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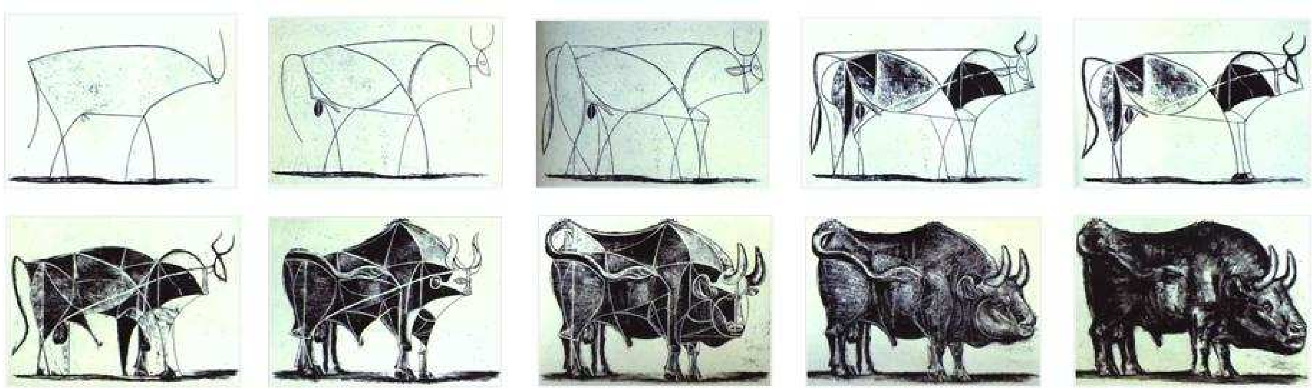

Picasso's Toros Stage I-XI, (c) Museum of Modern Art, New York

System dynamics and technological innovation system

Models of multi-technology substitution processes

Master of Science Thesis

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Department of Energy and Environment
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden, 2008
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Abstract

In order to switch to renewable energy technologies, major technological transformation processes have to take place in different industrial sectors. Such transformations have been referred as technological transitions. Theoretical frameworks have been developed that describe elements of technological transitions such as the emergence and growth of new technologies, physical and social constraints and the competition and co-evolution of different technological options. Such frameworks may be used to inform governments, firms and other actors of how to understand and influence change processes.

However, to this point no attempt has been made to develop a formal modeling tool based on these qualitative frameworks of technical change. In a formal model some generic patterns can be reproduced and visualized. Secondly, having a model, the effect of different inputs can be tested, such as different policy regimes and management strategies. Thirdly, playing with a model, patterns of change can be discovered that can be fed back into the design of more empirical and quantitative studies. Finally, the strictness of a formal model could sharpen the concepts used to describe real world processes.

This thesis presents two formal models of technological diffusion and substitution. Several researchers have used the Lotka-Volterra equations to model competition among technologies. Lotka-Volterra models assume that while a technology grows, it diffuses into a larger market in which it might compete with other technologies and different variables included in the equations represent this feature. Lotka-Volterra equations show that there are different modes of interaction between technologies: symbiosis, predatory prey, and pure competition. The model presented in this study demonstrates the failure of an emerging technology in pure competition with a mature and well-established technology, but also how a third technology called "bridging technology" could change the dynamics in favor of the emerging one.

Compared to the Lotka-Volterra model, the second and more detailed model of technology diffusion presented in this study provides us with a better understanding of the dynamics and feedback mechanisms governing the technology diffusion process. Different mechanisms such as technological learning, price reduction, increment in firm's income enhancing the technology's performance, and increment in technology's attractiveness among users, have been added to the model of diffusion. The diffusion model is used to show how on one hand the strategies and decisions made by the producer of the technology influence attitudes of the potential adopters by altering the technology attractiveness. On the other hand, attitudes of the potential adopters influence the adoption rate and consequently the firm's profitability and further decisions.

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Ali Ahmadian

Göteborg, Sweden, May 2008

Table of contents

Chapter 1. Introduction

1.1 Background

Today the world economy relies on the throughput of enormous amounts of fossil fuels such as coal, oil and natural gas. Fossil fuels make up for approximately 87% of the world's entire energy supply and combustion of fossil fuels is the single largest human impact on the environment which has several negative effects such as air pollution and climate change(IEA 2004).

Practical approaches for mitigating climate impacts could be shift to more efficient, carbon saving technologies or toward non-fossil fuel energy sources like renewable energies (IPCC 2001). Therefore governments have made plans to reduce the economy's reliance on fossil fuels to obtain a secure and sustainable energy future. Hence, development of alternative energy sources is a prominent economic and political topic which entangles environmental and sustainability interests (Devezas, LePoire et al. 2008).

The challenges to achieve a sustainable source for energy are enormous and need to be dealt immediately. However, switching to another source of energy is not easily achieved. The current situation of fossil fuel reliance has hindered the penetration of renewable sources and accompanying technologies, which has been described by the term "Carbon lock-in" (Unruh 2000).

Fossil fuels benefit from having been around for a long time, which has led to availability at low cost, high efficiency, and favorable institutional setting. On the other hand, renewable technologies, in their early market formation phase, are still relatively expensive, and suffer from mismatch with technological and institutional arrangements. Therefore, they hardly can gain attractiveness and open a market and will be suppressed by the fossil fuel. Thus one can conclude that the limitation on technical change and diffusion of new technological solutions, is not merely laid within science and technology itself, but as much within the inertia of organizational, social and institutional systems (Unruh 2002). So, there would be a pertinent question on, how renewable energy technologies can penetrate and diffuse into a market dominated by fossil fuel.

In order to switch in to renewable energy technologies, major technological transformation processes has to be bound to take place in different industrial sectors. Such transformations have been referred as technological transitions. Technological transitions involve change in technology, user practice, laws and regulations, industrial networks, infrastructure, and culture (Geels 2002). The process of technological transition has several critical issues such as: emergence and growth of the new technologies, long term physical and social constraints and the competition and co-evolution of different technological options.

There are large numbers of formal models developed for dealing with large scale transformations. These models generally are linear optimization models that capture the dynamics created by long term constraints, i.e. due to limited stocks of resources or flows of investment. As an example Azar, Lindgren et al. (2003), analyzed different fuel choices in transportation sector by creating different long-term scenarios and investigating the time that is more cost effective to switch to alternative fuels. Moreover, they looked into which fuel is cost effective to shift to, and particularly concerning biomass, and which sector it will be more cost effective(Azar, Lindgren et al. 2003).

Although these models are good at describing the impact of long term boundary conditions but have little to say about the micro dynamics in the early phases of a transition. These micro dynamics, including knowledge formation, technology development, entry of actors, the formation of markets and institutional adaptation, have been thoroughly described in qualitative narratives of the emergence and growth of several new energy technologies using a technological innovation systems approach (Jacobsson and Bergek 2004; Sandén and Jonasson 2005; Negro 2007). Moreover, a few future oriented studies have been made using this framework to construct qualitative socio-technical scenarios, i.e. Jonasson and Sandén (2007) examined different policy choices, with a socio-technical approach, on the development of alternative transport fuels in Sweden.

To this point no attempt has been made to develop a formal modeling tool based on these qualitative frameworks of technical change. A mathematical model can never reproduce the richness of actual technical change processes. However, some generic patterns can be reproduced and visualized in a formal quantitative model. Secondly, having a model, the effect of different inputs can be tested, such as different policy regimes and management strategies. Thirdly, playing with a model, patterns of change can be discovered that can be fed back into the design of more empirical and quantitative studies. Finally, the strictness of a formal model could sharpen the concepts used to describe real world processes.

1.2 Research questions and objectives

RQ1: How can such a technology substitution process be modeled?

RQ2: What diffusion patterns can such a model generate? Can historical patterns be reproduced?

RQ3: How do different parameter choices affect results?

RQ4: Can we learn something from the model for the outcome and impact of choices in ongoing real world change processes?

1.3 Methodology

In this paper, a formal model comprising of two separate models, will be developed based on the technological innovation system framework. It will target the issue of competition and co-evolution of different technological alternatives.

The first model incorporates Lotka-Volterra competition equations, and will describe how a new technology (E) (such as new transportation fuel or solar electricity run vehicle) grows in a system dominated by an old technology (M) (such as internal combustion engine). The model will then be designed to study how an intermediate technology (B) (such as ethanol flexi-fuel cars or hybrid vehicles) could affect the introduction of a longer term better option (E), that is the bridging or lock-out properties of B.

The second model is a model of diffusion of one particular technology considering various feedback mechanisms involve in the diffusion of a technology. These feedback mechanisms are considered to be generated from the producers and consumers of the technology.

1.4 Thesis outline

In chapter 2 (System dynamics) the research approach and System Dynamics, which is used mainly as the method of modeling, will be described.

In chapter 3 (Modeling of competition and co-existence of technologies), a brief introduction to Lotka-Volterra competition equations is presented and different models and implications of the equations, used in the ecology, is examined. Further on, the model of interaction between three technologies will be developed and described in this chapter.

In chapter 4 (Modeling of technology diffusion), a model of diffusion focusing on dynamics generated in the firms producing the technology, i.e. technological learning and growth of technology attractiveness, and dynamics in the producers side leading to growth of technology legitimacy, will be developed and simulated.

In chapter 5 and 6 (Discussion and conclusion) a discussion on the limitation of this paper is conducted, and the implication of the model simulations in answering the research questions will be presented.

Appendices A and B, descriptions of relations between factors in the model presented in chapter 4 is presented in these two appendices.

Chapter 2. System dynamics

The research in this report has an explorative nature and aim to contribute to technological change theory. The objective of the research is to develop and expand a new approach to modeling of the technological transformation considering the presence of bridging technologies. Taking into account this objective, the suitable research strategy for this research is a retroductive strategy. Retroductive research strategy involves the building of hypothetical models as a way of uncovering the real structures and mechanisms which are assumed to produce empirical phenomena (Blaikie 2000).

The modeling will be based on System Dynamics method. The modeling will begin with a simple description and gradually include more processes. The models are made up of functional relationships between the elements of the system to reflect cause-effect chains. In this way, the model will contain several intertwined feedback loops. Examples of such loops can be cost reduction via market expansion through learning-by-doing, enabling further market expansion, and legitimacy creation. The computer simulation will be done in the Software Vensim. This chapter provides with a brief introduction to system dynamics.

2.1 Central elements of System Dynamics

Over the last few decades there has been a trend in management emphasizing the importance of analyzing natural and social phenomena from a more holistic view. This holistic view is generally referred to as system view or system thinking. System Dynamics (SD) is a simulation tool that help decision makers better understand complex systems and the implication of system intervention. SD was developed in the late 1950s by Jay Forrester of the Sloan School of Management at MIT (Williams 2002). His book, Industrial Dynamic, was a very successful introduction of System Dynamics to Management Science area.

Later in 1990s the publication of Peter Senge's book "The fifth Discipline" gave a re-birth to the field (Dooley 2002). Highlighting the importance of feedback and delays through illustration of the Bear Game was one of Senge's main contributions for understanding the necessity of using more sophisticated tools like SD in management decision makings. Indeed, effective decision making and learning in a world of growing dynamic complexity requires us to become system thinkers- to expand the boundaries of our mental models and develop tools to understand how the structure of complex systems creates their behaviors (Sterman 2000).

System Dynamics is based on differential equations and has its origin in control engineering and is now considered an established research direction in Management Science. The popularity of System Dynamics has increased in recent years because of the new developments in softwares and their increased availability.

2.1.1 Open/Closed Systems

The understanding of system is central in using System Dynamics. Systems can be classified as "open" or "closed systems"[1]. An open system is the one characterized by outputs that respond to

[1] Forrester (1971) refer to closed system as feedback systems. Also Coyle (1977) calls these two types of systems, open loop and close loop systems.

inputs but where the outputs are isolated and have no influence on the inputs (Forrester 1968). In other words, in open systems, the output has no effect on the future performance of the system. Most of the systems around us, especially the systems manufactured by humans are open systems. A computer printer do not change performance based on how it was printing last time. Hence, an open system is not aware of its own performance, and past actions do not control future actions (Forrester 1968).

In contrast, closed systems change performance based on pervious performance. A computer printer together with the human user of the printer can be a closed system. The performance of the printer each time may cause the user to make decisions on changing the printer settings or doing maintenance, if the performance is not acceptable. However it is very difficult to find systems that are completely closed.

Usually systems are a combination of open and closed systems. Also the classification of a system as a close or open system is not intrinsic to a particular assembly of parts, but depends on the observer's viewpoint in defining the purpose of the system. System Dynamics is basically about analyzing closed systems and a principal activity in system dynamics modeling is to define the boundary of the system, and then translate what lays within the boundary into a closed system model with some rational modeling assumptions (Forrester 1968).

2.1.2 Feedback

The first step of building system dynamics models is to identify the variables existing in the system and defining the relationship between these variables. The variables and the relationships can easily be plotted in a causal diagram. A causal diagram consists of variables connected by arrows denoting the causal influences among the variables. These relationships can easily be shown by + and – showing the direction of change one variable will cause to the other variable.

The causal diagram shows the characteristics of a system in terms of component types and relationships. Drawing the causal diagrams helps to describe the dynamic behavior of the systems through identifying the feedback loops. That is because the most complex system behaviors arise from the interaction (feedbacks) among the components of the system, not from the complexity of the components themselves (Sterman 2000; Eden 2004).

Feedback structures exist in many systems. Feedbacks show the effect of the behaviors or actions of one component in a system on itself. A feedback in a causal diagram is shown by a loop shown by arrows which indicate relationships between the elements of the model. In a causal loop every element is influencing one or more elements of the model and is influenced by one or more elements of the model. These loops can be either positive or negative loops.

In positive loops, any change in an element causes the influence of other elements to be in the direction of intensifying the change, while in negative loops any change in an element will activate a control mechanism in the loop to bring the element value to the original value. The negative and positive loops are also called respectively goal-seeking and growth producing loops (Coyle 1996).

Once a causal diagram is created and the feedback loops identified, the diagrams can be used to qualitatively explore alternative structure and strategies, both within the system and its environment, which might benefit the system (Wolstenholme 1990; Coyle 1996).

Figure 2.1 shows a causal loop describing how lowering the cost through learning lowers the cost of capital and stimulating further growth.

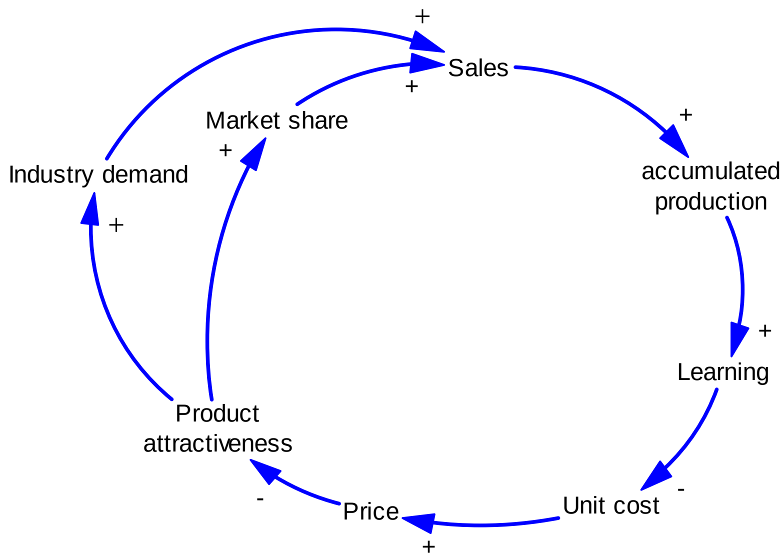

Figure 2.1 Example of causal loop system diagram

Some people call the causal diagramming of a system, the qualitative analysis of system, since causal loops create a forum for translating barely perceived thoughts and assumptions about the system, by individual actors into usable ideas which can be communicated to others. Therefore in cases where quantification of the models is impossible even drawing the causal diagram is very helpful in understanding of the system (Wolstenholme 1990).

2.1.3 Stocks and Flows

A quantified system dynamic model is built by translating the model structure from a causal diagram to stocks and flows and their corresponding mathematical definitions. Levels (Stocks) are the accumulations within the system. They characterize the state of the system and generate the information upon which decisions and actions are based. The flows are defined by rates and their connection to the stocks (Forrester 1961; Sterman 2000).

Modeling the system using the stock and flow diagrams is the step the modeler takes to quantify the causal diagram and run simulation iterations to analyze the output and behavior of the model.

In stock and flow diagramming there is a third type of variables which are called auxiliary variables which are neither stock nor flows. They are variables or constants which are defined by numbers or function of variables in the system and using them is only a good modeling practice. They can always be eliminated and the model be reduced to a set of equations consisting only of stocks and their flows (Sterman 2000).

In most of the software packages stocks are shown by rectangles. Inflows are represented by a pipe pointing to the stock and out flows are presented by pipes pointing out of the stock. The flow rates are controlled by valves which are noted on the pipes. A flow is either between two stocks or between a stock and a source/sink. A source represents the stock from which a flow originating outside the boundary of the model arises; sinks represent the stocks into which flows leaving the model boundary drain. Source and sinks are usually shown by clouds (Sterman 2000).

The visualization of the diagram is often called "system diagram" of the model. Figure 2.2 shows a system diagram consisting of stock and flows describing the effect of investment on marketing performance of a firm.

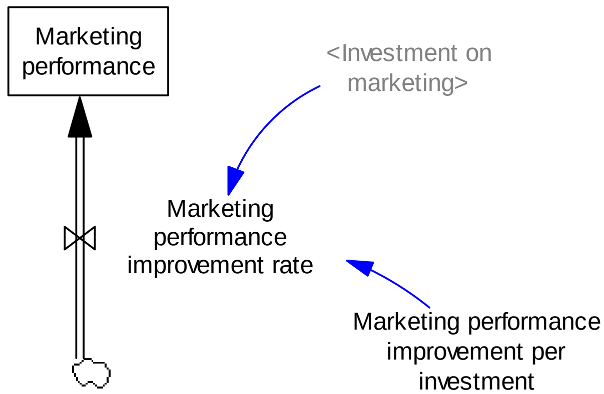

Figure 2.2 System diagram of growth of marketing performance through investments. The stocks are shown by rectangles, the flows by the arrows and the valves, the auxiliary variables with no bordering and source/sinks are shown by clouds

The values in the stocks equal their initial value plus the algebraic sum of the rates integration into and out the stock. In modeling the system using the stock and flow the stocks should be dependant only on the rates (not any auxiliary variable) and the rates should be dependent only on the auxiliaries and stocks (not any other rate). Also every feedback loop identified in the causal diagramming must be included in the model by at least one level and one rate; otherwise creation of behavior over time from tracing out the loop would not be possible (Wolstenholme 1990).

Sterman (2000) proposes the snapshot test for identifying key stocks in the system. Using this method the modeler should consider the system and imagine freezing a scene of the system. Stocks would be those things you could count or measure in the picture, including psychological states and other intangible variables.

As modeling moves from the hard to the softer areas of the system spectrum, obviously quantification becomes more difficult. However, it is always important to try to quantify all aspects of a model, even if some of these have to be on a normative scale, since one of the major axioms of the approach is that the behavior of whole systems is not predictable from the behavior of its individual components (Wolstenholme 1990).

2.1.4 Simulation of the Model

The most valuable insights can be obtained from a System Dynamics study is through the simulation of the model. The simulation of the model is a computational process where the values of the stock variables are calculated by progressing the time of the system. By definition the values of the stocks are the algebraic integration of the flows going in and out of each stock (Figure 2.3). The algorithm of the calculation is also shown in Figure 2.4.

$$Stock(t_2) - Stock(t_1) = \int_{t_1}^{t_2} Flow.d_t$$

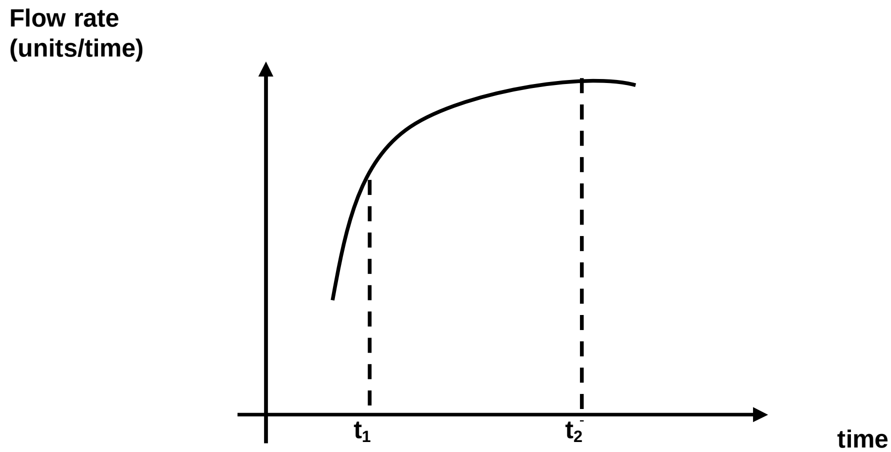

Figure 2.3 The value of the stock variables are calculated by integration of the flow rates

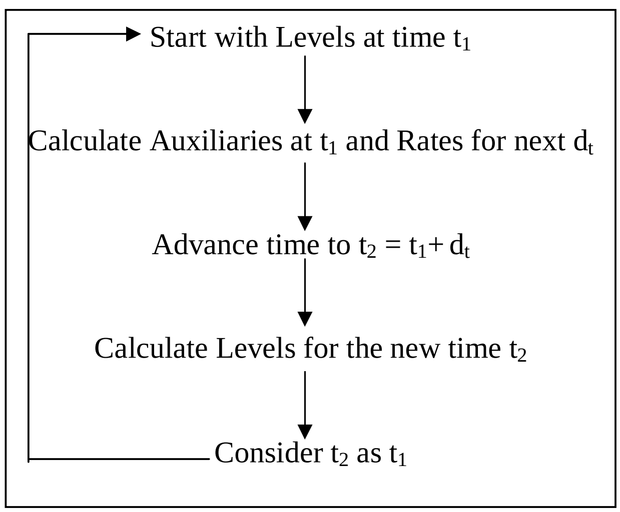

Figure 2.4 Computational sequence in the SD simulation (see Wolstenholme 1990)

What the a computer software does, is to define a time interval between states of the system in two consequent points in time, and calculate the values of the system variables at every point, by adding this time step to the system time and calculating the next value of the system variables based on the previous variables. Because most of the flow rates have not linear behavior this time step should be short enough, so that we are willing to accept constant rates of flow over the interval as a satisfactory approximation to continuously varying rates in the actual system (Forrester 1961).

