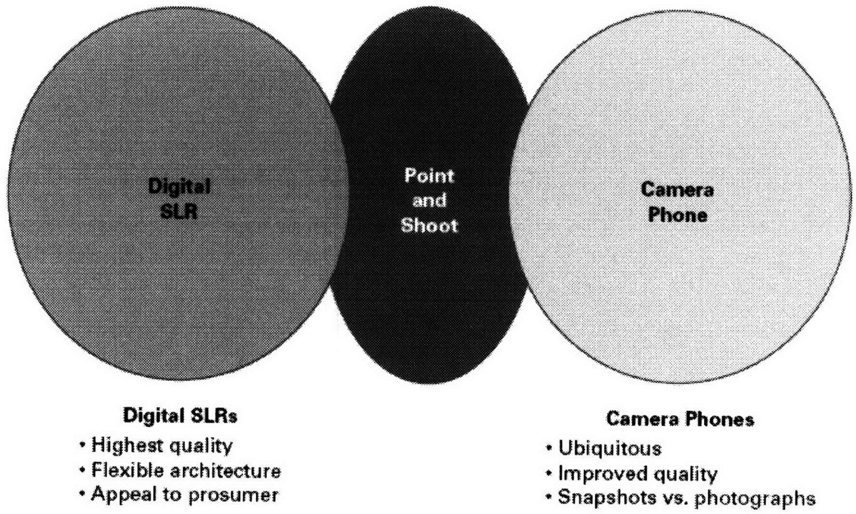


Figure 37 Pressures on Point and Shoot type cameras[34]

Hand held devices, particularly phones, are squeezing point-and-shoot type cameras from below as their image quality and resolution continuously increase. According to recent research, the top three factors encouraging camera phone use in place of digital camera use are improved resolution, improved zoom, and improved lenses (Figure 38). Although camera phones are improving at a high pace, many of the point and shoot cameras are still ahead in these attributes [Gartenberg and Wood 2006].

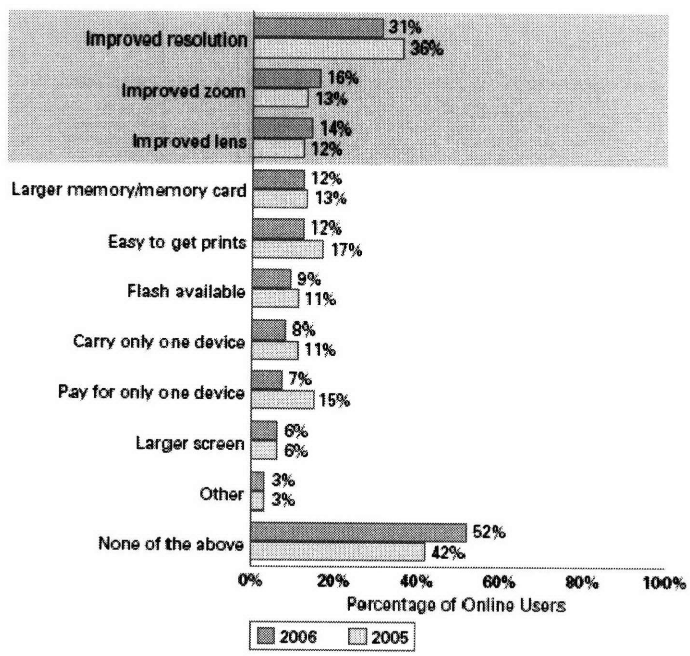


Figure 38 Camera phone quality requirements to overtake digital cameras[34]

[34] Gartenberg, M., "Digital imaging, uncovering new revenue opportunities in a mature market", Personal Technology, Jupiter Research, Vol 3, p.8, 2007

While camera phone technology appears to be making unparalleled advances, digital camera quality and functionality is improving simultaneously. As camera phone capabilities increase (i.e., resolution and memory), digital camera technology also improves (i.e., resolution and image sensor quality). As a result, no single device will dominate the digital imaging market in the near term. However when camera phone attributes reach a level that is optimum for average user, without losing its phone attributes, such as reception quality, and pocketability, it will have the strongest chance of displacing point and shoot cameras. In such a scenario, as mobile phones will become individual device, market limit in U.S. for digital cameras would be automatically bounded by the active population of U.S.

