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# FUNDAMENTALS OF TECHNOLOGY DIFFUSION AND MOBILE PHONE CASE STUDY*

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**Abstract.** The fundamentals of technology diffusion are introduced in this paper. Mathematical and heuristic (loose) modeling are defined and illustrated with real data. Starting with the embryonic phase, diffusion undergoes growing and mature phases and ends in the aging phase. The cumulative adoption function (of time) denoting the total number of users of a certain product is the output of the diffusion model used to either predict future trends (e.g. sales) or estimate certain model parameters. Problems often encountered in mathematical modeling and analysis are presented. Some of these shortcomings can be alleviated through loose modeling. A case study of mobile telephone diffusion in Finland is presented to illustrate some of the modeling principles and analysis.

## 1. Introduction

Circuits, systems, and signal processing research has been evolving in a number of directions and at different rates with considerably faster changes during the past few decades. The driving forces behind the trends arise from different sources. New problems for which traditional techniques are not suitable require new solutions. The area of image and video signal processing is one in which novel *nonlinear* techniques have been developed in the past few decades to complement classical linear techniques where the latter fail to produce satisfactory results. Another driving force is *technology*. New technologies, the product of recent research and development work, usually bring about and guide new opportunities for further research, both long term and applied, in the fields of circuits, systems, and signal processing. It is therefore necessary for researchers in these fields to acquire a minimal understanding of how these technologies diffuse, and evolve and how to forecast such processes, especially for new generations of technology.

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The *diffusion of an innovation* is by definition a process in which innovation spreads through certain channels in the social system (target population) in time ([25], p. 5). According to Ayres ([1], p. xii), *diffusion* (of a new technology) is the evolutionary process of *replacement* of an old technology by a newer one for solving similar problems or accomplishing similar objectives.

A *real diffusion process* usually consists of a large number of variables related through a very complex and highly nonlinear set of relations. This complexity can, to some degree, be modeled and managed by a *diffusion model*. The primary purpose of such a model is to manage the *regularity* encountered in the process. Traditionally, the model is a *simplified mathematical representation* of the main features of the process as a time series of indicators describing the phenomenon of interest. *Mathematical models* are used primarily for technological forecasting purposes, for which forecasting is based on the "*best fit*" of the empirical data to the model and trend extrapolation is applied outside the range of the empirical period. Some models also include *explanative factors*, which are model parameters that describe some behavioral properties of the underlying process.

An optional approach called *heuristic* (*loose*) *modeling* is derived from the principles of mathematical diffusion models. Available knowledge about a process is used by the *analyst* to first *understand* the changes in the process in the past and then to *reason* future improvement. The aim of heuristic modeling is to support change management, not to provide exact forecasting.

This paper provides an introduction to diffusion analysis and is based mainly on earlier publications of Jaakkola [8], [10]–[13]. In general, the world of diffusion modeling is more complicated than the one described here. The approach in this paper concentrates on the description of the diffusion of an innovation, called first the *adoption model*. Other approaches include, e.g., *replacement models*, describing the replacement of a product by a new one, and *figure-of-merit models*, describing the changes in the capacity of some technologies. In addition there are models developed for *multiadoption* processes, which model diffusion of parallel product *generations*, and adaptive models, which have simple built-in feedback mechanisms or flexibility variables.

Diffusion models date back to the late nineteenth century: a sociologist Gabriel Tarde (1890) applied mathematical models in the analysis of the spread of political ideologies [27]. Major developments in the history are the use of the Pearl curve (1925, see [23]), originally developed to describe the growth of a cell population, to describe technology replacement by Fisher and Pry (1972, see [5]). Other important models include Bass' first purchase model (1969, see [2]) and further modifications of it (e.g., the model of Majahan et al. in 1990), and Mansfield's model (1961, see [20]), including explanative parameters, further developed by Blackman (1972). All these models are based on the use of logistic distribution (or its derivatives) to describe the process. Another approach developed by Coleman (1964, see [3]), uses exponential distribution and its derivatives to model political changes in the society.

This paper is organized as follows. Sections 2 and 3 provide an overview to the basic principles of the diffusion process to the extent needed to understand the analysis and forecasts applying the mathematical model to the empirical diffusion data presented in Section 4. In Section 5, problems related to the mathematical analysis are discussed, and an optional approach is introduced in Section 6. A case study is presented in Section 7, where the diffusion of cellular mobile telephones in Finland illustrates the principles of heuristic modeling.