2.2 Why using System Dynamics models?

It is generally not possible to solve even small models analytically because of their high order and nonlinearities, so the mathematical tools many people have studied are of little direct use(Sterman 2000). Moreover, multiple feedback loops produce system behavior not seen in the simpler systems and non linearity can introduce unexpected behavior in a system (Forrester 1968). As an example, in a system that contains non-linearity and multiple loops, the behavior of the system can become surprisingly insensitive to change in value of the majority of the system parameters. This means that the major inputs of the system can be changed without substantially affecting the output behavior of the system. This is partly because of the dilution of a single parameter in a large number of others. This kind of behavior is common in models of complex systems. However, system dynamics can easily show which parameters in a system have enough ability to affect the whole system so that by changing them one can alter the system behavior. This is a significant advantage of using system dynamics in studying i.e. social systems and technical systems (Forrester 1968).

Moreover, system dynamics models will organize clarify and unify the knowledge about a certain system. It provides us with a more effective understanding about an important system that has previously shown controversial behavior. In general, a good system dynamics project is one that change the way people look upon a system (Forrester 1961).

In conclusion, System Dynamics is a powerful tool which can be used to analyze different systems both qualitatively and quantitatively. Certain characteristics of System Dynamics provide capabilities which make it one of the few analytical tools suitable for analysis of social and natural systems. System Dynamics is also a popular tool in analysis of environmental and even political systems. However this method is not yet well understood and practiced among practitioners and has high potential for increased use.

Chapter 3. Modeling of multi-mode interaction between technologies

In this chapter the model of coexistence of technologies and the way they interact with each other will be described. The modeling is based on the Lotka-Volterra competition equations (Lotka 1924), which are sets of coupled logistic differential equations used in modeling of the interaction of biological and ecological species competing for the same resources. The use of Lotka-Volterra equations in biology indicates that they also could be used to describe socio-technical processes that lead to growth and diffusion of technologies (Bhargava 1989; Porter, Roper et al. 1991).

In order to make a foundation for understanding patterns of growth, some of the basics behaviors such as exponential growth and logistic growth will be set forth in this section. Furthermore, to facilitate understanding of how Lotka-Volterra equations are used in studying the interaction between technologies, its application in ecological population dynamics is described in this chapter.

3.1 Population growth

The history of the application of mathematics in ecology probably dates back to 18th century to Thomas Malthus book "*An essay on the principle of population*" (Malthus 1798).

It was mentioned in his book that a population with the opportunity to reproduce grows exponentially as time passes. In modern notation and terms, the dynamic of a population with no resource limitations can be described by the following equation which is known as an exponential growth equation:

$$\frac{dR}{dt} = a \times R, a \succ 0$$
$$\Rightarrow R(t) = R_0 \cdot e^{at} \qquad (1)$$

In this equation R is population at time t, a is the constant growth rate and R_0 is the initial population of the species. This model assumes that the rate of growth of a population is always proportional to its size and results in exponential growth.

Suppose that there is a pair of rabbits (of course a male and a female) living in a farm which have access to all the resources and means of subsistence. These two rabbits might mate and give birth to some offspring. Within a short period of time, this second generation of rabbits would also be ready to mate and bear offspring. The number of rabbits born over time would increase as the number of rabbits available to give birth increased. Hence, the rabbit population would grow slowly at first, and then more rapidly as the number of rabbits increased.

The system diagram is given in the Figure 3.1 is that the stock of rabbit population grows as the birth flow increases. In this model the birth rate considered to be 1.1 rabbits per capita per month. This means that, on the average, there will be 11 rabbits born every month for every 10 rabbits in the population which admittedly is a very prolific number.

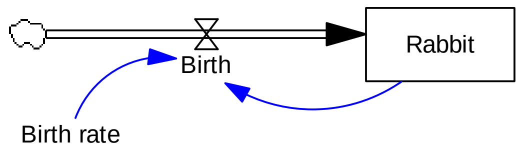

Figure 3.1 system diagram for rabbit population

It would be important to use realistic values of the birth rate before using the model to make predictions. However, this arbitrary value is used in order to illustrate how this model of population growth works. A graph of the number of rabbits versus time is shown in figure 3.2.

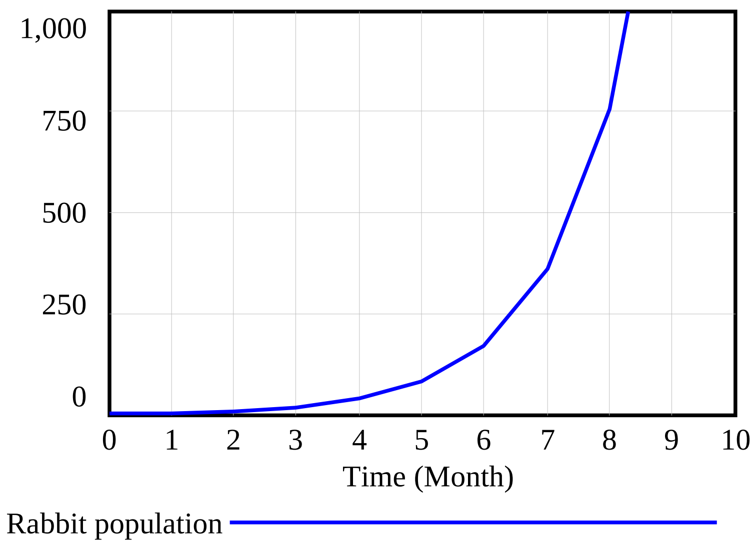

Figure 3.2 Population of rabbits versus time

In the real world exponential growth may occur in the initial stages and it cannot continue indefinitely. So the next step is introducing a model of population that is restricted in size by some limitation (Bazykin 1998). We need models to take into account the interaction of the population with its environment since population growth decreases as a result of limited food supplies, increased diseases, crowding and other factors. This means that we don't deal with a constant growth rate which is introduced in equation (1). Hence the constant growth rate *a* in equation (1) is replaced with a variable growth rate *f(R)* which is a function of the population R.

$$\frac{dR}{dt} = f(R) \times R \qquad (2)$$

For the most populations, the growth rate *f(R)* decreases with increasing *R*, so the simplest choice of a decreasing linear function of *f(R)=a-a.R/k, a>0, k>0* is made. By substituting *f(R)* in the equation (2), it can be written as follows:

$$\frac{dR}{dt} = a \cdot R - {aR^2}/{k}, a \succ o, k \succ 0 \qquad (3)$$

This equation is called a logistic growth equation. As it can be observed, the exponential growth factor of the equation *a.R*, is reduced by the factor of aR^2/k. This equation represents the following two states:

- For small R the population dynamics would be close to exponential growth
- For large R the population of rabbit would compete with each other for less resources

Hence the dynamics presented by equation (3) can be summarized as:

If R=0 or R=k then dR/dt=0 and the population won't change. However, for 0<R<k, and dR/dt>0, the population increases, while for R>k it decreases.

In this equation the positive factor of *a* is called the initial growth rate and the *k* is called the carrying capacity which is the maximum size of the population considering the resource limitation.

By solving the equation (3) and assuming initial population R_0 we have:

$$R(t) = \frac{kR_0 e^{at}}{k + R_0 (e^{at} - 1)}$$

Back to rabbit example, consider that those two rabbits are put into a barn and are provided with food enough for 1000 rabbits to survive. Hence, the carrying capacity would be 1000 rabbits. On the other hand *a* represents the birth rate of rabbits through breading and is independent from carrying capacity. So referring to equation (3), the size of inflow (birth) at any point in time is proportional to the current size of the population and operates exactly the same way as in an exponential system. The inflow is calculated as:

$$Inflow(birth) = a \times R \quad (4)$$

In this equation *a* is the relative birth rate of rabbits and *R* is the size of the population at the time *t*.

Since a carrying capacity was considered, there should be an additional outflow from the stock because of lacking of the resource and means of subsistence. Actually this outflow corresponds to the amount of death because of resource scarcity. The outflow (death rate) of the stock is calculated as:

$$Outflow = R \times b \quad (5)$$

Where *b* is the relative number of death rate

$$b = R \cdot {}^{a}\!/_{k} \quad (6)$$

Where k is the carrying capacity, in this case 1000 rabbits. Hence the outflow (death rate) is:

$$Outflow = R^2 .{}^{a}\!/_{k} \quad (6)$$

Figure 3.3 is showing a system diagram for the rabbit's population considering logistic growth.

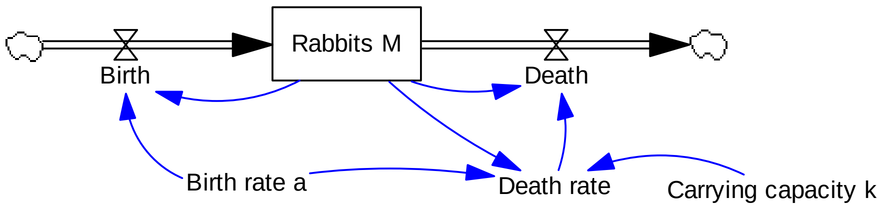

Figure 3.3 System diagram for rabbit population considering logistic growth

A graph demonstrating the number of rabbits growing in a logistic system is shown in figure 3.4. It is clear from the graph why this behavior pattern is sometimes referred to as "S-curve".

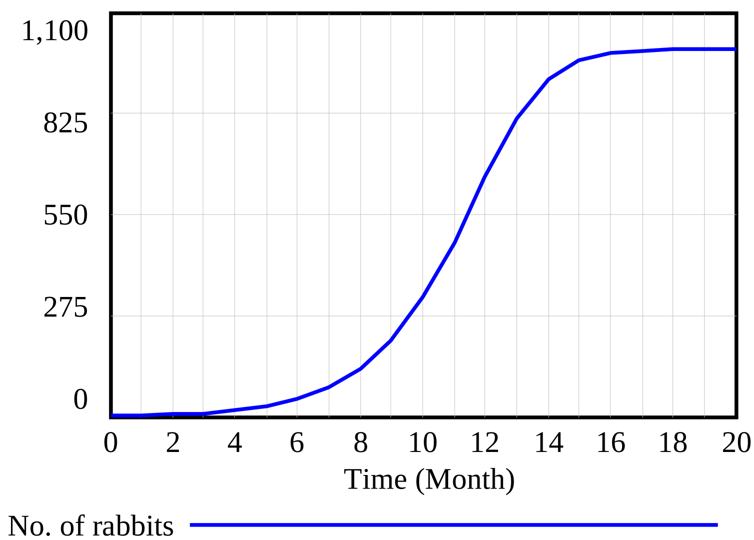

Figure 3.4 Population of rabbits versus time in a logistic system

This model shows that, when population is small compared with the carrying capacity of the system the ratio *R/k* in equation (6) will be initially close to zero. Hence, the death rate will be very small. This implies that the inflow (birth) will exceeded the outflow, and the system will grow exponentially; however as the system progress and the population reaches the carrying capacity, the ratio *R/k* will get closer to 1 and outflow rate (death rate) in equation (6) will increase and reach the birth rate. Whenever it happens, the number of "death" will be very close to the number of "birth", and the population growth will slow down and eventually will stop. This phenomenon is known as logistic growth.

The models mentioned above were basically intended to represent the dynamics of a single population. However the real ecological fields are composed of many species that interact with one another and the assumption of a population, such as rabbits, that is uncoupled to other species in our ecosystem is clearly unrealistic. Rabbits, and most other animals in an ecosystem, are either predator or prey, and thus are necessarily connected to other populations. It is clearly expect prey populations (like rabbits) to be influenced by the number of predators looking for a hearty meat.

In the next section, on of the most important systems in mathematical ecology, known as Lotka-Volterra predatory-prey systems, is introduced.

3.2 Lotka-Volterra predatory-prey systems[2]

A simple ecological system is considered now in which two species occupy the same environment. One species, the predator, feeds on the other one, the prey, while the prey feeds on something else already is in the environment. One example would be foxes and rabbits in woodland, where the foxes (predator) eat the rabbits (prey) and the rabbits eat natural vegetation.

Let F denote the population of foxes at time t and R denote the population of rabbits. The Lotka-Volterra equations for this Predatory-Prey model are as follows (Lotka 1924; Takeuchi 1996; Bazykin 1998):

$$\begin{aligned} \frac{dR}{dt} &= a_R R - c_R RF, a_R \succ 0, c_R \succ 0 \\ \frac{dF}{dt} &= -a_F F + c_F FR, a_F \succ 0, c_F \succ 0 \end{aligned} \qquad (8)$$

In this set of equations a_R, c_R, a_F and c_F represent the growth constants and proportionality constants for rabbits and foxes, respectively. As it can be observed from the set of equations there are the following assumptions in this model.

- In the absence of foxes $F=0$, the rabbit population grows exponentially and equation (8) is reduced to equation (1): $\frac{dR}{dt} = a_R \cdot R, a_R \succ 0$

- In the absence of rabbits, $R=0$, the fox population will die off according to unavailability of food and equation (8) because: $\frac{dF}{dt} = -a_F \cdot F, a_F \succ 0$

- When both foxes and rabbits are present, the intensity of interaction is proportional to population sizes. The proportionality constants c_R and c_F, increase the fox population ($+c_F RF$) and decrease the rabbit population ($-c_R FR$)

The system dynamics model considering the above Predatory-Prey problem is shown in figure 3.5. For the simplicity the birth rate of the foxes is considered to be just proportional to the predatory efficiency and other factors i.e. fertility is not considered in this model.

[2] American Alfred J. Lotka (1880-1949) was a biologist, physicist, and a mathematical demographer. He published in 1924 the first book in mathematical biology in which he formulated these predatory-prey equations. Lotka described an ecosystem in thermodynamic terms, as an energy transforming machine, and initiated the study of ecology. The same predatory prey model was developed independently in 1926 by Italian mathematician Vito Volterra (1860-1940), who turned his attention to mathematical biology after World War I (Takeuchi 1996, Bazykin 1998).

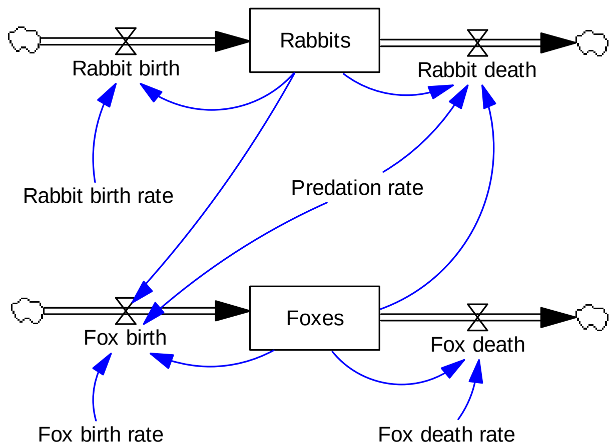

Figure 3.5 Fox and rabbit predatory-prey system

A set of exogenous variables are assumed to simulate the model. These assumptions, as well as the relation between the different variables, are shown in table 3.1.

Exogenous Variables	Quantity
Rabbit birth rate	0.05
Predation rate	0.0002
Fox birth rate	1
Fox death rate	0.05
Rabbit initial population	100
Foxes initial population	50

Variable	relation
Rabbit birth	Rabbit birth rate*Rabbits
Rabbit death	Rabbits*Foxes*Predation rate
Fox birth	Foxes*Predation rate*Fox birth rate*Rabbits
Fox death	Fox death rate*Foxes

Table 3.1 Assumption for run the model of Predatory-Prey

Figure 3.6 is the output of the system dynamics model showing the dynamics of fox and rabbit populations over time.

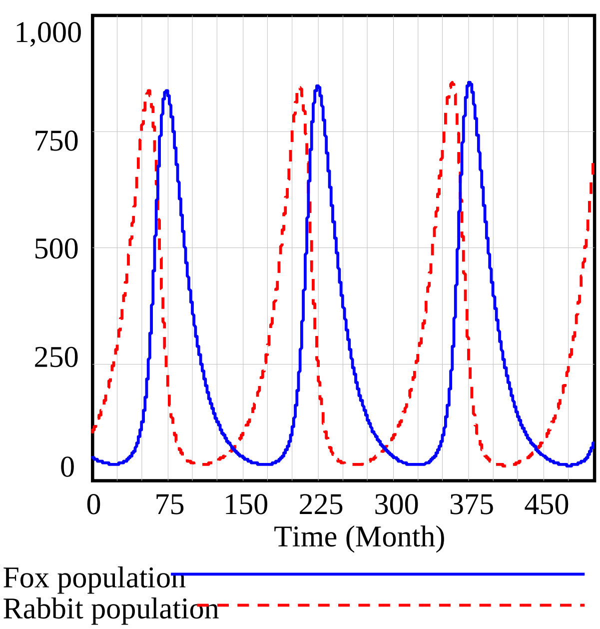

Figure 3.6 The population dynamics in a Lotka-Volterra Predatory-Prey system

As it can be observed, the dynamics of fox and rabbit populations have an oscillatory behavior due to the presence of strong counteracting feedback loop that forces the system to oscillate around a set of conditions. This feedback mechanism is illustrated in figure 3.7.

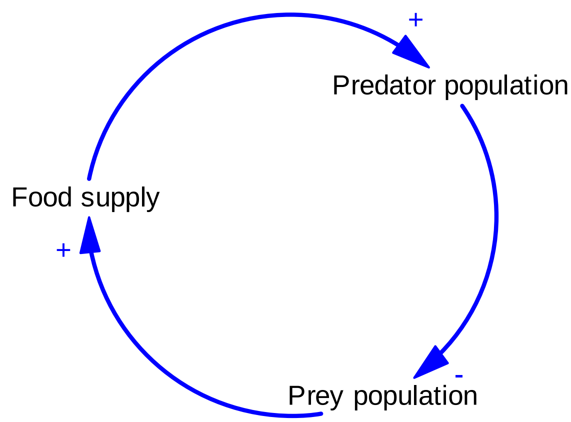

Figure 3.7 Counteracting feedback loop in the Predatory –Prey system

The loop explains that predator population has a negative effect on the prey population and prey population has a positive effect on the amount of food supply for the predator. Hence, as the predator population increases due to the abundant supply of prey, it leads to more population of predator. Additionally, growth of population of predators decreases the prey population since more population of predator leads to more prey being killed, and consequently predator population decreases due to the insufficient food supply (prey). Thus fewer predators lead to increment in the number of prey, due to the fact that, now there are fewer predators to kill the preys. Hence the abundant supply of prey as food supply increases the amount of predator and this cycle will go on as it can be seen in Figure 3.7.

The simplified Predatory-Prey model presented here is useful in describing the dynamics of populations where one feed from another.

3.3 Lotka-Volterra competition system

Another important population model describes systems in which two or more species compete for common resources. In this new system the species may or may not be predator or prey on one another. Several species of fish, for example, may compete for the same food supply but not feed on each other. On the other hand, lions and hyenas not only compete for a common food supply but will also kill their rivals.

In order to illustrate a system of differential equations corresponding to such a situation, the competition of rabbits and sheep for the limited grass resources, on a certain limited amount, are considered. Also the model is kept simple by ignoring other relations i.e. the presence of predators.