Re-invigoration of old technology

As mentioned in chapter 2, when a new technology rises, the established players with the old technology do not always sit back and relax. Most of them fight back. The burst of improvement from the established player in figure 5 of chapter 2 symbolically depicts this behavior. The established player briefly enjoys this burst of improvement, however eventually the performance of invading product surpasses the established product, which has the improvement becoming marginal over time. In Lotka-Volterra modeling this behavior cannot be modeled. However in the System Dynamics model, technology re-invigoration is a variable which affects product performance of the old technology.

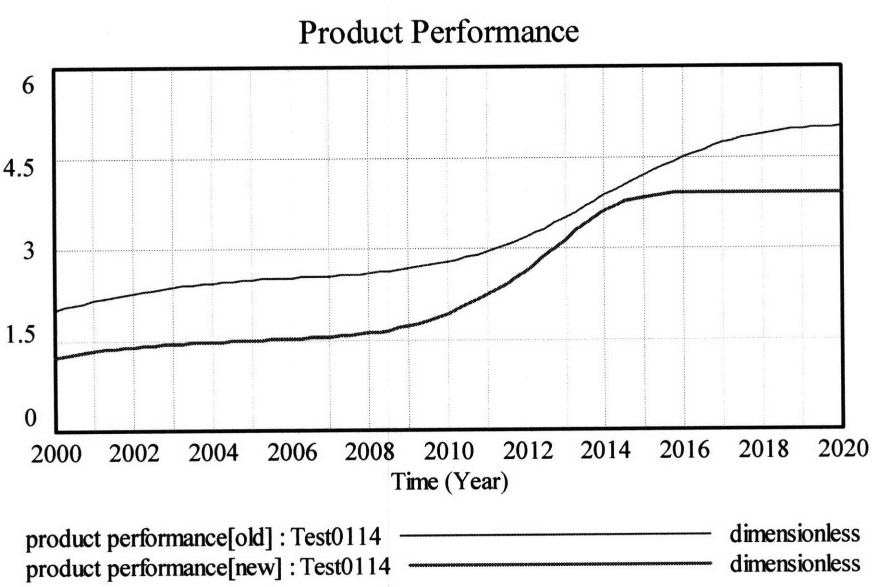


Figure 39 Technology re-invigoration[35]

[35] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

In figure 39, the re-invigoration effect for a generic run of the System Dynamic model is depicted. Performance of the new technology initially is well below the old products and improves significantly during 2009-15. The performance gap between the two generations of technology narrows. Indeed, performance of the new products in 2012 exceeds the performance of the old technology in 2008. But the old technology has been re-invigorated. As they feel more and more pressure from the new generation the incumbents find ways to substantially refresh the old technology, boosting its performance to much higher level. Thus the technology trajectory is not a simple "S-curve" but more like a "double-S" [Weil and Utterback 2005].

However, when we research actual market conditions, this effect is not seen as clearly in transition from film cameras to digital camera technology. There are two core competencies for digital cameras that a company needs to possess in order to become a key player; optics technology and electronics. Sony, while being the first in digital camera on the market with Mavica, rose to the No.3 spot in digital camera sales in U.S. with 15.8% of the market, just behind Canon at 17%, and Kodak 16.9%, according to a recent analysis of a research firm in Sterling, Va. Sony a long time manufacturer, also had good success in the video camera business, it had already developed a know-how of design and manufacture charged-coupled devices (CCDs). Leveraging its core competency in electronics manufacturing, its experience in video camera business, and buying Konica-Minolta's optics technology, Sony abandoned all its film photo business, and reached the No.3 position in U.S. market. Other major manufacturers who had in-depth optics technology, such as Canon, Nikon, and Kodak, after stopping all their development efforts on film cameras one after another, utilized electronics and image processing technology from other electronics suppliers such as Sony and absorbed this essential core competency over time.