## 2. Basics of diffusion modeling

The diffusion process is typically modeled by two functions describing the *cumulative* and *noncumulative* spread of the product. These functions have a regular form, as illustrated in Figure 1. Notation and labels in the figure denote the following:

| | |
|---|---|
| $f(t)$ | *noncumulative adoption function* |
| $F(t)$ | *cumulative adoption function* |
| $\overline{F}$ | *potential adopter population* (most models assume a priori fixed number of potential adopters during the adoption period; in many cases the potential is in reality a function of time, which most basic models lack (for discussion, see, e.g., Lakhani, 1975; Sharif and Ramanathan [26]) |
| {1} | the *whole population* of which the potential adopter population is a subset |
| {2} | the *lower threshold level* of penetration; if a substitution has progressed to this level, it will proceed to its completion; practically, the threshold level is 10% of the potential, and the behavior of the diffusion process before this point is irregular (Fisher and Pry [5]) |
| {3} | *at the inflection point* $t = t^*$, $f(t)$ has its maximum value, and increasing growth changes to decreasing growth |
| {4} | the upper threshold level, *maturation level*; after reaching this level of penetration, the process is practically finished and the behavior of the rest of the population is not regular and exactly moldable. |

The *fast growth phase* between levels {2} and {4} is the focal point of most diffusion models. Some of the models are valid only in this range because of the irregular behavior at the beginning and the end of the diffusion, or because they are limited only to some part of the process (e.g., models may assume symmetry with respect to the inflection point and describe only the area before or after that point). The whole period of diffusion can be divided into four phases with characteristic features of their own. These features will be discussed later in the paper in connection with the heuristic model.

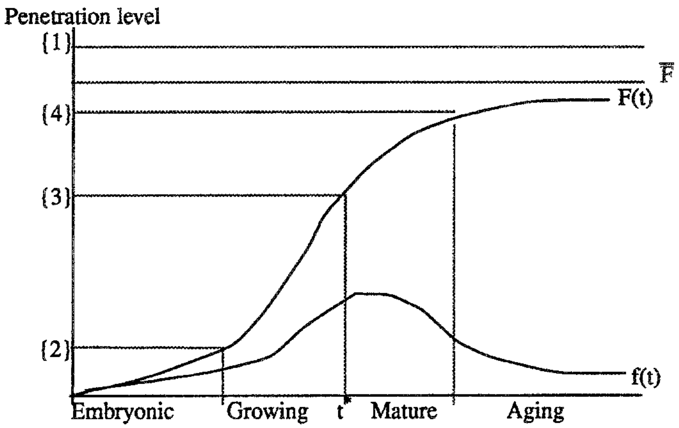

**Figure 1.** Components of a diffusion model.

## 3. What is the push for adoption?

To explain the behavior built into the models, one may focus on the *structural properties of the potential adopter population.* Two factors can be found in the background of the regularity:

- the limited "innovative power" of the product (ability to benefit from it)
- "built-in" behavioral features of a human being.

The *innovative power* is consumed in the beginning of the process by some *innovator* users, and later on an increasing number of users (imitators) as shown in Figure 2. At a certain level, common interest starts to decrease (most of the innovative power is already used), and finally the marginal change in the amount of new adopters approaches zero (*full penetration* is achieved).

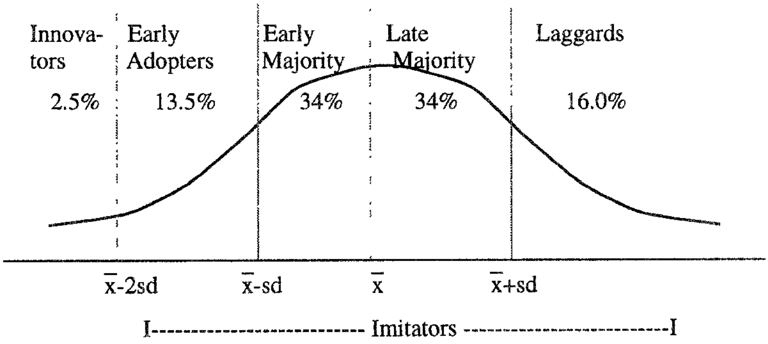

**Figure 2.** Adopter classification.

According to Rogers' "classical model" ([25], p. 247), the potential adopter population is normally distributed and centered at the inflection point. The whole population can be divided into five *adopter* groups. A small proportion of potential adopters decide about the adoption *independently*. They are called *innovators*, and their decision is controlled by *internal pressure*, whereas the decision of the rest of the population is controlled by *external pressure*. New adopters base their decision to adopt the new product on the experiences of earlier adopters. This group of potential consumers is manipulated by *communication* between individuals of the population.

In reality, the decision making involves more than just making a *positive* adoption decision. In practice, the user population can be divided into two classes: those who have already made a positive decision on the adoption and those who have not. However, this *binary character* of the diffusion is too simplified to work in reality. There also exist different *amounts of uncertainty* and *negative decisions* (giving up) among those who have already made the positive adoption decision. At a later stage and after reaching the full penetration level, a giving-up phase starts, in which a declining amount of users makes up the last phase of the process. This phase is usually induced by the replacement of the product with a new one. Further, in the limited market of goods there exists a *hidden positive decision*; i.e., a positive decision to adopt is made, but because of limited availability of the article in question, or other reasons, the adoption is not yet realized.