Let *R* and *S* denote the populations of rabbits and sheep, respectively. Since limited amount of food supply is considered, the model should represent a logistic growth pattern. The Lotka-Volterra equations for the competition model are (Takeuchi 1996; Bazykin 1998):

$$\frac{dR}{dt} = R(a_R - b_R R - c_R S), b_R = {a_R}/{k_R}, c_R \succ 0$$
$$\frac{dS}{dt} = S(a_S - b_S S - c_S R), b_S = {a_S}/{k_S}, c_S \succ 0 \quad (9)$$

In this set of equations, a_R and a_S represent constant growth factors for rabbits and sheep respectively. c_R and c_S are proportionality constants and k_R and k_S are the caring capacity for rabbits and sheep, respectively. As it can be observed, there are following sets of assumptions in the model:

Each species, in the absence of the other, will grow to carrying capacity and produce a logistic growth. According to equation (3) and (8) and considering $c_R=0$ and $c_S=0$ the equations are:

$$\frac{dR}{dt} = R(a_R - b_R R) = a_R R(1 - R/k_R)$$

where $k_R=a_R/b_R$ is the carrying capacity for rabbits, and

$$\frac{dS}{dt} = S(a_S - b_S S) = a_S S(1 - S/k_S)$$

where $k_S=a_S/b_S$ is the carrying capacity for sheep.

When grazing together, each species has a negative effect on the other. This introduces another term to each of the equations. For positive constants c_R and c_S, the interactive contributions to the rates of change of populations *are* $-c_R RS$ for rabbits and $-c_S RS$ for sheep. Hence the presence of one species has a negative impact on the growth of the one, which is governed by c_R and c_S.

Competition models are not limited to biology or ecology. Countries compete for getting more share of trade, companies and corporations compete to acquire more customers, political parties compete for votes, and new technologies and innovations compete for opening the market and taking a bigger share of the market which in most cases are dominated by an older, already well-established, technology (Bhargava 1989; Pistorius and Utterback 1995).

3.4 Towards a model of technological substitution using Lotka-Volterra equations

Studying technological substitution requires models that produce insights of the factors affecting technological substitution as well as have the ability to demonstrate the trend and behavior of the process. Many substitution models overlook to model the declining competitors and model only the invading technology whose population is increasing (Kumar and Kumar 1992; Young 1993).

As it is already seen in the previous section of this chapter, the Lotka-Volterra competition, i.e. equations (9), model both the growing and declining competitors. This allows us to have an intuitive understanding of the factors driving competition and substitution, from both emerging and declining technologies.

Several researchers have used the Lotka-Volterra equations to model competing technologies. Bhargava (1989) examined the Lotka-Volterra equations as a substitution model demonstrating that if technological substitution is looked as the result of competition between old and new technology in which the new technology wins, various substitution curve shape of technological substitution can be obtained and in some special cases, it produce the logistic substitution curve.

Farrel (1993) described Lotka-Volterra equations as one of the several tools for modeling the "daily struggle for existence" among technologies. He presented a theory of the development of technologies which started by ranking and classifying the types of technological artifacts. Then he used Lotka-Volterra equations in modeling the growth of a new artifact in the absence of a competitor. He further developed the model to explain the substitution of one artifact technology for another. He illustrated several realistic examples such as, lead-free cans replacing soldered cans, tufted carpet replacing woolen carpets, ball point pens replacing fountain pens and nylon tire cord replacing rayon tire cord. At the end of his paper he also outlined a method to derive coefficients in Lotka-Volterra equations from experimental data (Farrell 1993).

Modis (1997) used Lotka-Volterra equations to describe the competitive dynamics in a market occupied by two technologies competing with each other. He introduced different types of interaction between technologies: competition, predatory-prey, mutualism, commensalism, amensalism and neutralism. He presented examples from industry showing the possibility to change the relation between two technologies from one type of interaction to another. He also proposed methods to manipulate the interaction to optimize advertising and image-building strategies (Modis 1997).

Pistorios and Utterback (1995) discussed modeling the S-curve related oscillatory behavior in the mature phase of some technologies. They used Lotka-Volterra equations to investigate how other technologies can influence this kind of oscillatory behaviors. They addressed the question whether these oscillation behaviors are inherent and can be seen as mortality indicator of a mature technology, or if they are seen when the mature technology interacts with other technologies. In their paper, they investigated the interaction between plywood as mature technology being attacked by oriented strand board (OSB). It is concluded that factor, such as macroeconomic business cycle is the main reason for the oscillations in plywood S-curve, although the presence of OSB as emerging technology, contributes to the oscillatory behavior of the mature technology's S-curve. Moreover, by using Lotka-Volterra equations they showed that this oscillatory behavior can also result from the symbiotic interaction between two technologies in which both technologies benefits from the other technology (Pistorius and Utterback 1995).

Pistorius and Utterback (1996) also used Lotka-Volterra equations to model the interaction of technologies in three modes: pure competition (where both technologies suppress one another's growth), symbiosis (where both technologies benefits from the other's presence), and predatory-prey (where one technology expand in expense of the other technology decline). This is done mathematically by changing the algebraic signs of the competition coefficients in Lotka-Volterra equations (Pistorius and Utterback 1996).

Pistorius and Utterback (1997) further concluded that using Lotka-Volterra equations provides us with a broader understanding of the interaction between technologies. They discussed qualitatively the three modes of interaction which had been presented in their earlier paper (Pistorius and Utterback 1996) and discussed how emerging and mature technologies can have positive and negative effects on one another's growth rate. They also demonstrated examples of these three modes of interaction (symbiosis, pure competition and predatory-prey). They also attested that the interaction between technologies can be shifted from one mode to the other, which is also discussed by Modis (1997). They also suggested further research should be undertaken in to the nature of the interaction in different modes (Pistorious and Utterback 1997).

3.5 Model of technological change using Lotka-Volterra equations

Let M denote the market level of a mature technology and E denote the market level of an emerging technology. A system of Lotka-Volterra equations, describing the interaction between these two technologies, and set of equations related to this interaction is:

$$\frac{dM}{dt} = M \cdot (a_M - b_M \cdot M - c_{ME} \cdot E), a_M \succ 0, b_M \succ 0, c_M \succ 0$$
$$\frac{dE}{dt} = E \cdot (a_E - b_E \cdot E - c_{EM} \cdot M), a_E \succ 0, b_E \succ 0, c_E \succ 0 \qquad (10)$$

In this set of equations:

- a_M and a_E pertain to the production or positive feedback from adoption. It reflects the production ability and growth rate of each technology and has a unit of 1/time.

- b_M and b_E is inhibition coefficients for each technology that determines the loss of potential market caused by growth of the technology. It has a unit of 1/unit/time. According to set of equations (9), *b* can be written as *a/k* where *k* reflects the market capacity for the technology.

- c_{ME} and c_{EM} are the competition coefficients among technologies, which is the effect of technologies on one another. It shows the share of market capacity taken by the other technology. It has the same unit as b.

These three coefficients are different from one technology to another depending on characteristics of each technology. These characteristics can be addressed as market potential for each technology. Hence the terms ($a_M - b_M \cdot M - c_{ME} \cdot E$) and ($a_E - b_E \cdot E - c_{EM} \cdot M$), gauge the market potential for mature and emerging technologies, respectively. Hence by considering Lotka-Volterra equations in studying technological substitution, it is assumed that technological growth depends on two factors: “market level” and “market potential” of each technology.

According to the set of equations (10), *a* and *b* coefficients determine the S-curve or logistic diffusion pattern of each technology as they exist in one particular market without presence of the other technology. However, the interaction between two technologies is determined by coefficient *c* which introduces the effect of technology interaction. Hence, depending on the signs of c_{ME} and c_{EM} , the model can produce different modes of interaction between technologies which are summarized in table 3.2 (Pistorious and Utterback, 1997, Modis, 1997, Pistorius and Utterback, 1996).

C_{ME}	C_{EM}	**Denotation**	**Description**
+	+	Symbiosis	Both *M* and *E* benefit from presence of the other on
+	0	Commensalism	*M* benefits from the presence of *E*, but E remains unaffected
0	0	Neutralism	*M* and *E* do not affect one another
+	-	Predatory-Prey	*M* expands at expense of *E*
-	0	Amentalism	*M* growth rate decrease, but *E* remain un affected
-	-	Pure competition	Presence of *M* and *E* suppresses other's growth

Table 3.2 Different interaction modes among technologies

The equations presented here address the degree of technological growth over time i.e. *dM/dt*. Hence, as discussed in chapter two and this chapter, system dynamics is a suitable tool for the purpose of modeling and simulating interaction among technologies.

3.5.1 Modeling the predatory-prey interaction between two technologies

As a point of departure in this study a case presented by Pistorius and Utterback is modeled using system dynamics. In this case a predator-prey relationship between a mature technology *M* (Prey) and an emerging technology *E* (Predator) is examined. For illustrative purpose the following set of values are considered for the coefficients in equations (10): a_M =0.15, a_E =0.1, b_M = b_E =0.01, c_{ME} =0.01 and c_{EM} =0.02 (Pistorius and Utterback 1996).

Since it is a predatory-prey relation between two technologies, referring to Table 3.2, the sign of c_{ME} is negative and the sign of c_{EM} is positive. The initial value for the market levels of technologies are $M_0=5$ Million units and $E_0=10000$ units. This is basically due to the level of maturity of each technology(Pistorius and Utterback 1996). Hence the equations used for this model are as follows:

$$dM/dt = 0.15M - 0.01M^2 - 0.01M \cdot E$$
$$dE/dt = 0.1E - 0.01E^2 + 0.02E \cdot M$$

Figure 3.8 and 3.9 shows the system diagram and time domain plot of this model.

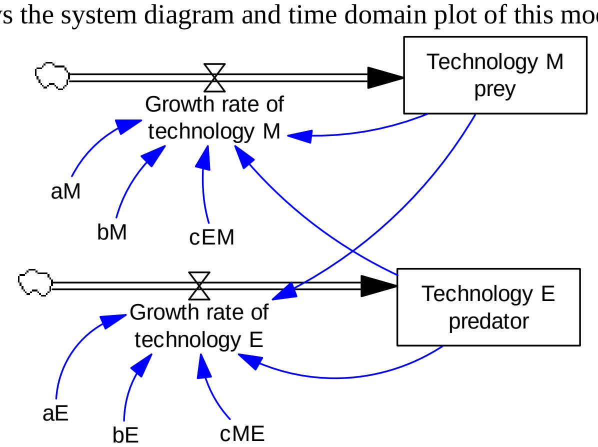

Figure 3.8 System diagram for the predatory-prey model

The terms “Growth rate of technology M” and “technology E” are actually *dM/dt* and *dE/dt*, respectively.

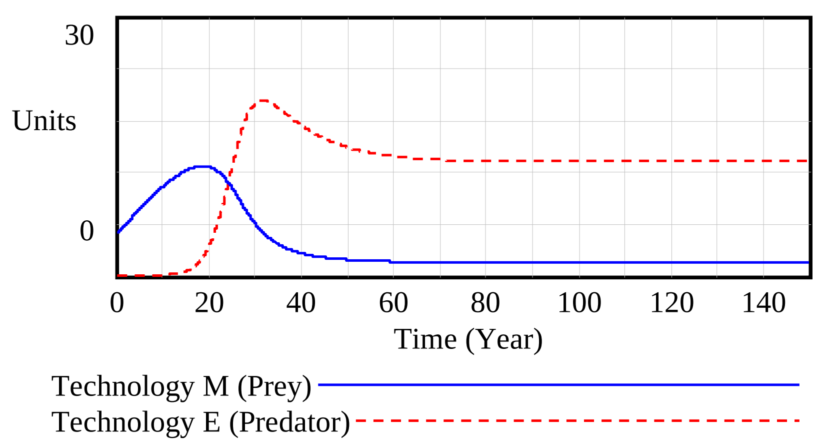

Figure 3.9 Time domain plot of two technologies in predatory-prey interaction (technologies will coexist)

In this model the emerging technology will benefit from the existence of mature technology, hence the mature technology has a positive effect on the emerging technology. However, the mature technology does not recognize this threat caused by the emerging technology, thus the mature technology does not initiate any improvement in order to be more competitive in the market with the emerging technology. This is the phenomena occurring i.e. before year 20 in this model, which at the same time emerging technology stealing some share of market from the mature technology.

Under these circumstances, one can state that the emerging technology has a negative influence on the mature technology's growth and hence, it is a predatory-prey relation among two technologies. (Pistorius and Utterback 1995; Pistorius and Utterback 1996).

It this model both mature (prey) and emerging technology (predator) reach an equilibrium condition in which both technology coexist in the same market (after year 50). It can be shown that the equilibrium situation will only be reached when. In the case where $a_M \cdot b_E / a_E \prec c_{ME}$, the prey technology will always die out (Pistorius and Utterback 1996).

The following set of equations demonstrates a case in which the mature technology (prey) will die off eventually due to above mentioned condition. The initial market levels are the same as the previous model. The time domain plot of this case is shown in figure 3.10.

$$dM/dt = 0.1M - 0.01M^2 - 0.01M \cdot E$$

$$dE/dt = 0.15E - 0.01E^2 + 0.02E \cdot M$$

M_0=5 million units, E_0=10000 units

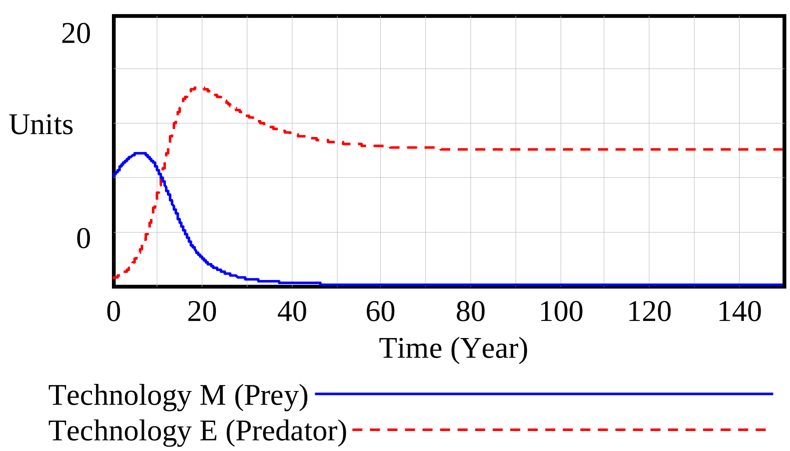

Figure 3.10 Time domain plot of two technologies in predatory-prey interaction (prey technology will die off)

3.5.2 Modeling pure competition between two technologies

As discussed earlier the growth of a technology, considering Lotka-Volterra equations, depends on two factors: market level and market potential of that technology. A mature technology has evidently much larger market presence than the emerging technology and by considering even the equal market potential, it is impossible for the emerging technology to grow when it is in pure competition with a mature technology.

Figure 3.11 shows the time domain plot of interaction between a mature technology and an emerging technology, considering equal market potential, when they are in a pure competition. The following Lotka-Volterra equations describe such a case:

$$dM/dt = 0.1M - 0.01M^2 - 0.01M \cdot E$$
$$dE/dt = 0.1E - 0.01E^2 - 0.01E \cdot M$$

M_0=5 million units, E_0=10000 units

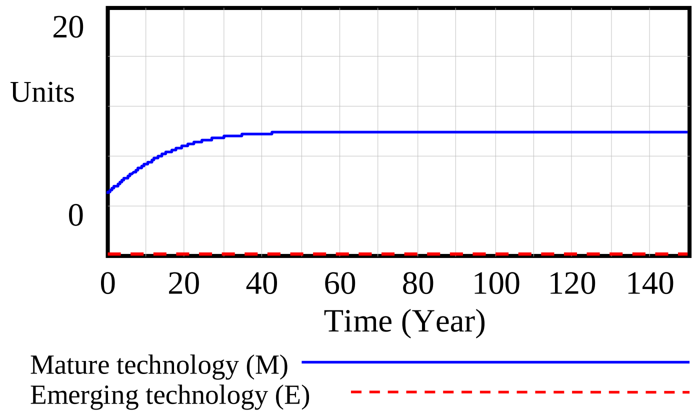

Figure 3.11 Time domain plot of two technologies in pure competition interaction

Referring to the above equations and the definition of pure competition presented in table 3.2, both technologies have negative impact on one another. In the case above, due to the large market level of mature technology, the emerging technology never gets the chance to diffuse in the market. The term *ME* present in both equations, which determine the strength of competition dynamics between technologies, remains in favor of mature technology since M_0 is much larger than E_0.This amplifies the interaction dynamics in favor of mature technology suppressing the emerging technology. Hence the emerging technology remains immature or will die off.

Concerning this behavior, some questions arise, e.g. how does the dynamics of growth of a technology, in a market dominated by a mature technology, look like? And, under what circumstances an emerging technology grow in such a market?

In the next section, a third technology is introduced to the competition model. The third technology is intended to act as a bridge to support the emerging technology in a market dominated by a mature technology.

3.5.3 *Modeling of the bridging technology using Lotka-Volterra equations*

As showed in last section, an emerging technology cannot compete in a market dominated by a mature technology and it will be inhibited in the early phase of the introduction to the market.

It is important to discuss about under what circumstances there would be a competition or predatory-prey interaction between two technologies. Presumably technical artifacts and infrastructures are factors which affect the market potential of a technology. For example if there is a common artifact used in production of both mature technologies and emerging technology, emerging technology can benefit from the presence of those artifacts. In this case, the mature technology has a positive effect on the emerging technology which makes the interaction predatory-prey interaction.

Here a system of three technologies interacting with each other is presented. Like the last example, emerging technology E is in pure competition with the mature technology M. Technology B is another emerging technology which is in predatory-prey interaction with technology M and E. Technology B benefits from the existence of technology M and technology E, on the other hand, benefits from existence and growth of technology B. The following set of Lotka-Volterra equations describes this case.

$$\frac{dM}{dt} = M \cdot (a_M - b_M \cdot M - c_{MB} \cdot B - c_{ME} \cdot E), a_M \succ 0, b_M \succ 0, c_{MB} \succ 0, c_{ME} \succ 0$$
$$\frac{dB}{dt} = B \cdot (a_B - b_B \cdot B + c_{BM} \cdot M - c_{BE} \cdot E), a_B \succ 0, b_B \succ 0, c_{BM} \succ 0, c_{BE} \succ 0$$
$$\frac{dE}{dt} = E \cdot (a_E - b_E \cdot E - c_{EM} \cdot M + c_{EB} \cdot B), a_E \succ 0, b_E \succ 0, c_{EM} \succ 0, c_{EB} \succ 0 \qquad (11)$$

In this set of equations:

- a_M ,a_B and a_E pertain to the production or sales capacity of the market for *M*, *B* and *E*, respectively.
- b_M , b_B and b_E is inhibition coefficient for each technology that determines the loss of potential market caused by growth of the technology
- c_{ME} , c_{BE} and c_{EM} are the interaction coefficients

Also, figure 3.12 shows the system diagram for this problem.

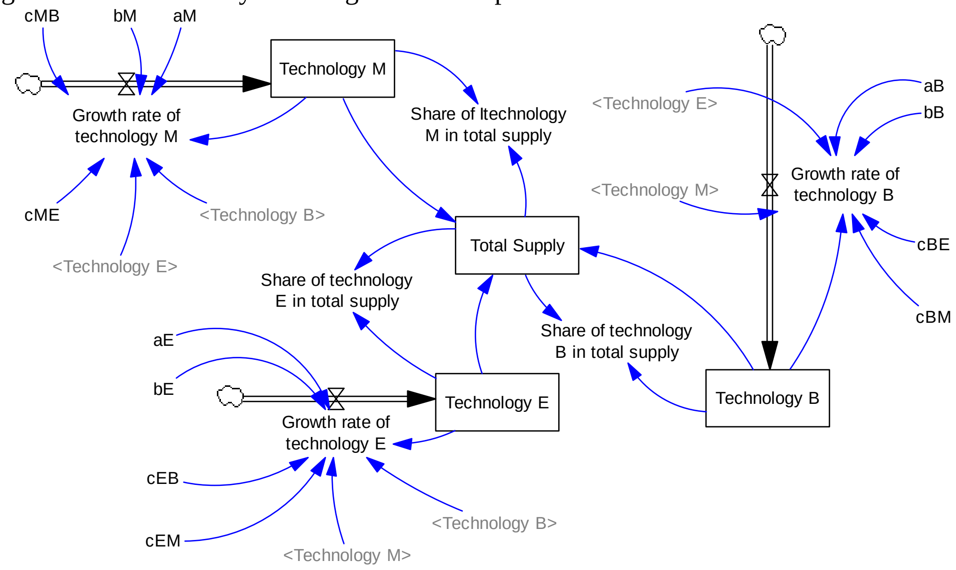

Figure 3.12 System diagram of three technologies interacting with on another's[3]

[3] In this diagram, M and B are in predatory-prey interaction (M as prey and B as predator), B and E are also in predatory –prey interaction (B as Prey and E as predator), and finally M and E are in pure competition.

The stock “Total supply” is the accumulation of all the technologies in the market. This stock and associated loops to each technology stock is added for illustration purpose. This will enable us to produce time domain plot of not just a technology’s level of existence, but also the share of the technology compared to the total supply due to the following relation.