While neither Pentax nor Olympus has followed Konica Minolta's lead and abandoned their consumer photography business, both have allied themselves with electronics companies. Pentax started producing Samsung branded D-SLRs, and supplying the Korean maker with its lenses. Olympus and Panasonic's parent company, Matsushita electric, have similarly joined forces and have yet to unveil its new products. As seen in this picture of markets, incumbent manufacturers of film cameras who grasped the inevitable transition to digital fairly quickly were not persistent on further improvement of film technology. They either exited the market for higher profit businesses such as medical imaging or accomplished a relatively smooth transition to digital technology without giving away their leading position to new comers by leveraging competency in electronics from other business units or through strategic alliances [Austen 2006, Scoblete 2004].

Niche market for old technology

Both models do not have a parameter to define a lower limit for old technology. Lotka-Volterra model reduces the unit number of old technology to below 1 million in the year 2007 very rapidly in comparison to the System Dynamics model which is still above 10 million at the same year.

In the early years of digital cameras there were few attributes where they were behind film cameras, which disturb professional or amateur photographers who take their camera seriously. In the following attributes, even though improved drastically since the first digital camera on market, the digital camera is still behind, if they are priced under $1000:

Shutter Lag: For shooting that requires split second timing, shutter lag is critical and digital cameras especially point-and shoot types are still fall behind film cameras.

Image quality: A glass plate from 1880 still has more resolution than a Canon 1Ds-MkIII, which is known to be the highest resolution camera in 2007 with 21.1 Megapixels. Film always wins here when used by a skilled photographer.

Color: Film records and reproduces a broader range of color. This is important for wild landscapes, deep red cars and flowers.

Dynamic range: Film has a huge advantage in recording highlights. It is usually taken for granted that spectacular highlights and bright sunsets look the way they do in painting and on film. Digital has a big problem with this attribute.

Noise: Almost all digital cameras have noise depending on quality of their CCDs and image processing capability. At higher ISO settings it became more apparent. Although expensive D-SLRs do a better job with noise, they cannot achieve the results of an analog machine.

Obsolescence: The technology stage of digital cameras is still fluid. Improvements in critical performance aspects such as resolution, and image quality still increases. New features making photography easier for average user such as, face or landscape detection, image stabilization, LCD live view etc. are added with upgrades to new models.

Batteries: Dependency on the battery was a big issue, though capacity of batteries has improved a lot since early digital cameras. Professionals still carry around extras for outdoor jobs.

As stated above, critical attributes of cameras are continuously improving while the average price reduces due to intensity in competition in market. Professional photography, which demands highest image quality, color sensitivity and responsiveness, is still in favor of film cameras. Outdoor, wildlife, and sports photography, being the leading examples of professional photography are most likely to stay as niches for film cameras for a long period of time.

Network effects boosting adoption of new technology

As consumers learn to think digitally about their photographic activity and are more inclined towards sharing their digital photos over internet, network effects for digital imaging increases. As it can be seen in figure 40 the number of users sharing their photos through a commercial site is 14% in 2007, more than the 11% of 2006. Fast and low cost sharing of photos through internet definitely boosted the sales of digital cameras as more people encouraged by the easy and effective use of new technology, creating a "Lemming effect". Network effects accelerating the adoption of a new technology is represented by a reinforcing loop in System Dynamics model where as it cannot be captured in Lotka-Volterra model.