Diffusion models view the diffusion process from a slightly different perspective. The penetra- tion level (at time $t$) divides the adopter potential into two groups: *adopters* and *nonadopters*, ($F(t)$, $\bar{F} - F(t)$, respectively). The increments in diffusion are based on the pressure (see, e.g., Lavaraj and Gore [15]) directed to nonadopters to make a positive adoption decision. Typically, the pressure consists of two types of influence, external and internal. *External influence* comes from advertising, mass media communication, and the like. *Internal influence* denotes interaction inside the potential adopter population, i.e., experiences with the product. This interaction may have positive or negative effects, and its source may be either the class of adopters or the nonadopters.

Different mathematical models seek to represent such a phenomenon in various ways. One of the basic models offering ready and comprehensible access to the problem of mathematical diffusion was introduced by Bass [2]. The paper of Majahan et al. [17] widely discusses the characteristic features of the diffusion models. In their work, Majahan and Schoeman [19] and Majahan and Peterson [18] seek to derive a general model of diffusion from the ideas of external/internal influence in the adopter population.

The fundamental diffusion model has the following form (Majahan and Peterson [18]):

$$f(t) = g(t)(\overline{F} - F(t)). \tag{1}$$

The amount of new adopters depends on two factors: the growth potential and the pressure function. The growth potential is the difference between the potential adopter population and the number of existing users. The pressure function $g(t)$ describes the pressure on the group of nonadopters to make a positive adoption decision. The shape of this function is discussed widely in the literature. Majahan used a simple linear function of the form

$$g(t) = a + bF(t), \tag{2}$$

which can model

- external influence ($b = 0$),
- internal influence ($a = 0$), or
- mixed influence ($a, b \neq 0$).

The solution of differential equation (1) can have one of the following characteristics:

- *a decaying exponential function-based* cumulative adoption function as in external influence,
- *a symmetric S-shaped logistic distribution-based* cumulative adoption function as in internal influence,
- *a nonsymmetric S-shaped curve* as a cumulative adoption function as in mixed influence; the asymmetry depends on the parameters.

Several scientists have been actively interested in the field from an either theoretical or application point of view. This has resulted in a wide collection of different mathematical models, most of which embrace the same fundamental constructions with varying capabilities to fill a gap in an existing model. The predefined mathematical functions (distributions) used in models are, e.g.,

- a logistic distribution or its derivative,
- a distribution having a basic shape close to the logistic distribution (Gompertz, normal, v. Bertalanffy, Weibull),
- an exponential distribution or its variations.

In addition to the basic models there is a wide variety of models derived from the basic ones; the goal of these derivatives is to *add flexibility* to the models by combining the properties of two or more basic models. Details of mathematical properties of diffusion models are dis- cussed in works by Jaakkola [8], [12], [13] and further references of these papers, e.g., Kumar and Kumar [14] and Majahan et al. [17].

## 4. A sample analysis

### 4.1. *The empirical data*

Figure 3 describes the macro-level diffusion, i.e., the sum of all cellular mobile telephone licenses in Finland (the population of Finland is a little over 5 million).

The empirical data considered is an interesting application for analysis for several reasons:

- Finland has the highest penetration in the world (33% at the end of 1997),
- the Nordic analog standard pioneered the international network,
- four generations of the product have so far been on the market.

Based on the plot in Figure 3, one can make the following general remarks:

- the embryonic phase of the process has been long (10 years) compared to the fast growth starting in the middle of the 1980s,
- the plot does not give any information on the inflection point; the progress is very exponential and does not give good a starting point for extrapolation.

Moreover, it is very difficult to estimate the expected level of the potential adopter population. According to the EUTELIS 1993 forecast [4], the penetration rate of 30–50% in business users and 15–35% in private users will be reached by the year 2010 in Europe. In Finland this level has already been reached, and some forecast 100% penetration at the beginning of the next decade. The size of the potential adopter population has traditionally been set through market studies, analogies (guesses based on the behavior of similar known processes), or simply pure guesses.