Market share= supply of technology/total supply

The objective of this modeling is to show the bridging effect of a particular technology and to attest the necessity of presence of that in growing of an emerging technology. So the coefficients used for this model are chosen in such a way to produce a symmetric behavior of interactions. The following set of equations and initial variables are used to model the dynamics.

$$dM/dt = 0.1M - 0.01M^2 - 0.1M \cdot B - 0.1M \cdot E$$

$$dB/dt = 0.1B - 0.01B^2 + 0.1B \cdot M - 0.1B \cdot E$$

$$dE/dt = 0.1E - 0.01E^2 + 0.1E \cdot B - 0.1E \cdot M$$

M_0=5 Million units, B_0= 10000 units, E_0= 10000 units

The time domain plot of market level of technologies as well as share of each technology in the interaction described above, are shown in figure 3.13.

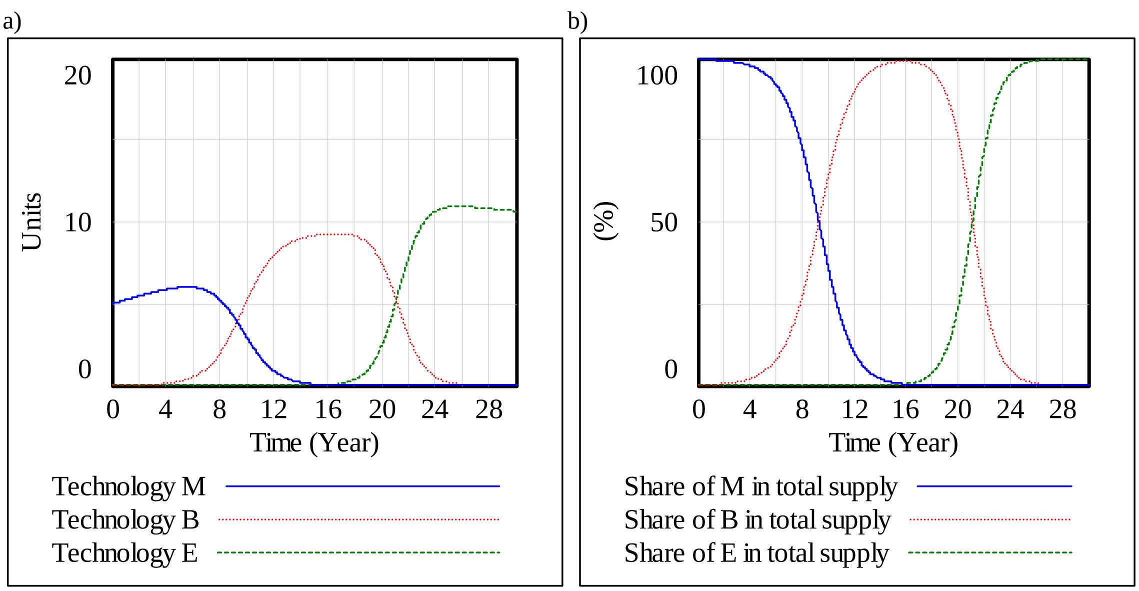

Figure 3.13 Time domain plot of: (a) market level of three technologies interacting with each other and (b) the share of the market of each technology

As it can be observed from the graphs, technology B starts to invade technology M because of the predatory-prey interaction between them (compare with figure 3.10). As soon as technology M dies off technology E starts to take advantage of the absence of technology M and begins to inhibit technology B and benefits from that. Hence, eventually technology E will be the dominant technology and the other technologies will die off. This is the simplest pattern of behavior of bridging technology. As seen already in figure 3.11, in the absence of bridging technology the growth of technology E is impossible.

Moreover, simulation of the model using the set of coefficients in table 3.3 shows that with a weak bridging effect, technology E will never get the chance to penetrate the market within 100 years. Nonetheless, since it is in predatory pray interaction with technology B it will start to evolve after almost 250 years which is far from what is expected from a bridging technology. In this new model all the coefficients of technology B is reduced from 0.1 to 0.01 and although the competition factor of E increased from 0.1 to 0.9, still it does not get the chance to evolve in the market. The output plot is shown in figure 3.14.

a_M	0,1	a_B	0.1	a_E	0.1
b_M	0,01	b_B	0.01	b_E	0.01
c_{MB}	-0,01	c_{BM}	0,01	c_{EB}	0,01
c_{ME}	-0,9	c_{BE}	-0,01	c_{EM}	-0,1

Table 3.3 coefficients used in simulating weak bridge effect

As can be seen, technology E never evolve and technology M and B, however, will be coexisted since $a_M b_B/a_B = c_{MB}$ (see section 3.5.1).

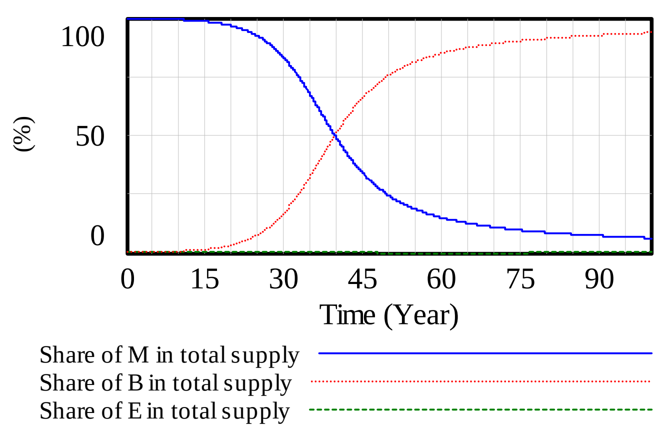

Figure 3.14 time domain plot of a weak bridging effect and $a_M b_B/a_B = c_{MB}$.

The symmetric behavior shown in this section is just selected for the illustrative purpose aiming to show the effect of bridging technology and growth of an emerging technology. However, different kind of pattern can be produced by playing with the coefficients associated with market potential.

3.6 Discussion

In this chapter the Lotka-Volterra formulation has been presented as a sort of conceptual model for interaction between three technologies, rather than as a model of a real case.

Lotka-Volterra models assume that while a technology grows, it diffuses into a larger market in which it might compete with other technologies. Different variables included in the equations represent this feature. Models created using Lotka-Volterra equations are not open to external forces. However, systems created by Lotka-Volterra assume that all of these forces are captured by the coefficients in the equation.

Hence, testing Lotka-Volterra model with a real case and data to determining which factors influence the coefficients is essential (Pistorius and Utterback 1995). This is not only useful for foresight, but it is also important for the firms to see how they can shift from one mode of interaction which put them in a prey situation, to another mode that make them compete with other technologies in the market.

To understand better this argument it would be helpful to observe the model presented in Figure 3.5 which is the model of predatory-prey interaction between rabbits and foxes. In that model the coefficients in Lotka-Volterra were interpreted as predation rate, birth rate, death rate and, even more complex and inter- related factors, fox birth rate. Hence the Lotka-Volterra coefficients translated into real factors and this enable, i.e. an ecologist, to use these factors to study the real dynamics between two species.

In the case of technology substitution we need such factors that can be used by, e.g., policy makers, and firms to pin point what factors can influence the growth and diffusion of an emerging technology.

Once we have those parameters we would be able to demonstrate and examine the market potential limited by market capacity in equations (11) and to use the model in studies of the real examples and cases.

In the next chapter diffusion of a technology will be modeled helping us to capture the real factors influence the coefficients used in the Lotka-Volterra equations

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Chapter 4. Technology diffusion model

As seen in chapter 3, dynamics between two or more technologies that interact with each other could result in different kinds of consequences such as lock out or bridging, phasing out, and diffusion of one or more of individual technologies. Moreover, coexistence of two or more technologies may occur. Those technologies might share different stocks such as stock of knowledge, values and physical infrastructures and have also benefit from the same micro dynamics. Interaction among these technologies can be modeled considering different assumptions regarding the micro dynamics. To have a better understanding of how the micro dynamics work, it is useful to study the micro-dynamics effecting diffusion of one technology.

In this chapter a formal model based on diffusion of one particular technology will be built using system dynamics. The model outlines some of the main dynamics generated by major factors involved in technology diffusion. The model includes the basic dynamics in the firms that produce the technology, and customers who adopt the technology. By combining these two sets of dynamics, the diffusion of a new technology will be modeled. It is expected that the result follows S-shaped growth pattern, where the growing population smoothly approaches equilibrium (Grübler 1997; Easingwood and Harrington 2002).

4.1 Technology diffusion feedback mechanisms

According to Sandén and Jonasson (2005), there are three main positive feedback loops driving the diffusion of a new technology (Figure 5.1). On the producer's side investment in the new technology increases the technology performance and lowers the cost of the technology through mechanisms such as economies of scale in production and learning by doing(Sandén and Azar 2005).

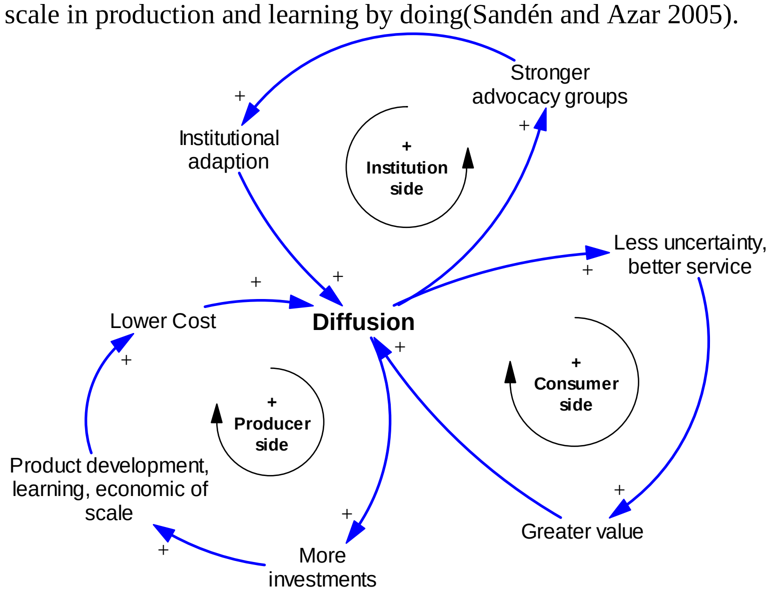


Figure 4.1 Positive feedback mechanisms involved in technology diffusion (Sandén and Jonasson 2005)

On the user's side growth in the adoption of technology will reduce the uncertainty of its merits and generate benefits for users by lowering their hesitation in adopting the new technology. Moreover, as technology being more adopted by the users they gain experience in using the technology and this eventually results in decreasing the uncertainties about the new technology. Hence, new technology provides users with a greater value and, consequently, encourage more users to adopt the technology

(Cowan 1991; Rosenberg 1995). Thus, as the technology diffuses into the market, users' attitude in favor of the technology will increase and it gains legitimacy (Bergek, Jacobsson et al. 2008; Jacobsson 2008).

As the technology diffuse, the advocacy groups increase in size as well as political strength and may influence the regulatory frame work in favor of the technology. As more adoption takes place, more institutional adaptation will occur (Sandén and Jonasson 2005).

This study is focused on modeling the technology diffusion and comprises the feedback mechanism in producers and consumers side. The model will be limited to these two feedback loops and the institutional loop is not considered in the qualitative and quantitative modeling.

The two feedback loops are developed in more detail in to a quantitative model of technology diffusion.

4.1.1 Feedback mechanisms on producer side

When a technology diffuses in to the market, there are several positive feedback mechanisms that contribute to its growth. In this study the main driving forces on the producer's side is considered to be "technological learning", which is a concept that assumes the decrease in unit production costs when the cumulative production increases (Arrow 1962).

Figure 4.2 illustrates three major feedback mechanisms that have been used for modeling the diffusion of the technology in this study.

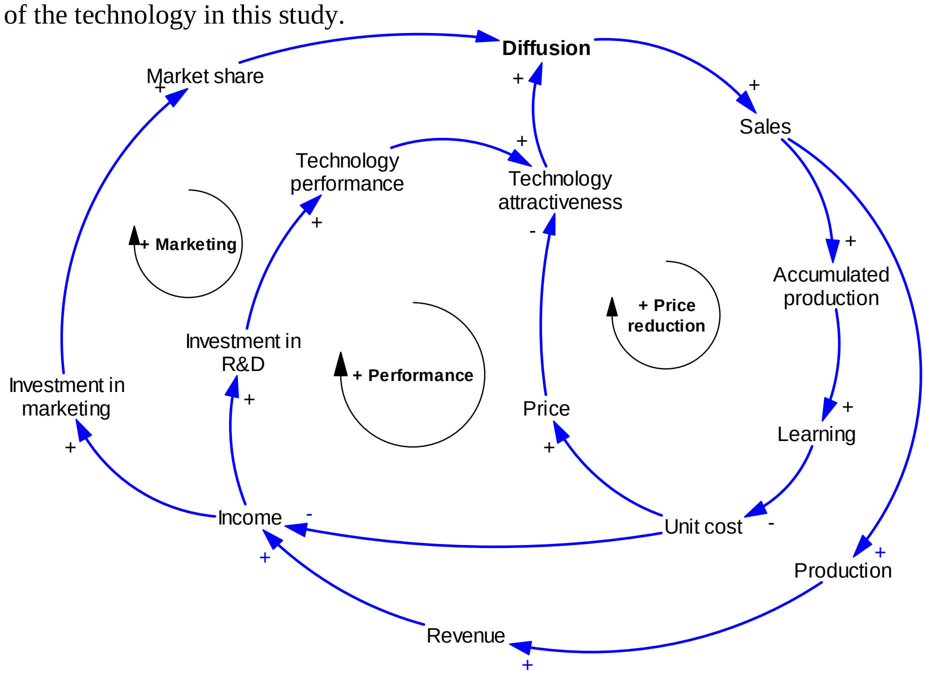


Figure 4.2 Positive feedback mechanisms on the producer's side

The first loop indicated as "price reduction" refers to when the production increases, the repetition of manufacturing tasks, which is measured as cumulative production, will increase and improve the production methods. This process is known as *learning-by-doing* (Arrow 1962). Labor's efficiency is increased by repeating the manufacturing process, or as the accumulated production of the technology increases. Additionally, new improved processes will be adopted and it changes the production methods as well as the administrative structure of the organization (Rosen 1972; Bodde 1976; Hall and Howell 1985). Hence more accumulated production leads to lowering the cost of the production and by lowering the cost, the price of the technology can decrease. Thus, eventually better price of the technology attracts more users to adopt the technology (Dhar 1997).

The second loop addresses another concept known as *learning-by-researching* that consider the research and development (R&D) as a learning mechanism that lets firms to indentify and develop the knowledge in its environment (Cohen and Levinthal 1989). Learning-by-researching represents the improvements related to the innovation process, i.e. technology performance, and the capacity of the firm to develop those processes. This mechanism is illustrated in the causal diagram shown in figure 4.2 by the loop denoted "performance". It shows that when the production increases, revenue of the firm will increase and at the same time the cost of the production will decrease. This contributes positively to the income of the firm and consequently this increase the ability of the firm to make more investment. As the firm's investment on R&D increases, the technology performance improves, and the uncertainties around the technology will be reduced. Hence, the technology gain more competitive advantage in the market and attract more of the potential adopters (Arthur 1989).

Moreover, as income of the firms increases, larger investment on marketing can take place which represents an important potential source of firms' competitive advantage (Foxall 1988; Otter, Kao et al. 2007). More investment in marketing, either on direct expenditure or increasing the marketing efficiency e.g. by education, increases firms' chance to be recognized by the potential adopters. Thus technology's advantages can be recognized by the potential adopters and eventually can lead to more adoption and reinforce the diffusion process.

In describing the technological learning, other scholars considered other mechanism such as learning-by-using, learning-by-interacting and economies of scale as driving forces in decreasing the cost of technology for each doubling of cumulative production (Grübler and Messner 1998; Junginger, Faaij et al. 2005; Junginger, de Visser et al. 2006). However in this study, the causal diagram shown in figure 4.2 is considered to grasp the dynamics of technological learning and other positive feedback mechanisms in the producer side.

4.1.2 Feedback mechanism on the consumer's side

According to Sandén and Jonasson (2005) and Arthur (1989), when new technology diffuses into the market, it generates benefits for users by lowering their hesitation in adopting it. As much as these uncertainties are being reduced, the technology, that now provides the consumer with a better service, gain attractiveness among users.

Technology attractiveness in this model can be interpreted as a link between consumers and producers of the technology. In one hand, by lowering the price and enhance the technology performance, firm will increase the technology attractiveness. On the other hand, as technology attractiveness increases, the consumers tend to adopt the technology and contribute to the diffusion of the technology.

One way to continue studying the positive feedback could be by studying the factors and dynamics that increase the attractiveness of the technology. However, in this study a model that examines how the technology spreads into a market is made. Figure 4.3 illustrates the extended description of the positive feedback mechanism on consumer side.

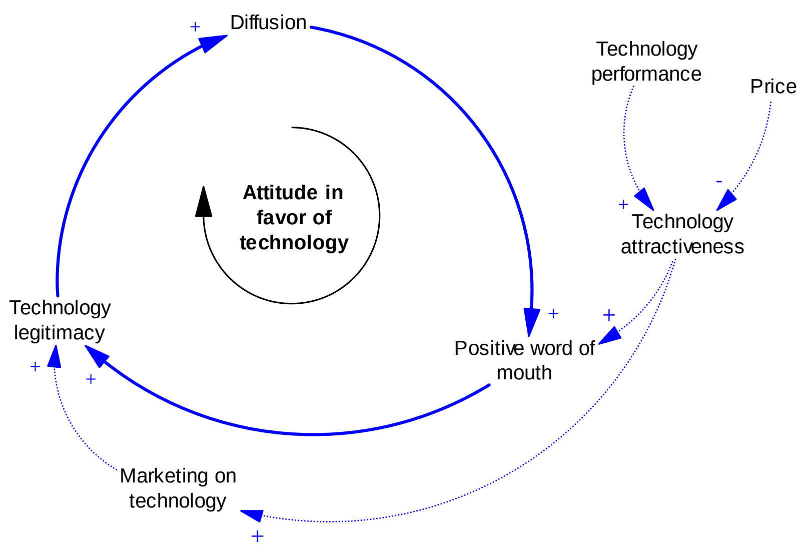


Figure 4.3 Extended feedback loops in consumer's side

In this study, it is assumed that the causal diagram shown in figure 4.3 captures the main driving forces generated by consumers in diffusion of technology. This driving force is considered to be their attitude in favor of the technology which will increase as technology legitimacy increases. Marketing and positive word of mouth are considered as actors that contribute to stock of legitimacy of technology by spreading the knowledge and familiarity about the technology. Word of mouth and marketing stimulate the awareness about technology and increase technology legitimacy and adoption. More diffusion increases the number of users of the technology and hence, increases the probability of contact between a user and non-user of technology or, in other word, generates more positive word of mouth. Moreover diffusion growth brings more sales and more turnover, which lead to more marketing investment and eventually more familiarity with the new technology (Struben and Sterman 2007).

The driving force that governs the diffusion of the technology in this model comes from the consumer's side. However, as it can be seen in the figures 4.2 and 4.3, the producers performance stimulate the technology attractiveness consequently triggers the positive word of mouth and diffusion. In the next section, in order to quantify the dynamics of the diffusion, a stock and flow model will be built and simulated based on the implication of causal loops illustrated in this section.

4.2 Quantitative model of technology diffusion

The modeling initially starts by considering the dynamics on producer side, and at the end the stocks and flows regarding the customer's side will be added to the model. Moreover, in order to have a more lucid understanding of the modeling process, the model has been divided into nine sub-models which will be discussed separately in this chapter:

- Market adoption
- Technology learning curve
- Cost of technology
- Price of technology
- Income and investment

- Firm's marketing performance improvement
- technology performance improvement
- Technology attractiveness
- consumer's attitude and technology legitimacy

In order to combine both groups of stock and flows, market adaptation model will be modified as the other part of the model being constructed. The modified result of the complete model will be presented in the last part of this chapter.

4.2.1 Market adoption

As been discussed qualitatively, the customer's attitude towards technology provides a main driving force for diffusion of technology. For simplicity, the modeling of the diffusion will start by having a "contagion" view of adoption. The basic idea is that the potential adopters of the technology catch the desire of purchasing the new product from those who have already purchased the product.