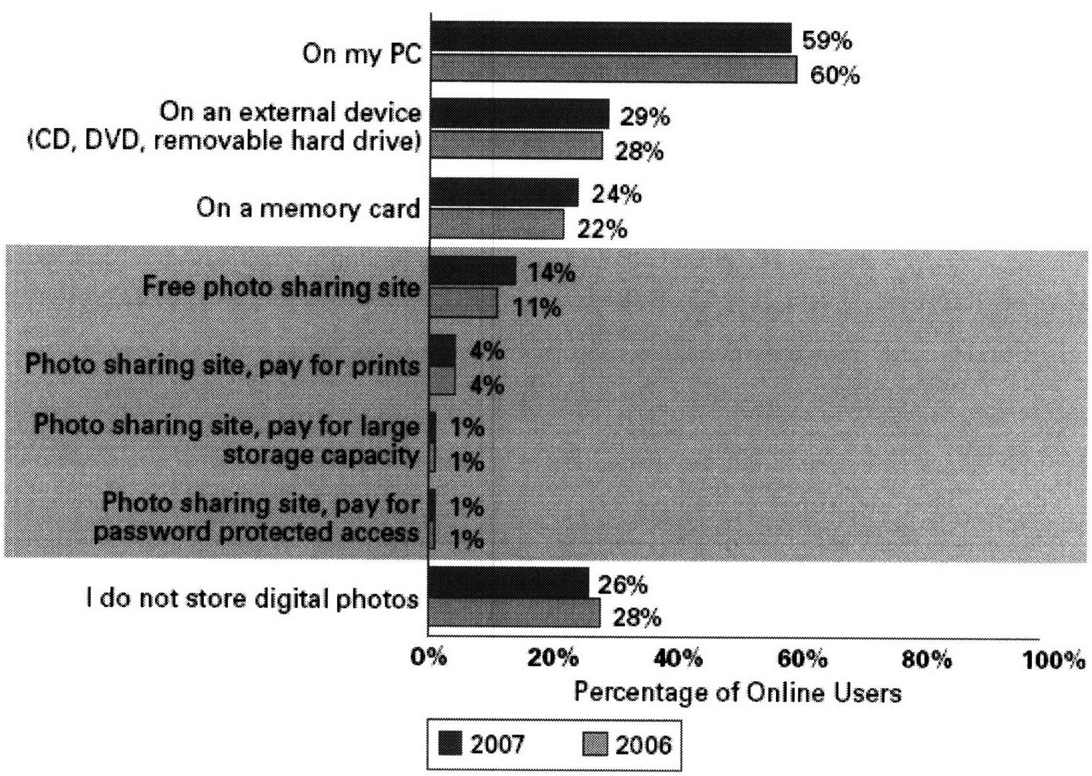


Figure 40 Activity in digital photo sharing which boosts network effects[36]

[36] Gartenberg M., Wood, A.., "Digital Imaging, Analyzing the changing face of industry", Personal Technology, Vol.2, p.11, 2006, Jupiter Research

7. Conclusion

In this thesis, we examined and compared two predominant approaches to modeling dynamics of innovation, the Lotka-Volterra and System Dynamics model. We first examined in detail the characteristics, and building blocks of each approach, and further applied both of them to a recent case of innovation dynamics. In this case study, we analyzed and simulated competition between film and digital cameras, with the hope of understanding how competition between these two technologies unfolded over the last decade and how it may evolve in the near future.

Outputs of both models and current trends and insights from market research reports helped us to conclude that the technological battle between digital and film cameras was over by 2007. Digital cameras initially inferior in many essential performance metrics of photography and quite expensive to buy for an average consumer, exhibited quantum leaps in performance and cost over the period of a decade, and convinced both consumers and manufacturers that it will be the photography technology of the future.

In our study we not only analyzed the technological innovation in the camera market but compared and developed insights on the capabilities of both models. In this respect, we can now drive conclusions for both models valuable for understanding the strengths and weaknesses of both approaches that could help for further research. First, we can summarize strengths and weaknesses of Multi-mode framework utilizing Lotka-Volterra solution model as follows:

Strengths:

- Multi-mode framework captures the fact that interaction between technologies is not always confrontational. It identifies three possible modes of interaction; *pure competition* where both technologies inhibit the other's growth rate, *symbiosis* where both technologies enhance the other's growth rate, and *predator-prey* interaction where one technology enhances the other's growth rate, but the second inhibits the growth rate of the first.
- Multi-mode framework accounts for the transitional effects as the interaction between the technologies transgresses from one mode to another with time. The notion that the modes of interaction between two technologies can shift with time is one of the main differentiators of this framework.