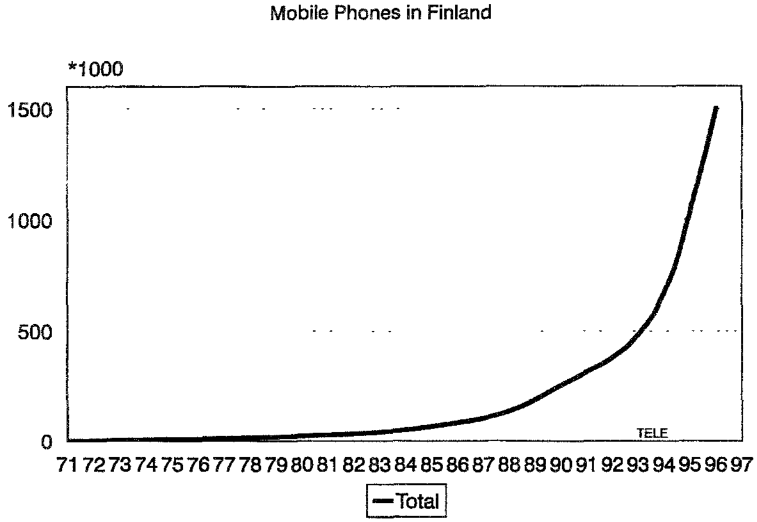

**Figure 3.** Mobile phones in Finland.

### 4.2. *Analysis model*

In principle, one could use any model from the literature, but we selected *Mansfield's model* [20] model for its simplicity. The cumulative adopter population at time $t$ for this model is given by the following expression:

$$F(t) = \frac{e^{c_1+c_2 t}}{1+e^{c_1+c_2 t}}\overline{F}. \tag{3}$$

The effect of the potential adopter population $\overline{F}$ on the cumulative number of adopters $F(t)$ can be clearly seen in Figure 4. Although $\overline{F}$ does not have a noticeable effect on the innovators, it certainly has a substantial influence on the early and late majorities.

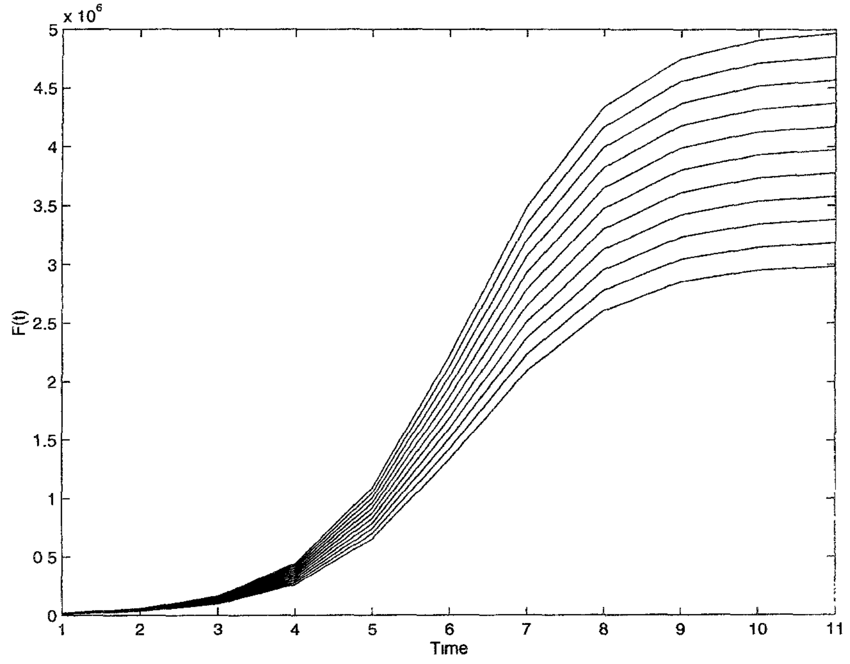

**Figure 4.** Model behavior for various values of $\overline{F}$ with fixed values of $c_1$ and $c_2$.

Parameter $c_1$, on the other hand, controls the rate of the embryonic phase of the diffusion. A larger $c_1$ indicates a slow diffusion or a larger time lag at the start of the product (this is the case for the total number of cellular telephone users in Finland; see Figure 3). Figure 5 illustrates this behavior.