No matter what advantage the new innovation has, technology are not adopted by potential adopters right away and adoption is a process that occurs over time (Norton and Bass 1987; Rogers 1995). Thus the adoption rate depends on following factors (Bass 1969; Geroski 2000; Sterman 2000):

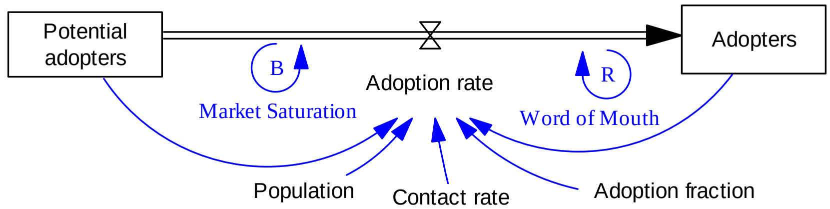
- Number of adopters who have already purchased the product
- Number of potential adopters
- How effective the adopters are in presenting the virtues of the product
- How often adopters meet with the potential adopters

This can be viewed as predatory-prey situation, where those who already have adopted the new technology are predators on the potential adopters (prey), and try to push them to buy the new product.[4]However, the more neutral term for this type of model can be interpreted as "word of mouth", which implies that, positive word of mouth from happy adopters leads the potential adopters to make a purchase.

Assume that there is a total population of N in the market and the total number of potential adopters N_p is equal to N less N_a, where N_a is the number of adopters of the technology.

Further assume that, contact rate R_w is the rate at which active adopter comes into contact with potential adopters. Also A_f represents the adoption fraction which is the fraction of times a contact between an active adopter and a potential adopter results in adoption. This can also be interpreted as how effective the adopters are in presenting the good features of the new technology. Figure 4.4 shows the stock and flow of the basic model of market diffusion driven by adoption rate.

[4] You may prefer thinking of those who have purchased the product (adopters) as zombies who attempt to convert the potential adopters into the zombie-like state of being actual adopters of the product.



Variable	Notation	Unit
Potential adopters	N_p	Households
Adopters	N_a	Households
Population	N	Households
Adoption rate	R_a	Households/year
Contact rate	R_c	1/year
Adoption fraction	A_f	Dimensionless
Initial cumulative adopter	N_{a0}	Households

Figure 4.4 Adoption of a technology into a market through word of mouth

Table in each figure represents the denotation and unit associated to each variable in the system diagram. These denotations are used in demonstrating the mathematical and algebraic relation between the variables. The equivalent equation for the above described model is:

$$N_a = N_{a0} + \int R_a \cdot dt$$

$$N_p = N - N_a$$

$$R_a = N_a \times A_f \times R_c \times N_p / N$$

Where, N_a and N_p represent number of adopters and potential adopters respectively. R_a is adoption rate that is the rate per year, at which a potential adopter becomes an active adopter; N is total population of the market. A_f and R_c stand for adoption fraction and contact rate respectively. N_{a0} is the initial number of adopters of the technology. The total population of the market (N) has been considered as constant and is the sum of the number of potential adopters (N_p) and adopters (N_a) of the technology.

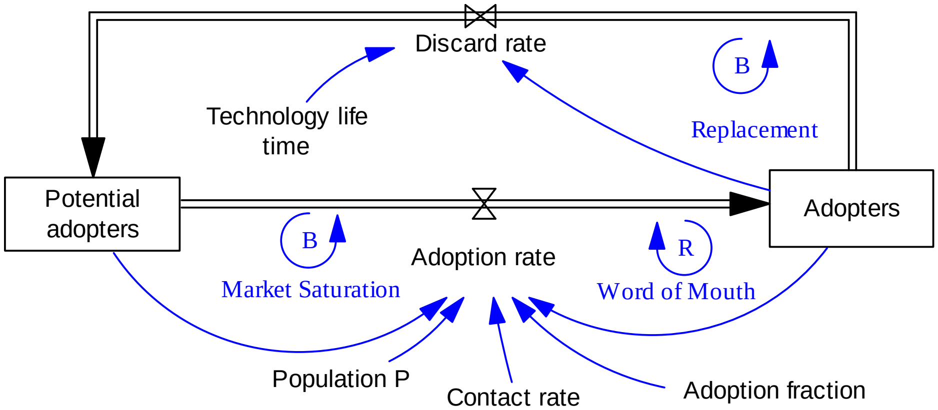
Considering the formulations and the model of diffusion, there are two major loops in this model. A reinforcing loop, which contribute to the diffusion of the technology and correspond to the positive feed back loop generate by word of mouth; and a balancing loop, which inhibits the diffusion of the technology, controlled by the limited population and known as market saturation[5].

This model is described as a first-purchase model because it does not capture situations where the products of the new technology is consumed, discarded, or improve, all of which they lead to repeat the adoption. A simple way to capture the re-purchase of the product is to assume that adopters, who have already discarded the product, move back to the potential adopters stock. In this case the rate at which the product is discarded and, hence the rate at which adopter move back to the stock of potential

[5] Up to this point, one can compare these loops by the dynamics presented in logistics growth part of the Lotka-Volterra differential equations. It can be observed how market saturation and word of mouth loops, presented in this model, correspond to coefficients a and b in the Lotka-Volterra differential equations.

adopters, depends on the number of adopters and the average technology life time (Sterman 2000). Thus product with longer technology life time is discarded later and visa versa.

The following stock and flow represents the diffusion considering the replacement of the product.



Variable	Notation	Unit
Discard rate	R_d	Households/year
Technology life time	T_f	year

Figure 4.5 Model of adoption of a technology into a market considering replacement loop

Considering the discarded product, the stock of potential adopters always contains some fraction of the population that can influence the adoption rate of the product. Since the discarded products are coming back to the pool of potential adopters, they are going to be treated exactly as the first-time purchase of the product. This implies that they have to become aware and being persuaded by adopters, yet again, to buy the product. The replacement loop, like the market saturation, is a balancing loop depending on the technology life time. It is a negative feedback loop obviously because as much as the technology life time is less, the amount of discarded product is more per time. The modified equations of the adoption considering the replacement loop are as follows:

$$N_a = N_{a0} + \int (R_a - R_d) \cdot dt$$

$$N_p = N - N_a$$

$$R_d = N_a / T_f$$

R_d and R_a are discard rate and adoption rate respectively and T_f is the life time of the product. In this model, a first-order discarding process is considered that can, however, be modified to represent other kinds of distribution of discarding rates around the average product life time.

Figure 4.6 shows a graph representing the diffusion of the technology considering different values for contact rate, as well as, the adoption rate of the technology considering different values for technology life time. Population is considered to be 100 million households in the market.

a) b)

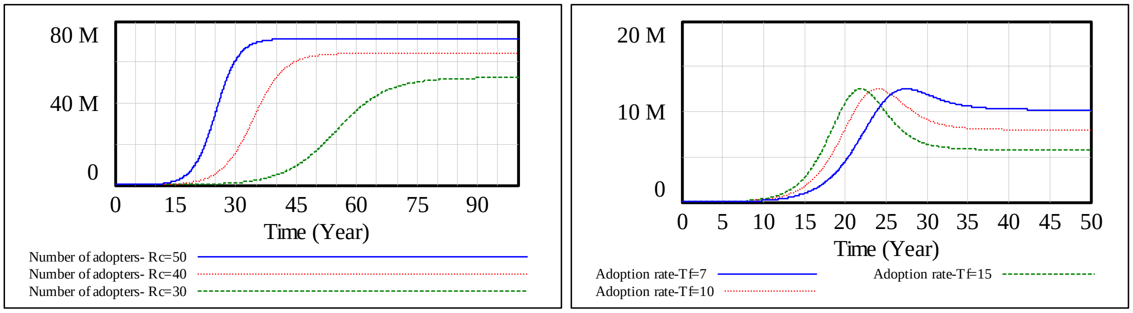


Figure 4.6 Time dominant plot of a) number of adopters (N_a) considering different contact rates, and b) adoption rate considering different values for technology life-time (T_f)

As it can be seen, the adoption pattern followed an S-curve as is expected, and adoption rate, which address the amount of product being adopted per time, has been sustained to a constant value. As the contact rate increases the speed of diffusion also increases and the total number of adopters will also increase. Also, depending on the technology life time, the behavior of adoption rate, which also corresponds to the amount of production of the firm's per year, will differ.

4.2.2 Technology learning curve

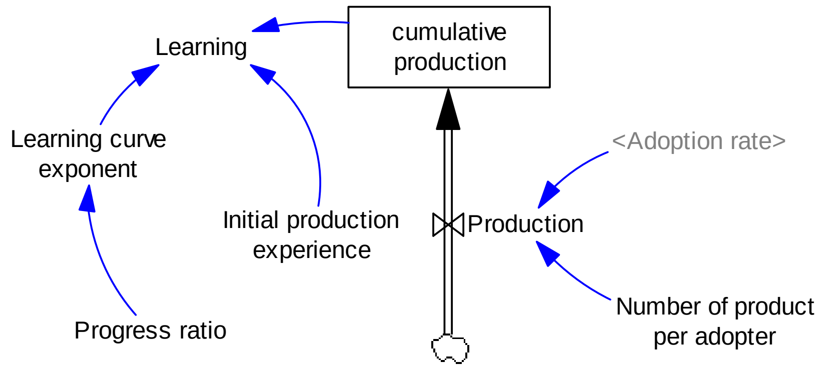
As discussed above, the unit cost of new technologies falls over time as experience, gained by production, increases. Since technological learning depends on the accumulation of experience and not just on the course of time, it is measured as a function of cumulative production of technology (Grübler and Messner 1998). Hence, in a manufacturing setting, cumulative experience is usually substituted by cumulative production. In this part, the modeling aiming to make the technological learning as an endogenous part of the model structure by incorporating the learning curve. Hence, in this part the effect of technology learning on the cost is merely modeled and in the next section of this chapter it will be incorporated with the cost and price of the technology.

As seen in last section, the number of households adopting the technology per time is calculated as "adoption rate". Considering the number of units of product per household, the amount of production per time and cumulative production can be calculated as follows:

$$\delta_P = q \times R_a$$

$$Q = Q_i + \int \delta_P \cdot dt$$

In these equations δ_P is the amount of production per time, q is the number of product per household, R_a is the adoption rate, Q is the cumulative production and Q_i is the initial production experience. Figure 4.7 represents the building blocks of technological learning and notations associated with it.



Variable	Notation	Unit
Production	δ_Q	Unit/year
Number of product per adopter	q	Unit/households
Cumulative production	Q	Unit
Learning curve exponent	S_L	Dimensionless
Initial production experience	Q_i	
Learning	L_c	Dimensionless
Progress ratio	ε_c	Dimensionless

Figure 4.7 Building blocks produce technology learning curve

Technology learning curve formulation is (Junginger, Faaij et al. 2005; Kahouli-Brahmi 2008):

$$L_c = \left(\frac{Q}{Q_i}\right)^{S_L}$$

Where L_c is a learning index that captures the effect of technology learning on cost, Q is cumulative production, Q_i is initial production experience, and S_L is the learning exponent, which itself is calculated as:

$$S_L = \frac{Ln(\varepsilon_c)}{Ln(2)}$$

Where ε_c is the progress ratio associated with the technology, which basically designates the strength of learning in reducing the cost. The exponent S_L in the learning curve equation determines how strong the learning curve is in reduction of cost per each doubling of production, which should be negative. This is because costs fall as cumulative production grows. As an example, to represent a learning curve in which costs fall by 20% for each doubling of experience, S_L is calculated as:

$$S_L = \frac{Ln(0.8)}{Ln(2)} = -0.32$$

Figure 4.8 shows the effect of technology learning on cost of technology considering different progress ratios. The numbers considered for the different variables are also shown in table 4.1.

Variable	Description	Quantity	Unit
Qa	Number of product per adopter	1	Unit/household
Qi	Initial production experience	$1X10^6$	Units

Table 4.1 values of exogenous variables used in simulating the learning curve

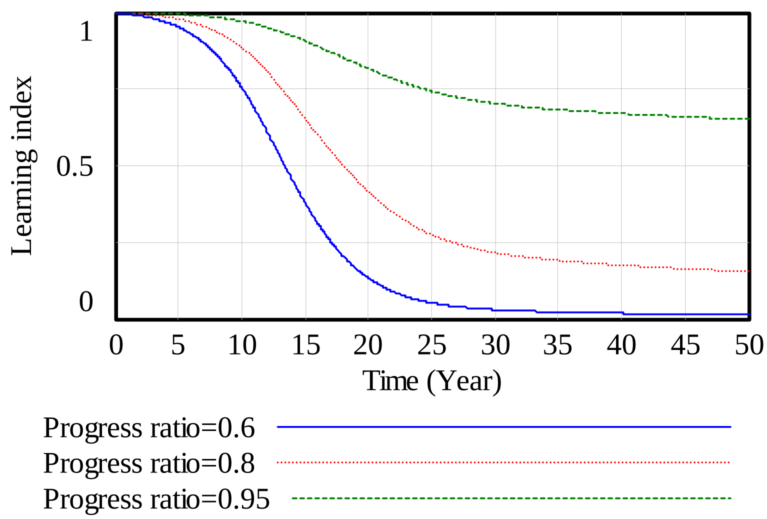


Figure 4.8 Technology learning curve considering different values for learning strength factor (ε_c)

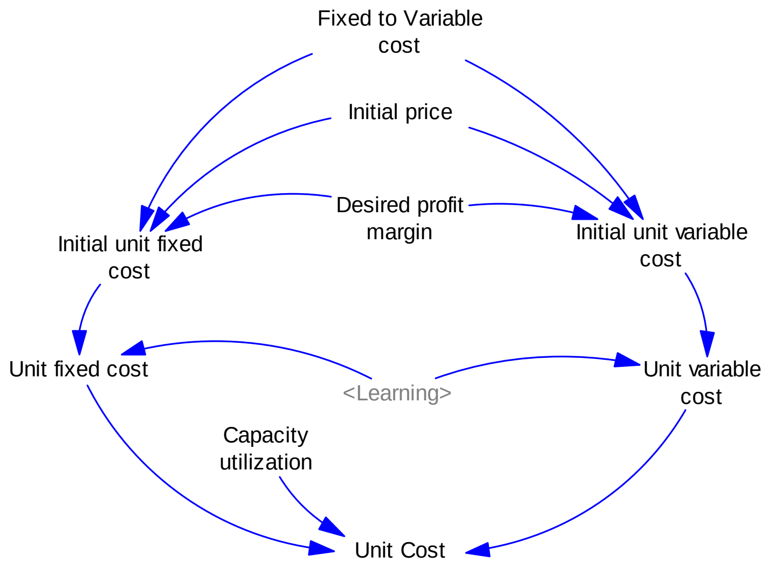
As it can be observed from figure 4.8 as time passes, cumulative production increases and the effect of learning in decreasing the cost will be amplified considering different progress ratios. By incorporating technology learning and costs for production of technology, the dynamics of the costs can be calculated. In the next section the learning curve calculated here will be integrated with the cost of production of technology.

4.2.3 Cost of technology

In economics and cost accounting, the total cost of a product describes the total economic costs of production and is made up of “variable costs” and “fixed costs”. “Variable costs” are costs that change proportionally to the business activity and the amount of production. It can be calculated by help of manufacturing and engineering analysis of the production facility and administrative departments. On the other hand, “fixed cost” is the portion of total cost of the production that does not change in the course of activity of the firm and is independent of the firm’s amount of production. For example cost of the production facilities and rent are irrespective of the firm’s sales or production, therefore they are referred as fixed costs. On contrary, the cost of raw material and energy use in course of production are variable costs (Fields 2002).

In this model, both fixed and variable costs are considered in calculation of the total cost of the product. This aims to a better understanding of the impact of both kinds of costs on the diffusion of the technology in a competitive market. Variable costs can simply be calculated from the amount of production and always considered by managers as a rough estimation of total costs in decision-making processes. However fixed costs, which are always independent of the volume of output and sales of the firm, are usually overlooked, although they are often more important, quantitatively. Evermore, in a competitive market a product can only survive if it produces revenues that can cover both fixed and variable costs associated with its production. Hence, the study of fixed and variable cost is vital in firm’s decision making processes (Spence 1976; Pinkse, Slade et al. 2002; Sterman, Henderson et al. 2006).

The System Dynamics building block of cost calculation is shown in figure 4.9.



Variable	**Notation**	**Unit**
Fixed to variable cost	γ	Dimensionless
Initial price	P_i	$/unit
Initial fixed cost	C_{fi}	$/unit
Initial variable cost	C_{vi}	$/unit
Unit fixed cost	C_{fu}	$/unit
Unit variable cost	C_{vu}	$/unit
Unit cost	C_u	$/unit
Capacity utilization	λ	Dimensionless
Desired profit margin	μ_d	Dimensionless

Figure 4.9 Building blocks of cost calculation

Cost of technology, in this model, is determined by a user specific price of the product that is called "initial price". A ratio of fixed-to-variable costs is considered in order to be able to apply different scenarios considering different ratio of fixed to variable costs. Also having the fixed to variable cost ratio as an exogenous variable in the model, enable the modeler to produce different simulations by changing this variable, depending on different circumstances. The initial cost of the product is further adjusted by desired profit margin, which is the amount of markup a company considers on its price. Additionally, the technology learning, determined in last section, is applied to the cost calculation in order to determine the unit cost of technology. Eventually the unit cost of the product adjusted by firm's capacity utilization that is the ratio, determines the degree up to which the firm uses its installed productive capacity, so it refers to the level of actual output and potential output of the firm.

Potential output is the maximum performance of the firm while using its full capacity (Corrado and Mattey 1997). As the capacity utilization of a firm increases, the cost of the product declines since capacity utilization influences unit fixed cost (Nelson 1989; Puty 2005).

Hence, the formulation of the Unit cost of the product, in this model, considered as:

$$C_{vi} = \left(\frac{P_i}{1+\mu_d}\right) \times \left(\frac{1}{1+\gamma}\right)$$

$$C_{fi} = \left(\frac{P_i}{1+\mu_d}\right) \times \left(\frac{\gamma}{1+\gamma}\right)$$

$$C_{vu} = C_{vi} \times L_c$$

$$C_{fu} = C_{fi} \times L_c$$

$$C_u = C_{vu} + {C_{fu}}/{\lambda}$$

Where P_i is the initial price of the product, μ_d is the desired profit margin of the firm, and γ and λ are fixed to variable cost ratio and capacity utilization ratio, respectively. C_{vi} is initial variable cost, C_{fi} is initial fixed cost, C_{vu} is unit variable cost, C_{fu} is unit fixed cost, and L_c is technology learning. C_u represents the cost of the product.

Figure 4.10 shows how unit cast varies by different amount of capacity utilization ration.

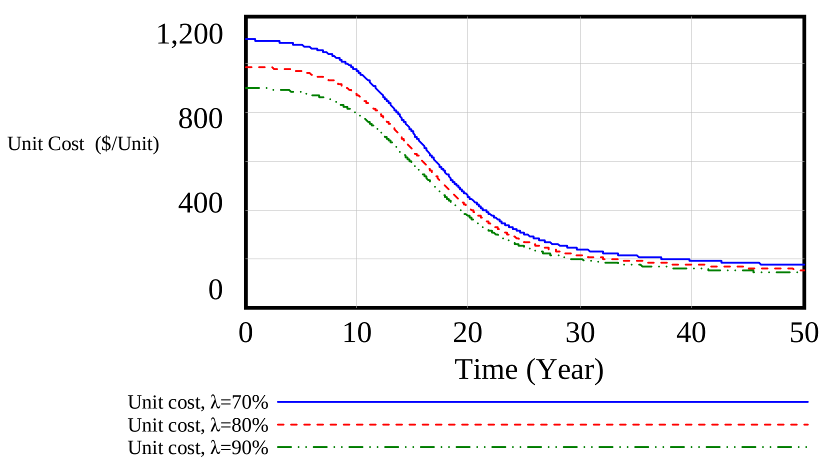


Figure 4.10 Time dominant plot of unit cost Cu, considering different capacity utilization ratios

As can be seen from figure 4.10 as capacity utilization increases, the unit cost of the product decrease, since firm utilizes more of its facility to have a larger amount of productivity.

4.2.4 Price of the technology

Having the cost of the technology calculated, and considering the desired profit margin, the price of the technology can be calculated. This price is called "cost price" in this model, which refers to the price which is determined by the amount of the technology unit cost regulated by desired profit margin.

However in the real word, particularly when technology is competing in a market, firms continually have to adjust their current price to the "target price" in order to be more competitive in the market, since price has a rigid positive relation with the profitability and survival of the firm (Blattberg and Wisniewski 1989; Besanko, Dubé et al. 2003).

Target price of the technology is dependant on different factors, i.e. market share, demand-supply curve, the cost of the technology, and etc. Boulding and Staelin (1990) introduced six different factors that might influence a firm's ability to put a higher price on the product or reduce the cost of the product. These six factors are: power over suppliers, power over buyer, lack of competitive rivalry, lack of threat of competitive entry, market position, and firms' factor.