Weaknesses:

- Lotka-Volterra equations, express the dynamics of multi-mode framework, proposed by Pistorius and Utterback, very well mathematically. The major drawback of this formulation is their coupled differential equation nature, which inhibits an explicit solution. However they can be solved numerically, Pielou has shown that equations can be solved in numerical form for the case of pure competition. Pielou's extended solution can be applied to a spread sheet and by use of partial real data as an input, optimal curve fitting can be performed to find best parameters of the model in order to predict the dynamics of future competition.
- Multi-mode framework provides only one dimension over time for the competition of technologies. The growth rate of the most important competition dimension is often expressed as unit sale. Bounded with the core differential model of Lotka-Volterra, this model does not provide any possibility for further analysis of other competition dimensions.

Next, we can summarize strengths and weaknesses of System Dynamics in modeling technological innovation as follows:

Strengths:

- System Dynamics enables a holistic approach for modeling dynamics of innovation. Building on fundamentals of casual loop diagrams, stocks, and flows, it is extremely flexible in modelling any system involving technical, social, or business components with any degree of complexity. The modularity that it provides is unbounded.
- Leveraging its flexibility, it is possible to model many aspects of dynamics of innovation. In this study, the competition between digital and film cameras, we simulated, dynamics of entry-exit of firms, price, product performance, willingness to switch to digital cameras, unit sales, and units in use.
- System dynamics approach is also very evolvable. Once a base model is established, new research and ideas can be built upon it in order to analyze and understand dynamics of new extensions or modifications to the existing system.

Weaknesses:

- System Dynamics flexibility and extensibility comes with a price, its complexity. Modeling a complicated system with this model takes a considerable amount of time, not less than weeks for an average system. This time frame even accounts for the use of professional modeling software (such as Vensim), which will incur licensing, other development or maintenance related costs.

Future work

For future work of this study, there are two main avenues. First one is more research on case studies in technology centric industries that will verify and improve the capabilities of the System Dynamics approach. Emerging "new" technologies, in competition with the "old" one, such as Radio Frequency Identification vs. Bar-Code, or internet based ERP service providers vs. in premise based ERP systems, are great new case studies that can add value to the research area, by giving more insights on dynamics of technological innovation.

The second avenue is extending the System Dynamics model for incorporating emerging forms of innovation. The current model captures many characteristics of innovation dynamics in the context of competition. Since early 1990s, another emerging form of innovation between firms is through collaboration, instead of competition. This new innovation and production model, coined as Virtual Enterprises, by Goldman, in his book, *Agile Competitors and Virtual Organizations*, describes how small and medium size enterprises collaborate actively to achieve a high degree of customization, and agility. Many scholars and authors cite Virtual Enterprises (VEs) as a key enabler of Agility (Goldman et al. 1995, Gunesekeran 2001). By definition, VE is a temporary consortium formed by real autonomous companies on the basis of strong collaboration to respond to temporary demands, which a single company with limited core competencies and production capacity is unable to. Among other enablers of agility such as concurrent engineering, e-commerce, integrated product/production information systems, VE is of special interest because it places a greatest demand on a company to co-operate in achieving collaborative innovation and production Indeed, a VE can accomplish tasks that could be not done by each of the competitors working sequentially or in tandem.

A future extension of the current System Dynamics model to capture collaborative dynamics of innovation will be a significant contribution to the field.

This page intentionally left blank

Bibliography

Abernathy, W.J., Clark, K.B., "Innovation: mapping the winds of creative destruction", Research Policy, 14, 3-22, 1985.

Austen, I., "Digital moves to top tier cameras", The New York times, Feb 20, 2006.