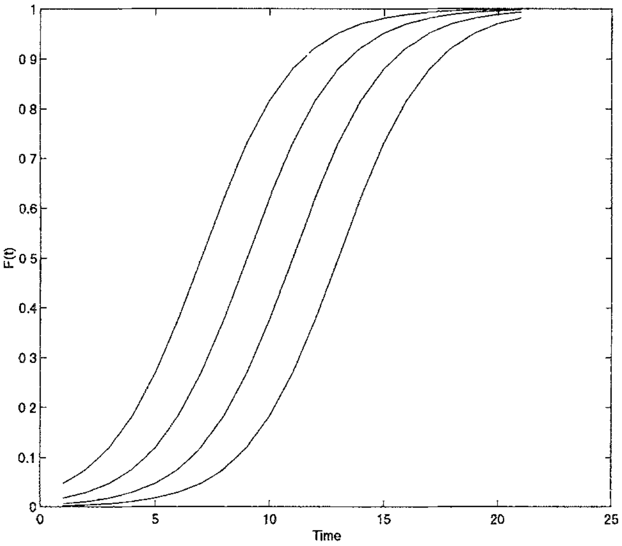

**Figure 5.** Model behavior for various values of $c_1$ and fixed $c_2$.

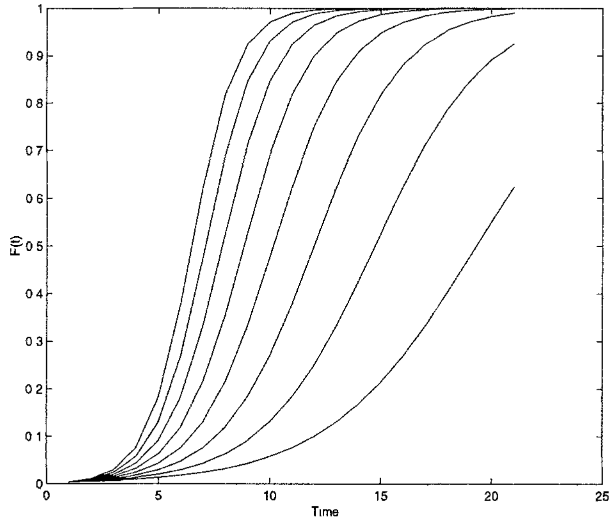

**Figure 6.** Model behavior for various values of $c_2$ and fixed $c_1$.

Finally, parameter $c_2$ is perhaps the most important factor in this diffusion model as it controls the exponential rate of growth ( see Figure 6). Its value should be carefully estimated for a meaningful interpretation and an accurate forecast of the process.

Different products and different generations of the same product have their own parameters, as will be illustrated in the case study in Section 7. The sensitivity analysis of the model with respect to its parameters is an essential research topic and will be elaborated on in what follows.

## 5. Important issues in the analysis

### 5.1. *Exponential growth*

The diffusion process tends to fit the logistic model, but only in the long term. In many practical cases the time series analyzed is not long enough to allow the process to reach its inflection point before a new product or a new generation of the product is introduced and starts to compete with the product under consideration. In some cases almost the whole population is reached following the exponential growth; the process turns in the latter part of the logistic model to a high penetration level, and the adoption process of the rest of the population is irregular and not moldable. In practice, this means that the diffusion process tends to better fit an exponential (Figure 7) rather than a logistic distribution.

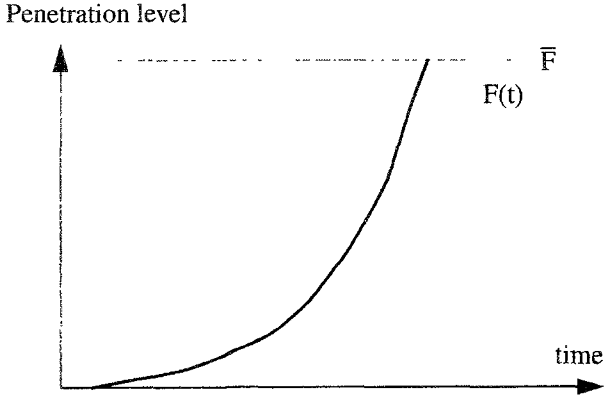

**Figure 7.** The exponential diffusion distribution.

The potential user population reached by this model may not be the population reached in the long term but a subpopulation of it. The expectation of the continuing exponential growth is unrealistic (see Figure 8) but works in some cases better than the logistic model. Sooner or later the progress turns towards a decreasing growth, and the latter part of the logistic model starts. In the analysis, there is a danger of strong belief in continuing exponential growth (Figure 8). The latter will be replaced by a decreasing number of new users, and the diffusion model should be switched to model this new behavior. In some cases the interest of the analyst concentrates on a certain phase of the whole process—perhaps only the exponential growth phase. If the analysis period continues long enough the analyst should be familiar with the switching point between two models or should be able to re-engineer the whole process to use a model that is more suitable for the analysis. This case is discussed by Irvin [7].