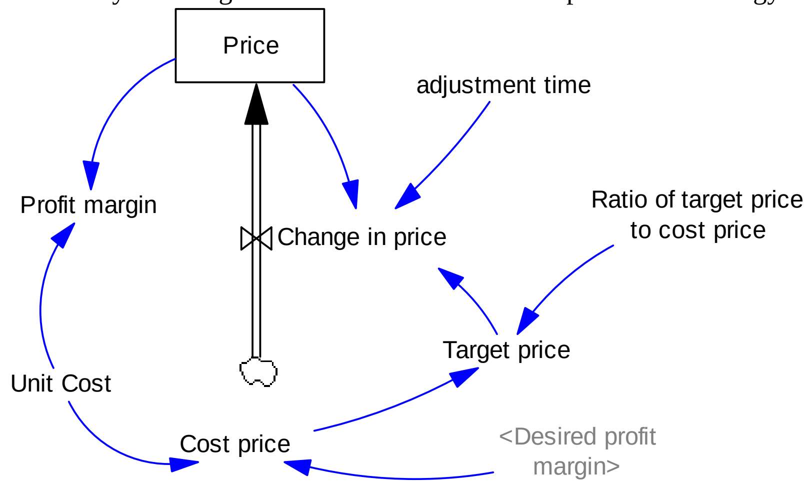
Firm's factors such as the production quality, high quality advertising or even firm's "good luck" also lead to firm's putting higher price on its products. (Blattberg and Wisniewski 1989; Boulding and Staelin 1990).

These factors can be described also as different positive feedback mechanism and be considered in the model. There are already a number of mathematical and economical models available that deal with these factors, which can be implemented in a price model. For example Mieghem and Dada (1999) presented two stage decision making model where firms make decision on capacity investments, production quantity, and price. Moreover, the relation between demand, supply and price and consideration of demand-supply curve in firm's strategic decision making processes is also discussed by different authors (Rose 1952).

In this model, an exogenous variable "ratio of target price-to-cost price" is introduced which consist of the aggregation of all factors discussed above that influence the target price of the product. This ratio can be set as a percentage above or below the cost price.

Additionally, the timing of making decision to adjust the price to the target price plays and important role in the firm's decision making processes(Mieghem and Dada 1999). Hence, the time taken that firms adjust the price of the product on to the target level, which generally is due to the administrative and decision making lags in the firm, is introduced to the model as "adjustment time".

Figure 4.11 shows the system diagram used in calculation of the price of technology.



Variable	**Notation**	**Unit**
Ratio of target price to cost price	θ	Dimensionless
Target price	P_t	$/unit
Cost price	P_c	$/unit
Adjustment time	T_a	year
Change in price	δ_p	$/(unit*year)
Price	P	$/unit
Profit margin	μ	Dimensionless

Figure 4.11 Building blocks of price calculation

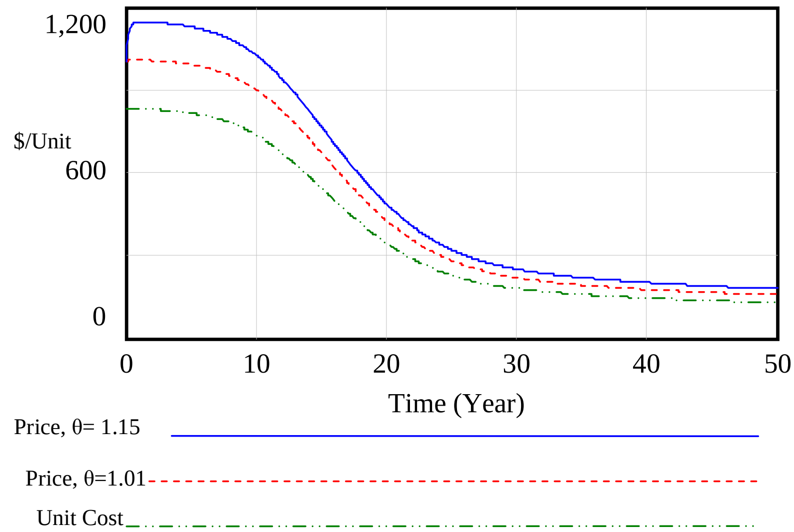
The relations between Price P, Target price P_t, Cost price P_c, and Unit cost C_u are as follows:

$$P_c = (1 + \mu_d) \times C_u$$
$$P_t = P_c \times \theta$$
$$\delta_P = \frac{dP}{dt} = \frac{P_t - P_c}{T_a}$$
$$P = P_i + \int \delta_p \cdot dt$$

Where μ_d is the desired profit margin which is the normal markup considered by the firm, P_c, P_t, and P, are the cost price, target price and price of the technology, respectively. θ is the ratio of the target price to cost price. T_a and δ_p are the adjustment time and change in price over time, respectively.

Figure 4.12, graph (a) shows the cost and price dynamics considering two ratio of target price to cost price θ=1.01 and θ=1.15, with adjustment time T_a = 0.25 year, and desired profit margin μ_d = 20%. In addition, graph (b) shows the price of the technology considering two adjustment time T_a = 0.25 year, T_a = 1.5 year, and two ratios of target price to cost price θ= 1.15 (higher target price) and θ= 0.9 (lower target price).

a)



b)

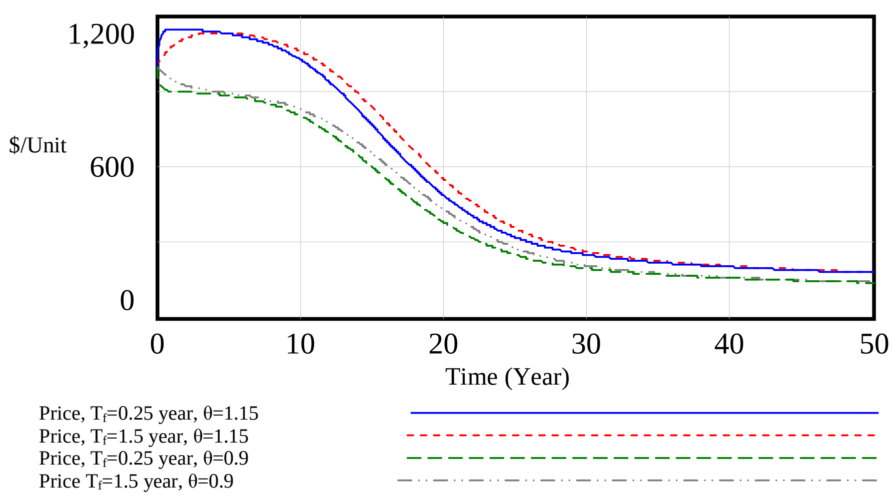


Figure 4.12 a) Time dominant graph of cost and price of the new technology considering θ=1.01, θ=1.15 Ta=0.25 year, and μ_d = 20%. b) Time dominant graph of price of the new technology considering θ=1.15 and θ= 0.9 and μ_d = 20% and two different adjustment times Ta=0.25 year and Ta=1.5 year.

As it can be seen in graph (a) the difference between unit cost and price of the technology, which corresponds to the mark up associated with one unit of product, varies over time. This can also be interpreted as the positive relation between price of the technology and firm profitability. Firm profitability has a positive relation with price, and on the other hand cost of technology generates negative effect on price and balances the profitability. Hence the amount of profit made by firms varies over time.

Moreover, the price of the technology is not just proportional to desired profit margin, but also with the target price of the technology considering market share, firm's capacity, and etc, which have been discussed previously (Sterman, Henderson et al. 2006). For instance, as the firm market power increases due to i.e. increment in market share, the firm's ability to adjust its annual market price will increase due to the new target price and consequently it brings higher profitability for the firm[6]. This behavior of the firms in adjusting their target price with the market share has been discussed also by Buzzell and Gale (Buzzell and Gale 1987).

Graph (b) describes the responding behavior of the firm to the new target price due to the new conditions in the market. Managers of the firm adjust the price to target price in response to different pressure or opportunities that might arise in the market. As already discussed, these opportunities could be any of the factors which presented by Boulding and Staelin (1990) and on the other hand, the pressure could arise from i.e. unit costs, demand-supply balance, or lost market share due to the competition. More particularly, firms increase the price over the current level when unit costs increase, there is excess capacity of production, and when market share grows (Sterman, Henderson et al. 2006). They will cut the price when unit costs fall, production reach the capacity level, and when market share falls below its current level (Sterman, Henderson et al. 2006). However, the time that firms adjust its price to the target price can generate different behavior which is shown in this graph.

Moving forward, by having the unit price and unit cost calculated, profit margin (μ), which is the actual markup of the firm through selling the new technology and indicate the firm's profitability, can be calculated as:

$$\mu = \left(\frac{P}{C_u}\right) - 1$$

Figure 4.13 shows the actual profit margin of the firm regarding the new technology.

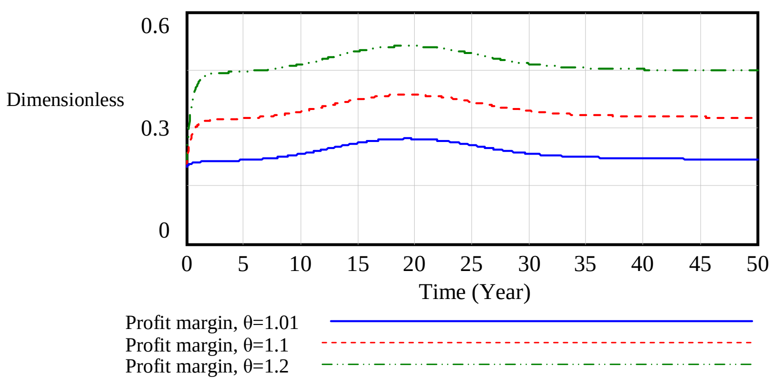


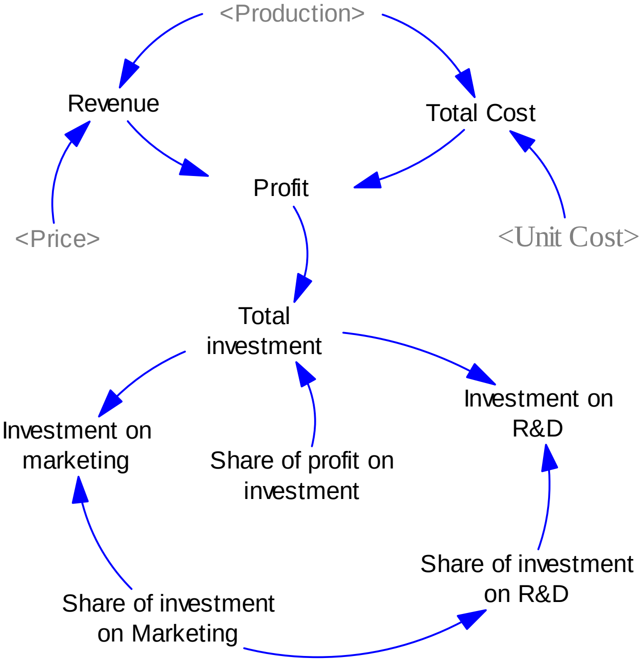
Figure 4.13 Profit margin of the firm considering different value for α

As it can be seen in figure 4.13 and as discussed earlier, the increment of the amount of the target price influences positively on the profit margin of the new technology.

[6] You can compare different prices shown in graph (a) considering different ratios of target price to cost price. The higher ratio could correspond to more power of different factors that allow firm to set a higher price on its product which has already been described in this chapter. For relation between market share and firm's profitability please see Boulding, W. and R. Staelin (1990). Environment, Market Share, and Market Power, INFORMS. **36:** 1160-1177.

4.2.5 Income and investment

Firm's income is the firm's revenue, R, take away firm's total cost. Figure 4.14 Shows the building blocks used in calculation of firms' income and investments.



Variable	**Notation**	**Unit**
Revenue	ρ	$/year
Total cost	κ	$/year
Profit	π	$/year
Total investment	I	$/year
Investment in marketing	I_m	$/year
Investment in R&D	I_r	$/year
Share of profit in investment	β	Dimensionless
Share of investment in marketing	β_m	Dimensionless
Share of investment in R&D	β_r	Dimensionless

Figure 4.14 System diagram for calculation of firm's net income and investment

The following equations are used in calculation of the firm's profit:

$$\pi = \rho - \kappa$$
$$\rho = \delta_p \times P$$
$$\kappa = \delta_p \times C_u$$

Where, π, ρ, and κ are firm's profit, revenue, and total costs per year, respectively.

Firms' income increases its aptitude on doing investment leading to gain power in the market. There are several varieties of opportunities that a firm can invest in, in order to get more share of market and enhance its products performance. As discussed earlier in this chapter, firms can invest i.e. on capacity building in order to have excess capacity, which enable the firm to increase the price, and consequently, increase the profit gained from selling its product. In addition, the positive relation between R&D, firm's productivity, and rate of return on investment, has been discussed by different scholars (Mansfield 1965; Minasian 1969) .On the other hand, the integration of R&D and marketing is a key concern for the firms that want to enlarge their market share(Leenders and Wierenga 2001). In this study, the impact of investment on marketing and R&D, on diffusion of the technology as well as on other factors involved in adoption, is going to be modeled.

As firms invest on R&D, they expand their capability to enhance their performance in the future. Moreover, current expenditure on R&D will increase the firm's profit, earnings, and operating performance in the future (Lev and Sougiannis 1996; Eberhart, Maxwell et al. 2004). Also empirical research has been done addressing that firm's increase in R&D expenditure is associated with its excess profit(Chan, Lakonishok et al. 2001; Chambers, Jennings et al. 2002). On the other hand, additional investment on marketing via advertisement, mass media, etc, have a large influence on the current market performance of the firm and positively influences the success of new products (Ofek and Sarvary 2003). Hence, by assigning a share of the company's investment on R&D and marketing, firm's can pave the way of launching the product success within the market, and gain market power via e.g. expanded market share and enhanced product quality. The integration of marketing and R&D in firms is a major concern when aiming to take advantage of future product generations (Ofek and Sarvary 2003).

In this model, a share of profit is considered for total investments of the firm. These total investments include all the firm's various investments in e.g. capacity building, marketing, R&D. Also it is assumed that 50% of the total investment goes to be spent in marketing and R&D collectively. By allocating resources and expenditure on marketing, the effectiveness of marketing expected to increase, and so the market shares of the new technology. Conversely, by investing on R&D, firm's performance in manufacturing of the new technology is expected to be improved as well as technology performance, through knowledge sharing, and knowledge development (Kirpalani and Macintosh 1980).

The dynamics of the allocation the investment to marketing and R&D is formulated as follows:

$$I = \pi \times \beta$$
$$I_r = I \times \beta_r$$
$$I_m = I \times \beta_m$$
$$\beta_r = 0.5 - \beta_m$$
$$0 \le \beta \le 1$$
$$0 \le \beta_m \le 0.5$$

Where, I, I_r, and I_m are total investment, investment on R&D, and investment on marketing, respectively. Exogenous variables β, β_r, and β_m are share of income on investment, Share of investment on R&D, and Share of investment on marketing.

Figure 4.15 shows a time dominant graph of firm's annual cost, revenue, and income (profit) in addition to different share of investments by firm[7].

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[7] Graphs shown in figure 5.15 describe firm's income on a quite long prospect. However, in the long run this can be influence by exogenous factors such as net present value, external funding, Regulations, and etc. These factors can be further added to the model adjusting the income of the firm in order to generate a more realistic trend.

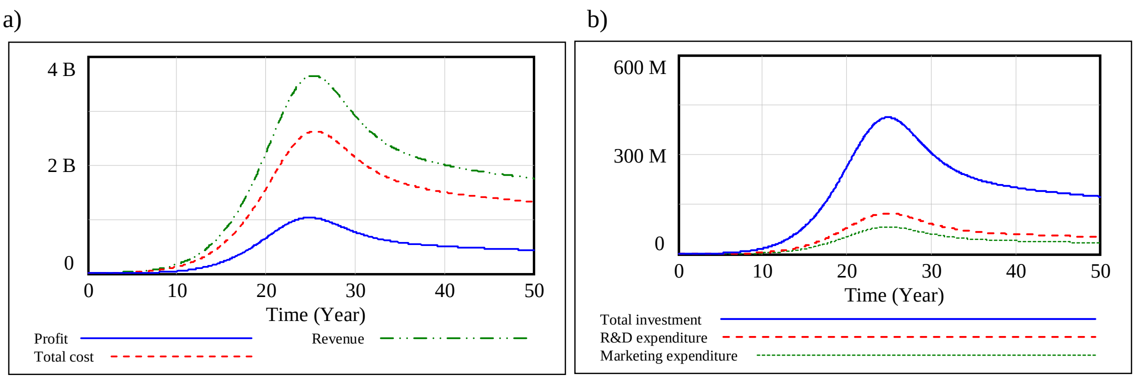


Figure 4.15 a) Firm's total cost, revenue, and profit considering θ=1.1 and T_f=0.75 b) Firm's total investment, investment on marketing, and investment on R&D considering β=0.4, and β_m =0.2

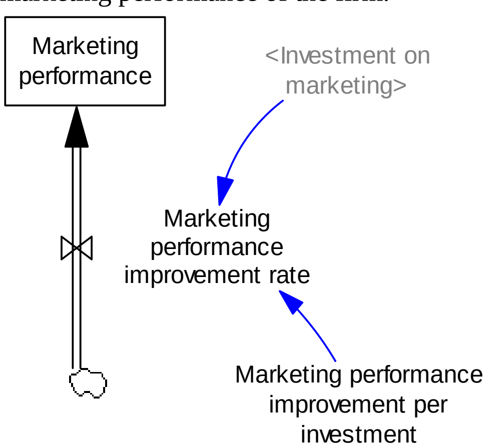
4.2.6 Firm's marketing performance improvement

As it is discussed, marketing is a means of maximizing return on investment which is a very important factor for a firm producing the new technology to endure and uncover adequate amount of market share. Through marketing, firms increase their profit by responding to individual demands and attracting new customers of the technology, which consequently lead to increase in sales and revenue (Otter, Kao et al. 2007).

In this model, firm's ability for marketing (marketing performance) is merely related to the amount of investment on marketing and more investment by firms in marketing will increase its ability in attracting more customers. Thus, other factors influence on marketing performance of the firm i.e. human resource factor, has not been considered in this model.

Therefore, by introducing an exogenous variable, as "marketing performance improvement per investment", the impact of investment on rate of marketing performance is introduced in the model. Afterwards, the rate that marketing performance is being improved by increase in amount of investment is added to the model. Eventually, the amount of marketing performance, as the level of the stock of marketing performance per time, is premeditated.

Figure 4.16 shows the system diagram of the rational relation between Investment on marketing and marketing performance of the firm.



Variable	Notation	Unit
Marketing performance improvement per investment	η_m	1/$
Marketing performance improvement rate	δ_m	1/year
Marketing performance	M	Dimensionless

Figure 4.16 System diagram of relation between investment and marketing performance

There is following relation between different factors influencing marketing performance:

$$\delta_M = \eta_m \times I_m$$
$$M = \int \delta_M \cdot dt$$

Where M, δ_m, and η_m are marketing performance, marketing performance improvement rate, and marketing performance improvement per investment, respectively.

Hence, as the investment on marketing increases, marketing performance of the technology will increase linearly too.

4.2.7 Technology performance improvement

Up to now, in this model firms allocate economic resource on marketing and R&D in order to gain more power in the market through enhancing the marketing performance plus the technology quality and performance (Leenders and Wierenga 2001).The model suggested in this section is a simple formal model, assuming the investment on R&D would directly influence the technology performance via knowledge accumulation. Hence, other factors influencing the knowledge accumulation, i.e. training and knowledge spill over from other firms are set aside from the model.

The modeling starts by considering the fact that, knowledge accumulation at the firm level can be determined by the amount of R&D investment of the firm(Cassidy, Görg et al. 2005). Thus, the rate of growth in knowledge accumulation is regulated by investment, and the amount of increment in knowledge per investment.

This approach in investigating the impact of R&D in knowledge accumulation, leading to positive impact on technology diffusion, can be compared with the impact of learning-by-doing that has already been discussed in this chapter. However, learning by doing demonstrate a bottom-up modeling approach in studying the endogenous dynamic of technical change, where in top-down models introduce the notion of "stock of knowledge" which accumulated over time via R&D investments[8]. Hence, knowledge accumulation could be occur from both learning-by-doing and R&D. Therefore, to avoid dual consideration, performance improvement is normalized with "contribution share of knowledge accumulation to performance improvement". Figure 4.17 Shows the system diagram reflect the mechanism considered in this model for technology performance improvement.

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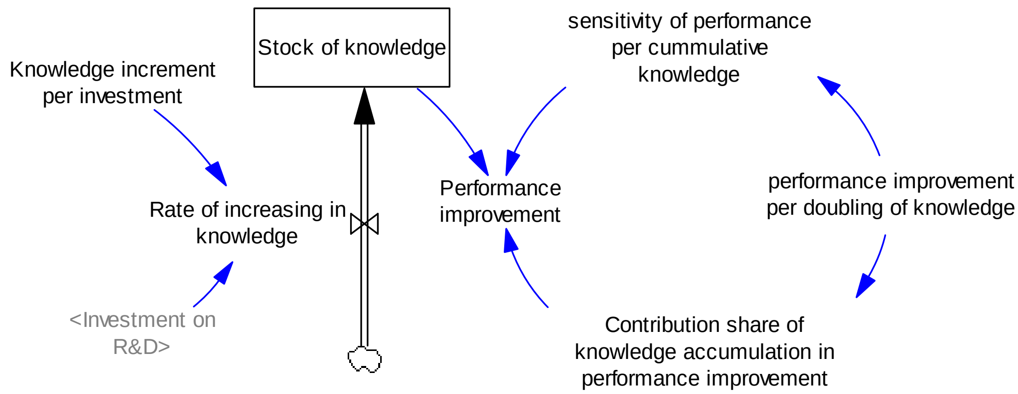
[8] As argued by Arrow (1962) in describing learning-by-doing as "accumulation of knowledge occurs not as a result of deliberate effort (here R&D), but as a side effect of predictable economic activity". However, respecting to impact of R&D on technology performance, accumulation of knowledge is the "purpose" of R&D efforts.