Bower, J.L, Christensen, C.M., "Disruptive Technologies: Catching the Wave", Harvard Business Review, Jan-Feb, pp. 43-53, 1995.

Christensen, C.M., The innovator's dilemma, Collins Business essentials, New York, 2002.

Cusumano, M.A., Gawer, A., "The elements of Platform Leadership", MIT Sloan management review, Spring, 2002.

Caroll G.R., "Dynamics of Organizational Expansion in National Systems of Education", American Sociological Review, Vol 46, pp.161-178, 1981.

Dosi, G., "Technological Paradigms and Technological Trajectories, A suggested interpretation of the determinants and directions of technical change", Research Policy, 11, 147-162, 1982.

Farell., C.J.,"A theory of technological progress", Technological Forecasting and Social Change, 44, 161-178, 1993.

Fine, C. H., Whitney, D. E., "Is the Make-Buy Decision Process a Core Competence?" ,Working Paper # 3875-96, Cambridge, Massachusetts, USA: MIT Center for Technology, Policy, and Industrial Development, 1996.

Fine, C. H., "ClockSpeed: Winning Industry Control in the age of Temporary Advantage", Perseus Books, 1998.

Foster, R.N., "Innovation, the attacker's advantage", Summit books, New York, 1986.

Franke, N. and Shah, S., "How communities support innovative activities: An exploration of assistance and sharing among end users", Research policy 32, no.1:157-78, 2003.

Gartenberg M., Wood, A.., "Digital Imaging, Analyzing the changing face of industry", Personal Technology, Volume 2, 2006, Jupiter Research.

Girifalco, L.A., "Dynamics of technological change", Van Nostrand Reinhold, New York, 1991.

Goldman, S.L., Nagel, R.N., Preiss, K., "Agile Competitors and Virtual Organizations", Can Nostrand Reinhold, 1995.

Gunesekeran, A., "Agile Manufacturing, The 21st Century Competitive Strategy", Elsevier, 2001.

Gartenberg, M., "Digital imaging, uncovering new revenue opportunities in a mature market", Personal Technology, Jupiter Research, Vol 3, 2007.

Henderson, R.,M., Clark, K.M., "Architectural innovation: The reconfiguration of existing product technologies and the failure of established firms", Administrative Science Quarterly, 35(1), 9-30, Mar., 1990.

Moore, G.A., "Crossing the chasm, Marketing and selling disruptive products to mainstream customers", Collins Business Essentials, 1999.

Meyer, M.H., Lehner, A.P., "The power of product platforms: Building value and cost leadership", The free press, 1997.

Meyer M., H., Utterback, J.M., "The product family and the dynamics of core capability", Sloan Management Review, pp. 29-47, Spring 1993.

Pielou, E.C., "An introduction to mathematical ecology", Harper & Row, 1969.

Pistorius, C.W.I., Utterback, J.M., "Multi-mode interaction among technologies", Research Policy, 26, 67-84, 1997.

Pistorius, C.W.I., Utterback, J.M., "The death Knells of mature technologies", Technological forecasting and social case, 50, 133-151, 1995.

Pistorius, C.W.I., Utterback, J.M., "A Lotka-Volterra Model for Multi-mode technological interaction: Modeling Competition, Symbiosis and Predator Prey Modes", Proceedings of the Fifth international Conference on Management of technology, Miami, FL, Feb 27 – March 1, 1996.

Porter, M.,E., "The competitive advantage of nations", The Free Press, 1998.

Roger, E., "Diffusion of Innovations", Free Press, 1995.

Sanderson S., Uzumeri, M., "Managing product families: The case of Sony walkman", Research Policy, 24, 761-782, 1995.

Scoblete, G., "Digital camera vendors flood mass market", Twice, June, 2004.

Suarez, F.F., "Battles for technological dominance: an integrative framework", Research Policy, 33, 271-286, 2004.

Sterman, J., "Business Dynamics, Systems thinking and modeling for a complex world", McGraw-Hill, 2000.

Utterback, J.M., "Mastering the dynamics of innovation", HBS, 1994.

Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005.

Von Hippel, E., "Innovation by User Communities: learning from Open-source software", MIT Sloan management review, Sumer 2001.

Von Hippel, E., "Democratizing innovation", MIT press, 2005.

This page intentionally left blank

Appendix A

This appendix contains detail models of System Dynamics. These models, created by Weil and Utterback, were implemented in Vensim software for simulating generically dynamics of competition between "old" and "new" technology.

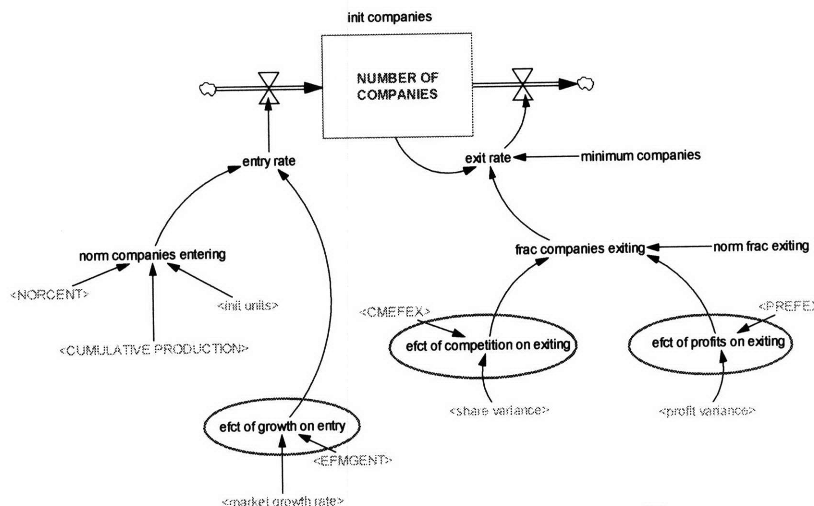


Figure 41 Number of companies in the market[37]

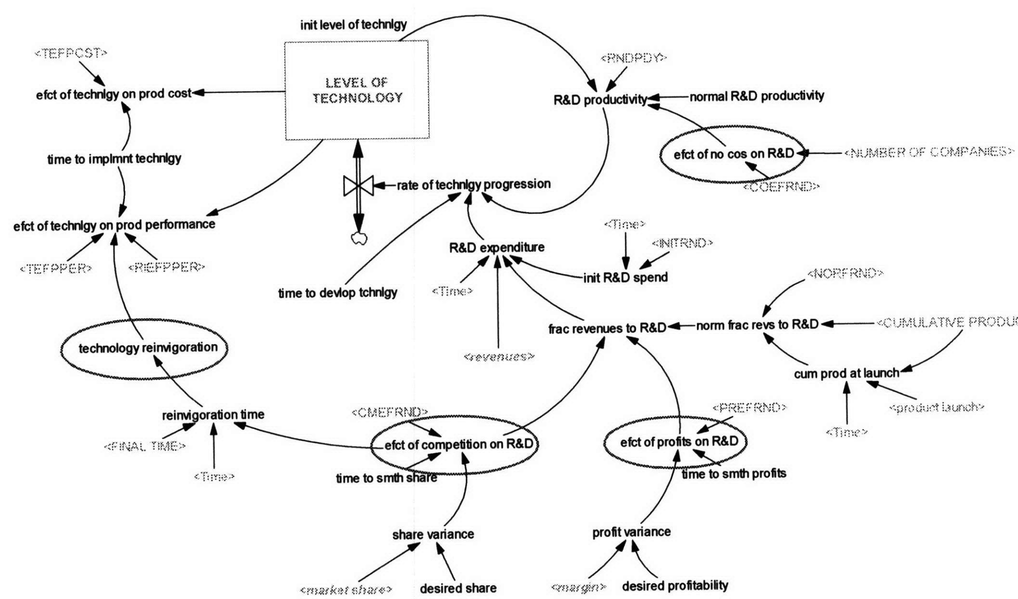


Figure 42 Level of Technology[38]