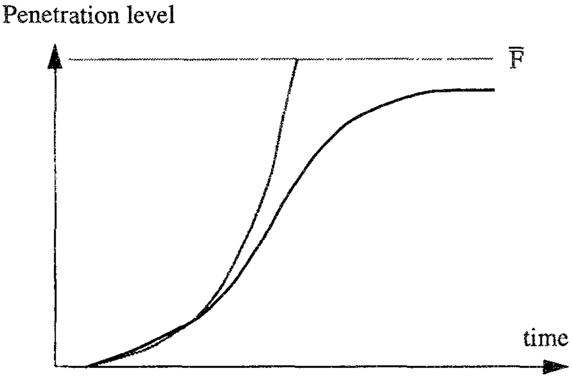

**Figure 8.** Logistic and exponential diffusion curves.

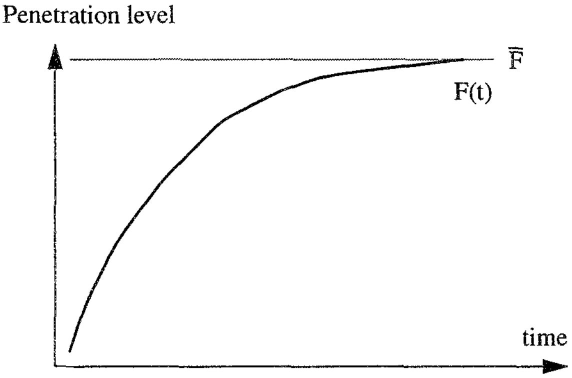

**Figure 9.** The reverse diffusion exponential distribution.

A third model worth discussing in this context is the reverse exponential distribution (Figure 9). This model is used to analyze the diffusion of "trend" or "fashion" articles; for such products typical features are a fast-approached full penetration and a fast-decreasing interest in the adoption (from the point of view of the adopter distribution function, which is a decaying exponential distribution). This model has been used, e.g., by Coleman [3] for the analysis of social innovations in the 1960s. Similar to the exponential model, this is partially a deficient one. For some reasons the embryonic phase of the total progress is missing, and the diffusion process turns to the fast-growth phase immediately in the beginning or has just a short "early tale" that is either not encountered or is not of interest to the analyst.

### 5.2. *Risk analysis*

The diffusion of an innovation of the technical improvements in a product are always uncertain. Martino [21] has studied the combination of risk analysis in the diffusion. In this work, the author introduced a risk analysis associated with the diffusion process. The technique is based on the statistical uncertainty and is managed by the use of *confidence contours* of the progress analyzed. Figure 10 shows an instance of this analysis where the diffusion curve (solid line) is enclosed between two estimates (dashed lines) beyond a given prediction point. The width of the limiting curves quantifies the uncertainty or risk associated with the forecast at a given point in the future.

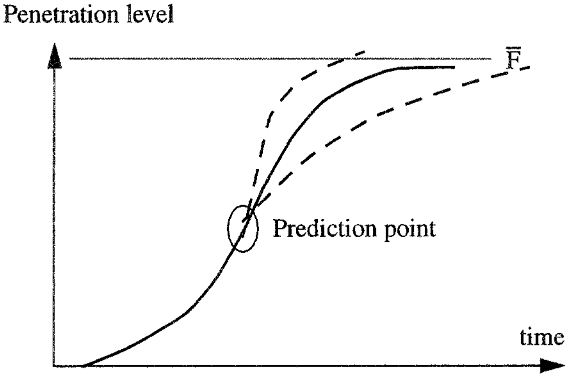

**Figure 10.** Risk analysis.

## 6. Towards the essence of the diffusion—loose modeling

Diffusion models derived from primitive mathematical diffusion models and incorporating understanding of the dynamics of the process being investigated are called *heuristic models of diffusion*. The main advantage of heuristic over mathematical models is an enhanced understanding capability for qualitative description, not a focus on getting exact quantitative forecasts.

### 6.1. *Principles*

The purpose of this section is to introduce the *use of heuristic analysis* in technology management. The heuristic model itself is introduced (in short) in subsequent sections. The following principles are discussed:

- dependency between meta, product, and process levels of innovation,
- flexibility of user potential,
- sequence of technology generations,

- modularity, key technologies and unification,
- discontinuity in the process,
- quality dimension of adoption, and
- information hiding.

The case study in Section 7 illustrates the essential parts of these principles.

### 6.2. *Meta level, process, and product*

In technology diffusion, three interdependent levels can be distinguished:

- *meta level*; the level of elementary technologies applicable to products and processes,
- *product level* (*physical level*); final products based on meta-level technology; leading to the pressure on improvements in process level, and
- *process level*; the technology needed for competitive production of (physical level) products.

As an example in the analysis of information technology, the *meta level* refers to the improvements in microelectronics (e.g., capacity and performance of a chip), the *physical level* exhibits the spread of PCs among a certain population, and the *process level* denotes improvements in the production technology of PCs (the capacity of production lines, the spread of production, and the design automation dedicated for PC assembly, etc.). The time dependency between these three abstraction levels is shown in Figure 11. Improvements in the *meta level* can be interpreted as a maturity of the basic technology measured by the capacity/performance variables. The behavior of these variables resembles the dif- fusion measured in quantitative variables in other levels (product, process).