Variable	Notation	Unit
Performance improvement per doubling of knowledge	ε_k	Dimensionless
Contribution share of knowledge accumulation in performance improvement	ω	Dimensionless
Sensitivity of performance per cumulative knowledge	s_k	Dimensionless
Performance improvement	R	Dimensionless
Stock of knowledge	K	Dimensionless
Knowledge increment per investment	η_r	1/$
Rate of increase in knowledge	δ_k	1/year

Figure 4.17 System diagram showing the mechanism of technology performance improvement

The following relation is considered for system diagram shown in figure 4.17:

$$\delta_k = I_r \times \eta_k$$

$$K = \int \delta_k \cdot dt$$

$$S_k = \frac{Ln(1+\varepsilon_k)}{Ln(2)}$$

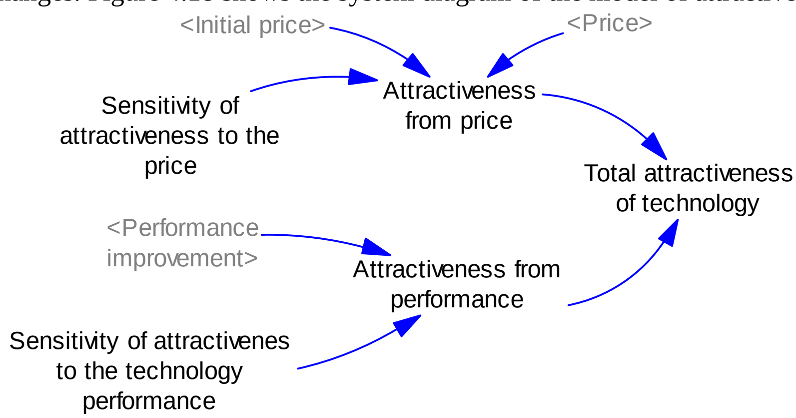
$$R = K^{S_k} \times \omega$$

Where η_k and δ_k are Knowledge improvement per investment and rate of increase in knowledge, respectively, K donates stock of knowledge accumulation, S_k, ε_k are sensitivity of performance improvement per knowledge and performance improvement per doubling of knowledge, respectively. Rand ω are technology performance improvement and contribution share of knowledge accumulation in performance improvement, respectively. The variable ω is added to the model to differentiate the contribution of R&D from contribution of learning-by-doing in performance improvement.

As it is discussed and shown in figure 4.2, two mechanisms through which, firms try to attract more customers, are lowering the price and enhancing the performance and quality of technology. Moreover, the price reduction process and the mechanism that increases technology performance, through investment in R&D, are also described earlier in this chapter. A simple model of technology attractiveness, which links the dynamics from the firm's side to the dynamics generated by adopters, is going to be presented in the next section.

4.2.8 Technology attractiveness

Technology attractiveness influences the sales growth of the technology and as attractiveness increases, technology's share in the market will increase(Sterman 2000). In the model, the level of technology attractiveness is adjusted through two different driving forces: price reduction and performance improvement. The attractiveness of technology through price is a comparison between initial price of the technology and price of the technology per each time, baring in mind that price of the technology has a negative impact on the attractiveness. Regarding attractiveness from the technology quality and performance, it is assumed that attractiveness changes linearly as technology performance changes. Figure 4.18 shows the system diagram of the model of attractiveness.



Variable	Notation	Unit
Sensitivity of attractiveness to the price	S_p	Dimensionless
Attractiveness from price	α_p	Dimensionless
Sensitivity of attractiveness to the technology performance	S_r	Dimensionless
Attractiveness from technology performance	α_r	Dimensionless
Total attractiveness of technology	α	Dimensionless

Figure 4.18 System diagram of technology attractiveness

It can be seen in figure 4.18 that the total attractiveness of the technology is the aggregation of attractiveness from price reduction and technology performance enhancement. The relations between different variables in this model are:

$$\alpha_p = EXP\left(\frac{S_P \times P}{P_i}\right)$$

$$\alpha_r = S_r \times R$$

$$\alpha = \alpha_p + \alpha_r$$

Where α_p, α_r, and α denote attractiveness from price reduction, attractiveness from performance improvement, and total attractiveness, respectively. Sp is sensitivity of attractiveness to the price and Sr is sensitivity of attractiveness to the technology performance.

Figure 4.18 shows the time dominant plot of technology attractiveness, which certainly is a dimensionless variable, considering S_p= -4, S_r=0.5, and performance improvement per doubling of knowledge ε_k =0.4.

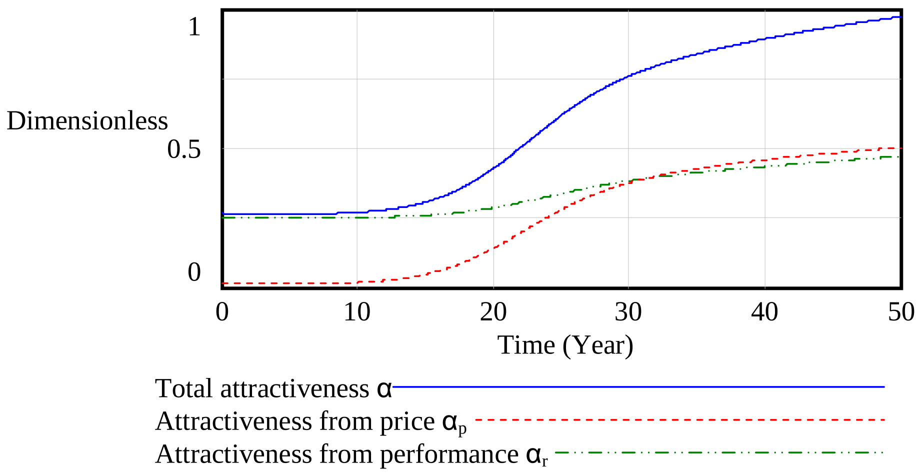


Figure 4.19 Technology total attractiveness, attractiveness from price reduction, and attractiveness from performance enhancement, considering S_p= -4, S_r=0.5, and ε_k =0.4

Having the technology attractiveness modeled and comparing the quantitative models with the qualitative model represented in figures 4.2 and 4.3; it is the time to introduce another important building block, in order to close the loop that is engendered so far.

Regarding the feedback mechanism on the producer's side, what has this far been developed is an open loop system comprised of a number of sub-systems that sequentially influence one another. Also, since it is an open loop system, the output of the system, in any stage, doesn't have any influence at all on the input of the system. For instance, different parameter choices in model of e.g. price or attractiveness don't influence the market adoption or cost of the new technology.

Technology attractiveness in our model acts as a bridge to bond the dynamics produced on the producer's side with the dynamics in the consumer's side. On the other hand, the impact of attractiveness, as discussed earlier, is on the consumer's attitude to give the new technology legitimacy, which eventually causes more diffusion of the technology. Hence, by introducing the consumer's part and the dynamics that produce the legitimacy, we will be able to connect all these loops to the market adoption of the technology and make a closed loop model.

In the next part of this chapter, the model of consumer's side, which produces legitimacy and attitude in favor of the new technology, will be discussed and built up.

4.2.9 <u>Consumer's attitude and technology legitimacy</u>

Legitimacy is a matter of social acceptance and recognition of new technology to be considered desirable and appropriate in order to be utilized and adopted by the customers. A more legitimate technology would be recognized not only as a more valuable, but also as more important, reliable, and dependable one. Thus it can influence on behavior of adopters (Theoharakis, Vakratsas et al. 2007; Bergek, Jacobsson et al. 2008).

Additionally, knowledge and information about new technology's characteristics should be spread in to the market; hence information about the new technology in the market, where the adopters of the technology are parts of, plays a significant role in diffusion.

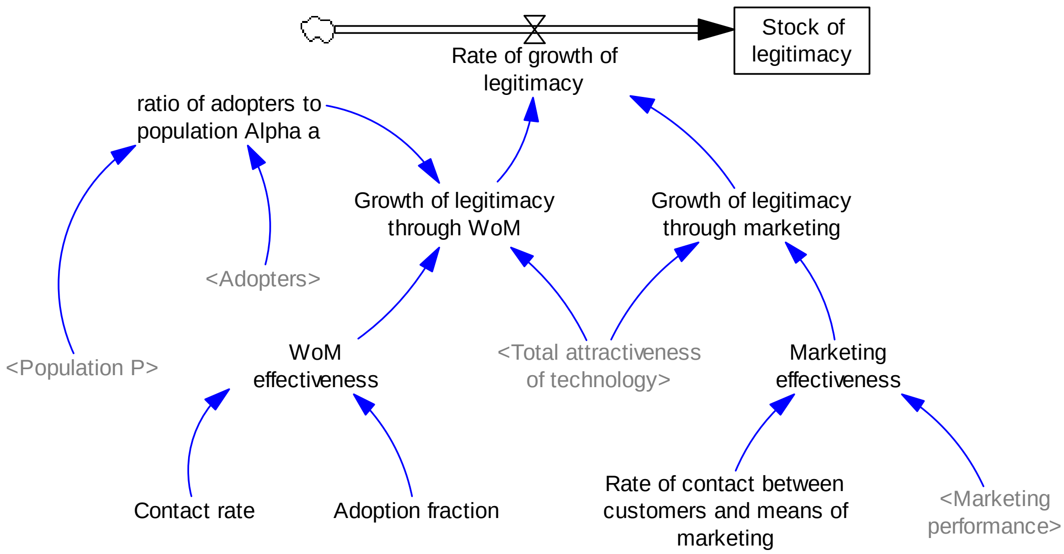
Market level information creates awareness and familiarity, and can form new adopters' attention regarding the new technology (Struben and Sterman 2007). Thus, as the new technology becomes more familiar to the market, the adoption of that technology will be taken for granted which is the goal of the firm's producing the technology. Therefore the information about the technology in the market create a "cognitive" and "sociopolitical" legitimacy towards the adoption of the new technology (Aldrich and Fiol 1994). Hence, as an innovation become more observable through more tangible information and by dispersion of information in to the market, the diffusion of technology will be accelerated (Rogers 1995).

Literature on diffusion has examined several sources of information that influence the adoption of technology (Bass 1969; Dodson and Muller 1978; Horsky 1990; Geroski 2000). Geroski (2000) represented an epidemic model of word of mouth in spreading the information leading to legitimating the technology. Dodson and Muller (1978) presented a model of diffusion considering word of mouth and advertising as twin drive force for diffusion of new technology. Price and word of mouth is also considered by Horsky (1990) in the model he presented, in which he concludes that word of mouth would not affect in diffusion of some kind of technology, such as black and white TVs, and a price skimming strategy instead should be applied.

In the model presented in this study, growth of technology attractiveness positively influences on growth of values that make the technology gain legitimacy among its customers. Additionally, the mechanism that spread the legitimacy through the market, considered to be word-of mouth and marketing resulting in growth of market demand for the new technology, and consequently more acceleration in adoption.

Firms can influence on growth of legitimacy and customer's attitude in favor of new technology, by marketing appropriately, increasing the investments on R&D in order to betterment of technology quality, lowering the price, etc. On the other hand, as it is seen so far, the rate of adoption, which can be influence by all these factors, contributes ultimately to price reduction, increase of income, and R&D performance.

Figure 4.20 shows the system diagram of growth of attitude and legitimacy in favor of the new technology.



Variable	Notation	Unit
Rate of contact between customers and means of marketing	R_m	1/year
Marketing effectiveness	E_m	1/year
Growth of legitimacy through marketing	L_m	1/year
Contact rate	R_c	1/year
Adoption fraction	A_f	Dimensionless
WoM effectiveness	E_w	1/year
Growth of legitimacy through WoM	L_w	1/year
Ratio of adopters to population	σ	Dimensionless
Rate of growth of legitimacy	δ_L	1/year
Stock of legitimacy	L	Dimensionless

Figure 4.20 System diagram of consumer's attitude and technology legitimacy

In this model legitimacy spreads via word of mouth, marketing, and technology attractiveness. As discussed in the qualitative model, word of mouth has a contagious nature and has been considered as the back bone of models made by pioneer scholars modeling the adoption-diffusion. Modeling of this concept is borrowed from population ecology, pointing out the epidemic spread of disease for example in herd management (Bass 1969; Dodson and Muller 1978). In this model, word of mouth plays a significant role in the growth of the new technology. The larger the number of adopters, the greater the contact with the potential adopters and hence, better transformation of information to potential adopters and eventually, greater probability of considering the new technology to purchase.

On the other hand, marketing is a process which is related to the firm's performance, and not like word of mouth, it depends on the firm's returns on investment. So both interpersonal source of creation of legitimacy and marketing are under influence of technology attractiveness, which improves endogenously through learning by doing and R&D[9].

The following set of relation in considered between the components presented in figure 4.20:

[9] Learning by doing generate the price reduction mechanism and R&D contributes directly to enhancement of technology quality and performance.

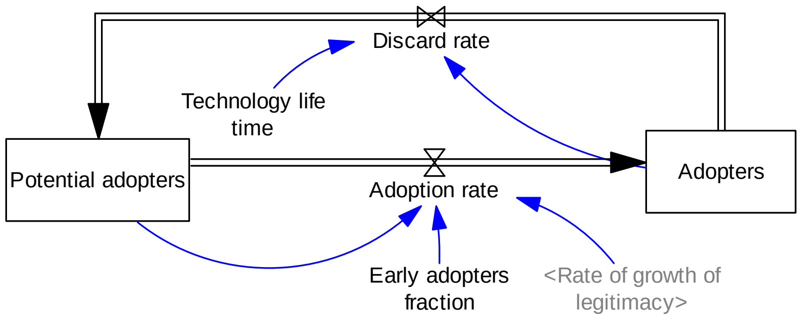
$$E_m = R_m \times M$$
$$E_w = R_c \times A_f$$
$$\sigma = {N_a}/{N}$$
$$L_w = E_w \times \sigma \times (1+\alpha)$$
$$L_m = E_m \times (1+\alpha)$$
$$\delta_L = L_m + L_w$$
$$L = \int \delta_L \cdot dt$$

Where R_m is the rate of contact between customers and means of marketing, E_m and E_w denote effectiveness of marketing and word of mouth, respectively. σ is ratio of adopters per total population; L_m and L_w are growth of legitimacy through word of mouth and marketing. δ_L and L denote rate of growth of legitimacy and the level of stock of legitimacy.

In this model, as it is discussed in graph 4.3, growth of legitimacy is driven and regulated by word of mouth and firm's marketing effort. To facilitate observation of this change in adoption process, the market adoption model shown in Figure 4.5 is modified and described in the next section.

4.2.10 Modified market adoption model

When a new technology is introduced to a market, it goes through different phases which appeals to different audience and potential adopters. However, in the very early phase of adoption, it is adopted by innovators and technical enthusiasts, and by early adopters or visionaries, who are ready to take the risk, and despite all the uncertainties around the new innovation, adopt the new technology (Easingwood and Harrington 2002). Hence another driver is introduced, independent from the legitimacy, named "early adopter's fraction". It is assumed that early adopters contribute to only early phase of adoption coupled with "rate of growth of legitimacy". Figure 4.20 shows the modified system diagram of market adoption.



Variable	Notation	Unit
Potential adopters	N_p	Households
Adopters	N_a	Households
Adoption rate	R_a	Households/year
Early adopters fraction	δ_E	1/year
Discard rate	R_d	Households/year
Technology life time	T_f	year

Figure 4.21 System diagram of modified market adoption model

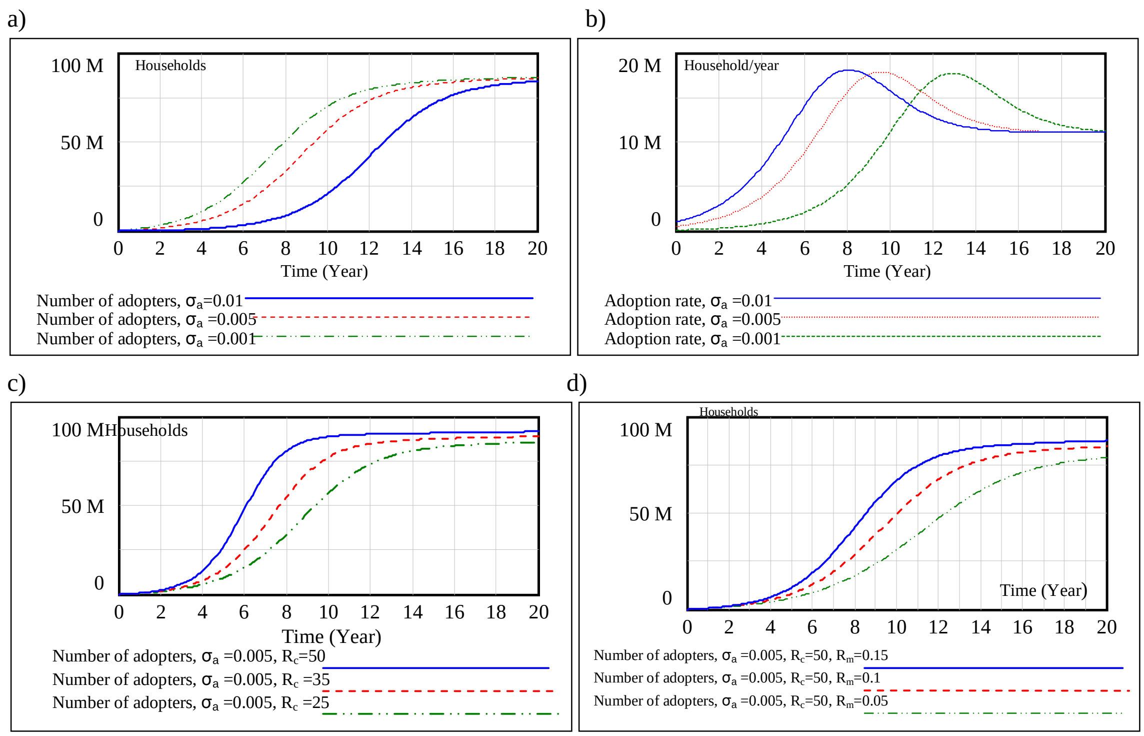
Also, the following modifications applied to the model:

$$R_a = (\delta_a + \delta_L) \times N_p$$

Where δ_a is the fractional rate per year that early adopters adopt the new technology independently from legitimacy.

In order to demonstrate the behavior of the model, which now is influenced by different factors and not just word of mouth, a set of graphs representing number of adopters and diffusion rate of the technology is shown in Figure 4.22. In these graphs the values that are previously used in the simulations are fixed, so presentation of these graphs is aiming to understand the effect of some of the exogenous.

Figure 4.22 consist of six graphs illustrating the effect of different exogenous variables within the model on diffusion, price, and profit margin. Graph a) shows the diffusion pattern of the modified model, considering different portion of early adopters of the technology M_e=0.01, M_e=0.005 and M_e=0.001, b) shows the diffusion rate of the new technology considering different values for early adopters M_e=0.01, 0.005 and 0.001, c) shows the effect of contact rate in the adoption : Cr=50, 35, and 25 (1/year), d) shows the effect of contact between potential adopters with means of marketing e) Shows the effect of contact rate on the price of the technology, considering Cr=25, 50, and 100 (1/year), and f) shows how profit margin of technology alter as contact rate changes.



e) f)

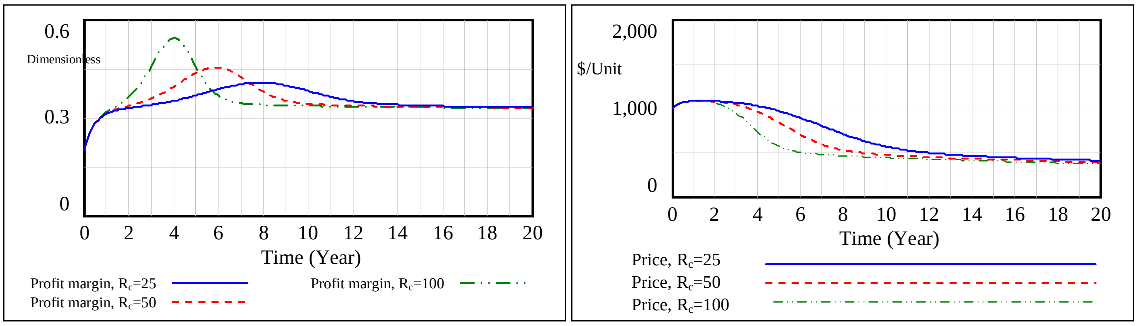


Figure 4.22 a) Diffusion pattern considering different values for early adopters b) Diffusion rate of the new technology considering different values for early adopters, c) shows the effect of different contact rates on the adoption d) shows the effect of contact between customers with means of marketing, e) price of technology altering by different values for contact rate, f) profit margin altering by different values for contact rate

As it can be observed in graph (a) presented in figure 4.22, the rate of adoption through early adopters advance the diffusion time. The driving forces of diffusion at the early stage come from word of mouth, marketing, and the inherent tendency of early adopters in purchasing the product.