---

[37] [38] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

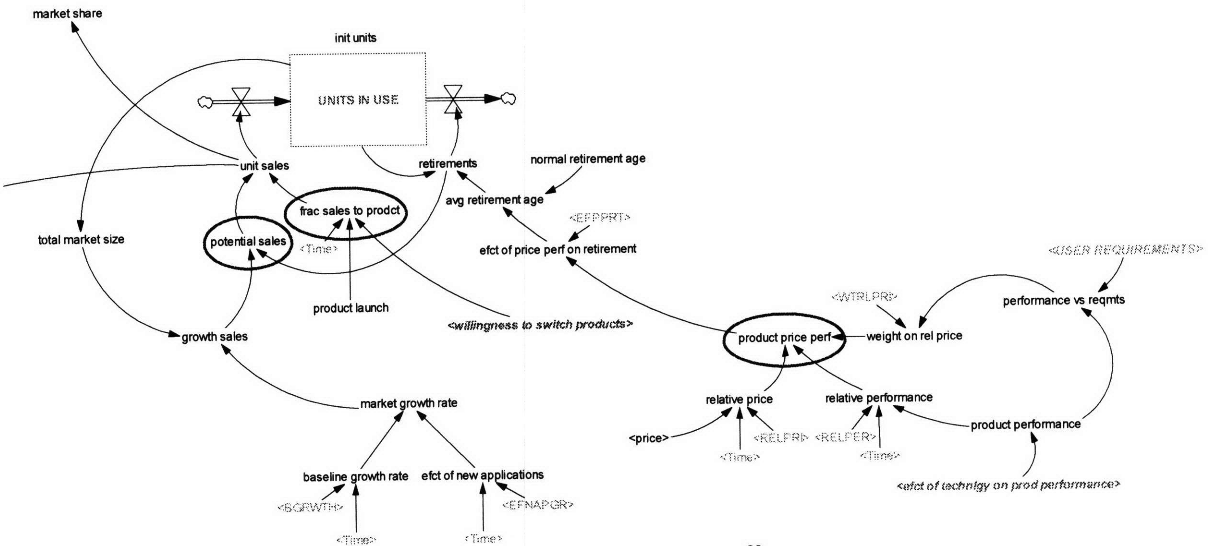


Figure 43 Product units in use[39]

[39] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

Appendix B

Table 3 Actual data used as input to Lotka-Volterra and System Dynamics models[40]

Year	Film Actual	Digital Actual
1994	15,500,000	0
1995	15,000,000	0
1996	15,100,000	350,000
1997	15,600,000	890,000
1998	16,400,000	1,100,000
1999	17,800,000	1,600,000
2000	19,700,000	2,000,000
2001	16,300,000	6,500,000

Table 4 Prediction output by Lotka-Volterra model

Year	Film Prediction	Digital Prediction
1994	15,500,000	0
1995	15,000,000	0
1996	15,100,000	350,000
1997	15,743,342	679,236
1998	16,459,033	1,277,567
1999	17,093,162	2,301,056
2000	17,295,083	3,917,437
2001	16,500,986	6,245,525
2002	14,213,775	9,325,133
2003	10,603,269	13,152,143
2004	6,700,046	17,600,043
2005	3,608,588	22,117,122
2006	1,707,282	25,808,329
2007	739,640	28,188,290
2008	304,705	29,458,203
2009	122,423	30,057,663
2010	48,629	30,321,233
2011	19,222	30,432,573
2012	7,583	30,478,529
2013	2,989	30,497,232
2014	1,178	30,504,774
2015	464	30,507,797
2016	183	30,509,002
2017	72	30,509,482
2018	28	30,509,672
2019	11	30,509,748
2020	4	30,509,778

[40] Weil, H.B., Utterback, J.M., "The dynamics of Innovative Industries", The Twenty-third International Conference of the System Dynamics Society, Boston, MA, July 17-21, 2005

This page intentionally left blank