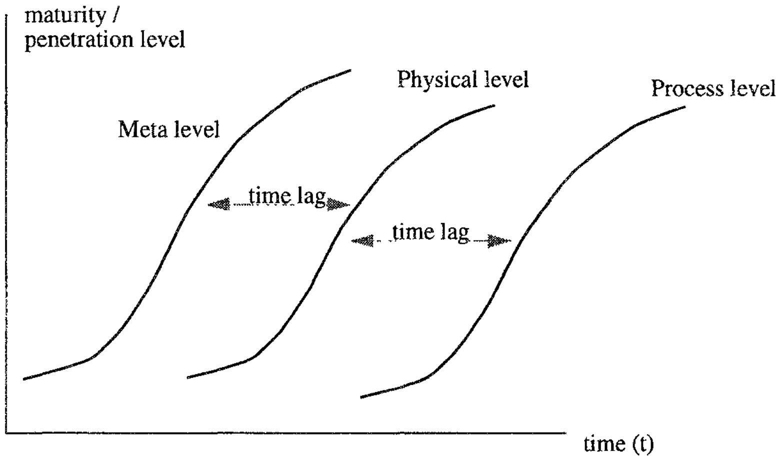

**Figure 11.** Diffusion in the meta, physical, and process levels.

*Process innovations* have interrelations both in meta and physical levels. Meta-level improvements are elementary factors, not only for products but also for process innovations. The interrelation between process and product innovations is based on the changes in the demand of the physical product. The pressure to improve the production process is growing as the demand for the product grows. At the same time more advanced production processes will lead to more advanced product properties, lower prices, etc. A result of this cyclic process is the*expansion* of the user population.

There exists a technology- and organization-dependent time lag between changes in the three abstraction levels. The time lag represents the *reaction time* of the organization to adopt the new technology; in contrast, the maturation time is the time needed by a *technology* to become utilizable in the organization.

### 6.3. *User potential is flexible*

In mathematical diffusion models, the potential user population is assumed fixed. As a precondition for the diffusion model, this provides a *stable environment* for the diffusion. In reality, the process is affected by several external factors. In studies of mathematical diffusion models, Sharif and Ramanathan [26] have discussed the flexibility of the user potential. According to their study, factors affecting flexibility in the user potential can be divided into two categories: *factors affecting the demand and factors affecting the supply.* Factors affecting the supply include social, psychological, and territorial changes in the user potential, the technical complexity of the innovation, the condition and aging grade of the technology, and the economy, among other things. Factors affecting the demand include prices, advertising and maturity of the technology.

All of these factors have a direct and an indirect effect on the adoption by changing the structure and the extent of the *user potential.* These factors cause changes to the regularity of the diffusion process itself, as well. These changes can be taken into account when a fixed user potential is replaced by a time-dependent user potential function (see Figure 12). The interrelation between the user potential function and the adoption function is twofold: the increase in the amount of users and improvements in the technology both create new user potential. The growth rate in the adoption is based on the lag between the penetration level and the potential level (the deeper the lag, the faster the growth speed). The shape of the potential function $\overline{F}(t)$ is milder than the shape of the adoption function $F(t)$ because there exists an *absolute upper limit of the potential,* which is closer to the potential than to the adoption function.

In general, the *growth of the adoption function is faster than the growth of the user potential.* However, this is not true for all cases. According to a study by Randles [24] concerning the adoption of computer terminals, the potential grew faster than the amount of adopters. This study indicated that nonprofessional users experienced the computer terminal as technically complicated. In the beginning the user potential was and remained reasonably low. After a learning period, computing skills grew in the *expert organization* of the study and created a faster demand for computer terminals than economical resources permitted to fulfill. The organization adapted to the demand; at the same time, the prices of terminals dropped, and the *temporary* abnormal behavior was normalized.

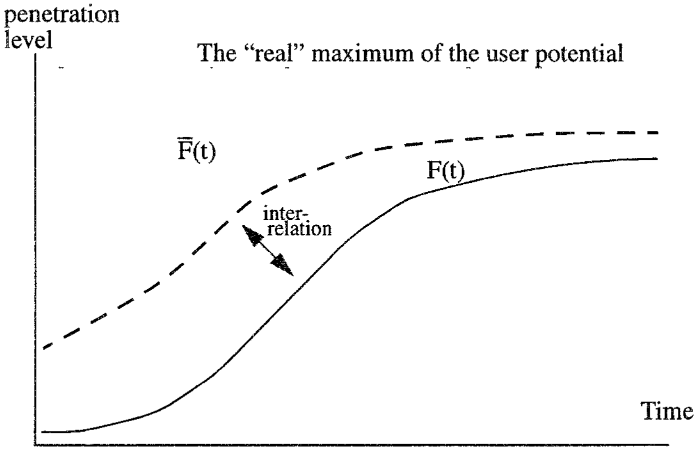

**Figure 12.** Time dependency of the user potential.

An analogous situation was encountered in Finland in the adoption of the newest generation of cellular mobile telephones (digital GSM). The GSM technology is very complicated in terms of both the telephones themselves and the network equipment as well. The standardization procedure took longer than expected. For these reasons the product development phase of GSM products has been delayed not only in Europe but worldwide. The availability of *validated* equipment was restricted. During the product development phase of GSM equipment, two independent operators began fiercely competing for their market share and, as a side effect, created a fast-growing demand for telephone sets around a year earlier. As a consequence, the number of potential users grew faster than the number of real users.