Moreover, by comparing graph (b) with the adoption curve presented by Moore (1999), it can be observed that the simulation of adoption curve here corresponds to what Moore presented qualitatively. It can be thus seen that the number of adopter in the early phase of the diffusion process, effect the time of entrance of "early majority" of the non-adopters, to purchase the product.

Graph (c) demonstrates the effect of contact rate, as one of the factors that influence the word of mouth effectiveness, on the diffusion pattern. Contact rate thus has a slight effect on formation phase of the diffusion and instead more on accelerating the growth phase. The reason is exponential growth of the number of adopter in growth phase of technology through word of mouth and marketing.

Graph (d) shows the effect of contact between non-adopters of the technology and means of marketing. As the rate of the contact between a potential adopter with means of marketing such as advertisement increases, it speeds up the diffusion process.

Graph (e) and (f) shows how different contact rates between potential adopters and adopters of the new technology influence the profit margin (Graph e) and Price (Graph f) of the technology. These graphs show the closed loop system between price and legitimacy of the technology by which a parameter choice in growth of legitimacy (output) can influence the price (input).

The model in this chapter provides us with a better understanding about the dynamics and feedback mechanisms governing the technology diffusion process. The model was a formal model describing some of the major dynamics behind the technology diffusion. Each part of the model can be further developed in order to have a better understanding of that particular part, by introducing more factors in to the model. Moreover, the model can be calibrated with some real data in order to test the robustness of the results.

The model showed on the one hand how strategies and decisions made by the producer of the technology influence the attitude of the potential adopters by altering technology attractiveness. On the other hand, attitude of the potential adopters influences the adoption rate and consequently the firm's profitability and further decisions. Accordingly, some of the factors (i.e. demand for the new technology) influencing the price, which plays an important role in both firm's profitability and technology attractiveness. These factors are market oriented factors which the adopters of the technology are part of.

Chapter 5. Discussion

Technological diffusion and substitution are social rather than unprejudiced phenomena and public opinion plays a critical role in determining adoption decisions. Hence, an argument can be made that there is no predictability in the growth of a technology as well as in technological substitution processes based on technical parameters only.

This master's thesis work was intended to lead to a better understanding of the mechanism of technological diffusion, and substitution processes. The description is based on the premise that the substitution is the result of competition between old and new technology in which the new technology wins and gain market. The diffusion pattern of a technology, or in this report "diffusion/adoption rate", is determined by various factors. These factors could be induced and manipulated by the built-in characteristics of the innovation system (Pistorius and Utterback 1995) .Hence, insights about these factors to getter with external and internal forces altering them would be important in easing the understanding of technological diffusion and substitution.

Nowadays terminologies used in biology are used for technological matters. The "evolution" of the computer, the "birth" of the internet, etc are familiar phrases used in everyday language. In chapter 3 of this report, a model of substitution based on Lotka-Volterra competition equations has been presented as a way to model multi-mode interaction between technologies. Multi-mode interaction has been demonstrated in biological and organizational ecology and has also been used in studying the interaction among technologies. By using Lotka-Volterra differential equations, the effect of one technology on another's diffusion rate is taken as the decisive principle, by which the form of interaction is measured. In the models presented in chapter four, two forms of interaction are discussed: pure competition and predatory-prey.

Technological substitution often substantiates technological competition since the emerging technology grows in the same market that the mature technology is present in. The competition model showed that in a pure competition, where both technologies impose negative influence on one another, the mature technology inhibits the growth of the emerging technology.

Predatory-prey interaction implies a situation where the emerging technology benefits from the presence of the mature technology and gradually get market share. Thus, the emerging technology has a negative effect on the mature technology which is described by the predator-prey relationship.

On the other hand, substitution happens when emerging technology benefits from the presence of existing technology, and then gradually transforms it. For this purpose a bridging technology is introduced in to the model as one of the strategies to make this transformation(Sandén 2004).

A bridging technology can benefit from the presence of the old technology and can gain market share, on the other hand, the emerging technology can benefit from the presence of the bridging technology. As it is simulated in the Lotka-Volterra model, the bridging technology inhibits the mature technology and prepares the market for emerging technology.

By simulating the competition models with different values, it is shown that the presence of the third technology is necessary for emergence of a new technology that is in pure competition with the old mature technology.

Lotka-Volterra equations are useful because they can portray such a wide range of dynamic behaviors occurring in technological substitutions. Moreover, simulations of Lotka-Volterra models produce general pictures that include different kind of diffusion and substitution patterns. However, although it is feasible to produce patterns using Lotka-Volterra equation, the coefficients used in the equations are constant, which are likely to change over time in real technology interactions. Hence, the challenge would be to explore the realistic factors that influence the coefficients and generate different Lotka-Volterra like patterns of diffusion and lock-out. By developing the second model presented in chapter five as a "technology diffusion model", some real factors influencing the diffusion are explored.

Same as Lotka-Volterra models, the growth and stability of the diffusion model is generated by positive feedback that produce the initial period of accelerating the growth, and negative feedback that makes the growth to slow as it approaches the carrying capacity. However these loops use realistic factors and mechanisms, which accelerate, or balance the diffusion process. The positive feedbacks that elevate the adoption rate are considered to be price reduction, performance improvement, R&D expenditures, and investments on marketing, from learning-by-doing. Attitudes in favor of the new innovation depend on firms' marketing effectiveness and positive word of mouth.

Technology diffusion is a path dependant process (Sandén 2004), hence the eventual state of diffusion depends on the state of the starting point. Even small deviation in the formative state of diffusion can be amplified by positive feedback processes and then the cost of switching back to normal becomes prohibitive and the self-forcing equilibrium generate lock-in of the system. The model bears out that how the portion of early adopters, producer's price and investment strategy, and cognitive processes within the consumers, can influence the diffusion process. Moreover, the model gave us insight about how these forces, even in small quantities, can influence largely the diffusion process by either accelerating or decelerating the growth phase of diffusion.

Hence, as it is seen in the model and needless to say, the strategy of the firms involved in producing the new technology, and the emotional and cognitive process within the consumers plays an important role in the diffusion process.

Furthermore, the diffusion model showed that management of innovation is a challenging field since it deals with hard and soft variables simultaneously. It involves with uncertainties and ambiguities, large amount of capital investment, and it has to deal with feedbacks. Hence, it is a highly complex system and is not merely complex because of the number of elements within a system. But it is complex due to the interrelatedness of the system, linear or non-linear relationships, or whether there is time delay in the system. Even a system with few elements, a highly interrelated and non-linear dynamic system can show tremendous complexity.

Although the diffusion generated by word of mouth is the kind of S-shape curve that we were looking for, using word of mouth or other types of epidemic models have a serious weakness. They cannot explicate the adoption process of an innovation from the date it is invented and just explain it from the day that early adopters have begun using it. Diffusion processes generated by word of mouth never starts unless an initial amount of users has been built up.

Moreover, ever since early adopters have purchased the new technology despite no information about previous experiences of using the new technology, they must be different from the following adopters. In addition, as discussed by Rosenberg (1995), there are always uncertainties involved around the acceptance of the new technology and as long as these ambiguities presents, these sorts of assumptions can be strongly challenged. Hence, the early adopters of technology must have different characteristics from the psychological, attitude, and sociological point of view that are willing to take the risk and adopting the new technology. Some of these characteristics are also discussed by Rogers (1995).

Hence, it would be better to not mix early adopters with the following adopters and treat them in the model separately.

Models in this report can help us to understand the process of technological diffusion and substitution. The models are capable of providing a better understanding of the root mechanisms of technological change and technological improvement. Depend on the audience and the purpose of using these models, different part of the model can be further developed. Also the boundary of the model can be expanded or contract depending on the purpose of using this formal model. However, one should always bear in mind that increasing the complexity of models, make it more difficult to understand.

Chapter 6. Conclusion

The study is concluded by answering the research questions outlined in the first chapter.

RQ1: *How can a multi-technology substitution process be modeled?*

By using Lotka-Volterra models a big picture of how multi-technology substitution is taking place can be produced. It provides us with a framework to study the multi-mode interaction among technologies as well as multi-technology substitution. Lotka-Volterra models showed that when an emerging technology is in pure competition with a mature technology, presence of another emerging technology is necessary for substitution. Hence, the multi-technology substitution is modeled by introducing another technology as "bridging technology" to the model of interaction between a mature and an emerging technology. Moreover, the model of technology diffusion presented in this study showed how some of the forces that are involved in the technological diffusion can influence on the diffusion process. These forces are driven from both "hard variables" such as price, investment, and contact rate among adopters, as well as "soft variables" such as knowledge formation and attractiveness. In further work, the Lotka-Volterra concept could be combined with the positive feedbacks presented in the diffusion model, into a more detailed model of multi-technology substitution processes.

RQ2: *What diffusion patterns can such a model generate? Can historical patterns be reproduced?*

The models presented in this study reproduced expected patterns. Lotka-Voltera models and diffusion model produced an S-shaped curve corresponding to the logistic growth of an emerging technology. There was not attempt made to simulate any real historical substitution or diffusion process.

RQ3: *How do different parameter choices affect results?*

Lotka-Volterra models illustrate technological substitution in a stylized way. The pattern produced using Lotka-Volterra alters by the parameter choices in the simulation of the models and different parameters resulted in different scenarios. The model of diffusion showed how different parameter choices can affect the diffusion pattern. It is also possible to extend Lotka-Volterra models to time-varying parameters by combining the Lotka-Volterra mode and the model of diffusion.

RQ4: *Can we learn something from the model for the outcome and impact of choices in ongoing real world change processes?*

Real world change processes have a tremendous complexity due their highly interrelated and non-linear dynamics. The models presented here are simplifications of these complex processes and tell us something about "what is going on". Hopefully the models in themselves and the patterns they produce can make people, who are involved in the decision-making, think in different ways and look upon problems from a new perspective. The System Dynamics models presented in this report help us in understanding the observed and agreed upon structure of technological substitution, and prepare for further study of the different parts of the process.

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Appendix A

The complete model formulation for Model of technology diffusion represented in chapter 4

In this appendix the model formulations for the detailed simulation model of technology diffusion is documented as follows:

Total Cost= Unit Cost*Production
Unit: $/Year
Description: Total firm Costs per year

Adoption rate= (Early adopters fraction +Rate of growth of legitimacy)*Potential adopters
Unit: Households/Year

Rate of growth of legitimacy= Growth of legitimacy through WoM + Growth of legitimacy through marketing
Unit: 1/Year

Stock of legitimacy= INTEG (Rate of growth of legitimacy,0)
Unit Dimensionless

Early adopters fraction= 0.002
Unit: 1/Year; range: [0.001,0.1]

WoM effectiveness= Adoption fraction*Contact rate
Unit: 1/Year

ratio of adopters to population Alpha a=Adopters/Population P
Unit: Dimensionless

Growth of legitimacy through marketing=Marketing effectiveness*(1+Total attractiveness of technology)
Unit: 1/Year

Marketing effectiveness= Marketing performance*Rate of contact between customers and means of marketing
Unit: 1/Year

Growth of legitimacy through WoM= ratio of adopters to population Alpha a* WoM effectiveness*(1+Total attractiveness of technology)
Unit: 1/Year

Rate of contact between customers and means of marketing= 0.12
Unit: 1/Year

Total attractiveness of technology= Attractiveness from price + Attractiveness from performance
Unit: Dimensionless

Rate of increasing in knowledge="Investment on R&D"*Knowledge increment per investment
Unit: 1/Years

Knowledge increment per investment=0.0001
Unit: 1/$

Contribution share of knowledge accumulation in performance improvement= IF THEN ELSE(performance improvement per doubling of knowledge>0, 0.5,0)
Unit: Dimensionless; range:[0,1]

Performance improvement=(Stock of knowledge^sensitivity of performance per cumulative knowledge)*Contribution share of knowledge accumulation in performance improvement
Unit: Dimensionless

Unit Cost= Unit variable cost+Unit fixed cost/Capacity utilization
Unit: $/Unit
Description: Total unit cost is the sum of unit fixed and variable costs (fixed costs per unit of capacity are adjusted for normal capacity utilization).

Initial unit variable cost= (Initial price/(1+Desired profit margin))*(1/(1+Fixed to Variable cost))
Unit: $/Unit
Description: Initial variable cost per unit determined by a company specified ratio of fixed to variable cost adjusted by Normal capacity utilization and normal profit margin

Initial unit fixed cost= (Initial price/(1+Desired profit margin))*Fixed to Variable cost*(1/(1+Fixed to Variable cost))
Unit: $/Unit
Description Initial fixed cost per unit determined by company specified ratio of fixed to variable cost adjusted by normal profit margin

Capacity utilization=1
Unit: Dimensionless

Adoption fraction=0.01
Unit: Dimensionless, Range: [0,0.1]

Contact rate= 25
Unit: 1/Year [0,100]

Sensitivity of attractiveness to the technology performance= 0.5
Unit: Dimensionless

Attractiveness from performance=Performance improvement*Sensitivity of attractiveness to the technology performance
Unit: Dimensionless

Performance improvement per doubling of knowledge= 0.5
Unit: Dimensionless

Sensitivity of performance per cumulative knowledge= LN(1+performance improvement per doubling of knowledge)/LN(2)
Unit: Dimensionless

Stock of knowledge= INTEG (Rate of increasing in knowledge,1)
Unit: Dimensionless

Marketing performance improvement rate= Marketing performance improvement per investment*Investment on marketing
Unit: 1/Years

Adoption rate through marketing= 0.005
Unit: 1/Years

Marketing performance= INTEG (Marketing performance improvement rate,0)
Unit: Dimensionless

Share of investment in profit=0.4
Unit: Dimensionless; range: [0,1]
Description: Percentage of income set aside for investment

Marketing performance improvement per investment=0.0001
Unit: 1/$
Description: The effect of investment per each unit of investment on marketing

"Share of investment on R&D"=0.5-Share of investment on Marketing
Unit: Dimensionless

Share of investment on Marketing= 0.2
Unit: Dimensionless; range: [0,1]

Investment on marketing= Total investments*Share of investment on Marketing
Unit: $/Year

"Investment on R&D"= Total investments*"Share of investment on R&D"
Unit: $/Year

Total investments= Profit*Share of investment in profit
Unit: $/Year
Description: Investment on performance improvement of the company per year

Revenue= Price*Production
Unit: $/Year
Description: Firm total revenue per year

Profit= Revenue-Total Cost
Unit: $/Year
Description: Firm net income

Population =1e+008
Unit: Households

Potential adopters= INTEG (Discard rate-Adoption rate, Population -Adopters)
Unit: Households
Description: The number of households in the population who have not adopted the product but considered as potential adopters

Initial price=1000
Unit: $/Unit

Attractiveness from price= EXP (Sensitivity of attractiveness to the price*Price/Initial price)
Unit: Dimensionless
Description: Attraction from the price of the new technology

Price= INTEG (Change in price, Initial price)
Unit: $/Unit

Sensitivity of attractiveness to the price=-2
Unit: Dimensionless; range: [-4,1]

Ratio of target price to cost price= 1.1
Unit: Dimensionless
Description: the impact of costs, demand/supply curve, market share and the price of the new technology

Target price= Cost price*Ratio of target price to cost price
Unit: $/Unit
Description: Target price which indicates by costs, demand/supply curve, market share and the price of the product

Profit margin= (Price/Unit Cost)-1
Unit: Dimensionless

adjustment time= 0.5
Unit: Year
Description: The time adjust the price to the target price

Cost price= (1+Desired profit margin)*Unit Cost
Unit: $/Unit
Description: is the price by total unit cost and normal mark-up

Change in price= (Target price-Price)/adjustment time
Unit: $/Unit/Year

Number of product per adopter= 1
Unit: Units/Households
Description: Number of units used per each household

Adopters= INTEG (Adoption rate-Discard rate,Initial Cumulative Adopters M0)
Unit: Households
Description: The cumulative number of adopters of the technology

Production= Number of product per adopter*Adoption rate
Unit: Units/Year

Unit variable cost= Initial unit variable cost*Learning
Unit: $/Unit

Learning curve exponent=LN(Progress ratio)/LN(2)
Unit: Dimensionless

Progress ratio= 0.8
Unit: Dimensionless
Description: reduction in unit cost per each doubling of cumulative production

Accumulative production= INTEG (Production,Initial production experience)
Unit: Units

Desired profit margin= 0.2
Unit: Dimensionless
Description: The normal mark-up on unit cost, this is used to determine cost price

Fixed to Variable cost= 3
Unit: Dimensionless

Initial production experience=10000
Unit: Units

Learning=(Accumulative production/Initial production experience)^Learning curve exponent
Unit: Dimensionless

Unit fixed cost= Initial unit fixed cost*Learning
Unit: $/Unit

Discard rate= Adopters/Technology life time
Unit: Households/Year

Initial Cumulative Adopters = 0
Unit: Households

Technology life time= 8
Unit: Year

****
.Control
**~
Simulation Control Parameters

FINAL TIME = 20
Unit: Year
~ The final time for the simulation.

INITIAL TIME = 0
Unit: Year
~ The initial time for the simulation.

SAVEPER = TIME STEP
Unit: Year [0,?]
~ The frequency with which output is stored.

TIME STEP = 0.0625
Unit: Year [0,?]
~ The time step for the simulation.

\\\---/// Sketch information - do not modify anything except names

Appendix B

List of variables used in the model of technology diffusion presented in chapter 4

Variable	Notation	Unit
Potential adopters	N_p	Households
Adopters	N_a	Households
Adoption rate	R_a	Households/year
Early adopters fraction	δ_E	1/year
Discard rate	R_d	Households/year
Technology life time	T_f	year
Rate of contact between customers and means of marketing	R_m	1/year
Marketing effectiveness	E_m	1/year
Growth of legitimacy through marketing	L_m	1/year
Contact rate	R_c	1/year
Adoption fraction	A_f	Dimensionless
WoM effectiveness	E_w	1/year
Growth of legitimacy through WoM	L_w	1/year
Ratio of adopters to population	σ	Dimensionless
Rate of growth of legitimacy	δ_L	1/year
Stock of legitimacy	L	Dimensionless
Sensitivity of attractiveness to the price	S_p	Dimensionless
Attractiveness from price	α_p	Dimensionless
Sensitivity of attractiveness to the technology performance	S_r	Dimensionless
Attractiveness from technology performance	α_r	Dimensionless
Total attractiveness of technology	α	Dimensionless
Performance improvement per doubling of knowledge	ε_k	Dimensionless
Contribution share of knowledge accumulation in performance improvement	ω	Dimensionless
Sensitivity of performance per cumulative knowledge	s_k	Dimensionless
Performance improvement	R	Dimensionless
Stock of knowledge	K	Dimensionless
Knowledge increment per investment	η_r	1/$
Rate of increase in knowledge	δ_k	1/year
Marketing performance improvement per investment	η_m	1/$
Marketing performance improvement rate	δ_m	1/year
Marketing performance	M	Dimensionless
Revenue	ρ	$/year
Total cost	κ	$/year
Profit	π	$/year
Total investment	I	$/year
Investment in marketing	I_m	$/year

Investment in R&D	I_r	$/year
Variable	**Notation**	**Unit**
Share of profit in investment	β	Dimensionless
Share of investment in marketing	β_m	Dimensionless
Share of investment in R&D	β_r	Dimensionless
Ratio of target price to cost price	θ	Dimensionless
Target price	P_t	$/unit
Cost price	P_c	$/unit
Adjustment time	T_a	year
Change in price	δ_p	$/(unit*year)
Price	P	$/unit
Profit margin	μ	Dimensionless
Fixed to variable cost	γ	Dimensionless
Initial price	P_i	$/unit
Initial fixed cost	C_{fi}	$/unit
Initial variable cost	C_{vi}	$/unit
Unit fixed cost	C_{fu}	$/unit
Unit variable cost	C_{vu}	$/unit
Unit cost	C_u	$/unit
Capacity utilization	λ	Dimensionless
Desired profit margin	μ_d	Dimensionless
Production	δ_Q	Unit/year
Number of product per adopter	q	Unit/households
Cumulative production	Q	Unit
Learning curve exponent	S_L	Dimensionless
Initial production experience	Q_i	
Learning	L_c	Dimensionless
Progress ratio	ε_c	Dimensionless