### *6.4. The case of technology generations*

A special case in the analysis of external changes to the diffusion are *changes between technology generations*. The pressure to make the positive adoption decision is based on the benefit expected from the innovation. This benefit depends on the *innovative power* of the technology/product. This limited power is "*consumed*" during the diffusion period (adopters are consumers of a limited resource). When the innovative power of a product is finished, the full penetration rate is achieved, and new adoptions no longer exist.

New *technology generations* increase the innovative power of a product. After the introduction of a new generation product, it does not immediately replace the previous one, but starts to compete with it. This creates a sequence of simultaneous diffusions of the same product on the market. This *generation model* is a special case of the *multistage diffusion*, which can be defined as a *sequence* of separate diffusion processes *competing* against each other (the products are substitutes for each other).

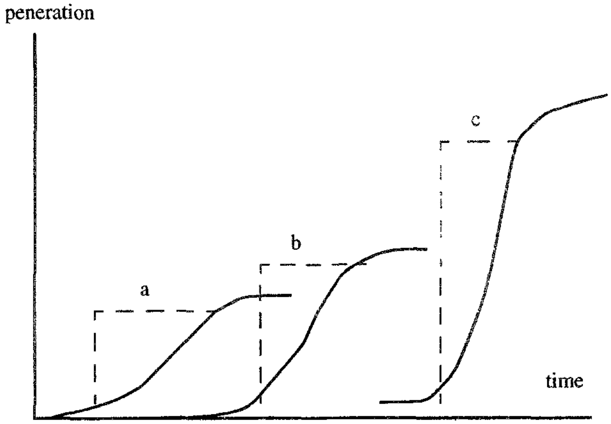

**Figure 13.** Technology generations.

In the sequence technology of generations (see Figure 13), diffusion of the older generation is still proceeding at the mature or aging phase when the new generation is introduced. This is very typical today in consumer and professional electronics. Norton and Bass [22] have analyzed differences between the diffusion of technology generations and have reported the fol- lowing observations:

- the *fast-growth phase* (takeoff from lower threshold to higher threshold) is shorter in new generations than in older generations,
- all changes in the diffusion of older generations occur more slowly than those in newer generations (e.g., the time to achieve the lower threshold after introduction and full penetration after the upper threshold),
- the user potential grows from generation to generation.

These changes can be explained by the imitation effect, better quality of newer generations, improved product properties generating new uses, etc. Evidence for the preceding phenomena can be found in the study by Randles [24] concerning the diffusion of pocket calculators. In the study by Jaakkola ([8], p. 129) a short-run reaction, in which the introduction of the new technology temporarily accelerated the diffusion of the older generation product, was encountered in the case of black-and-white and color televisions.

### *6.5. Modularity and key technologies*

In the analysis of technology diffusion, two categories are distinguished:

- *micro technology* (single-component technology); the object is typically an individual product having a simple quantitative measure representing its diffusion. Such an example is the spread of PCs, which can be measured by the number of PC sales with respect to the potential user population,
- *macro technology* (compound technology); the object is a structure of subtechnologies; the measure is a hierarchical structure having single-component technologies as "leaves" of the "*technology tree*"; an example is the spread of manufacturing automation, which is a weighted sum of component measures such as the spread of robots, spread of CNC-machines, spread of organizational changes in companies, etc.

The *macro-level diffusion* is analyzed by a compound measure. In time, the *weight* of component technologies changes: some component technologies become meaningless, and some have an increased or decreased weight and new components appear. Some of the component technologies have a *simultaneous* effect, and some follow each other *sequentially* in time.

The complexity of a macro-level analysis of diffusion depends on the amount of component technologies and interdependencies. In the worst case, the number of factors in the expression needed to describe the total behavior is the product $n_1{}^*n_2{}^* \cdots {}^*n_m$, in which $n_i$ is the number of simultaneous behavioral factors affecting the total behavior in the $i$th detection period. Joining sequential detection periods together, in the worst case, the complexity is the product of former products (conditional paths from detection period to detection period). The analysis can be simplified in two ways:

- supposing that the weight of component technologies is constant in the study period,
- decreasing the amount of simultaneously manageable subtechnologies.

In some cases the weight of a single component technology grows so high that it starts to dominate the total behavior, and the effect of other subtechnologies becomes almost meaningless. The dominating subtechnology *of the period* is called a *key technology*. Key technology analysis simplifies the analysis of several simultaneous subtechnologies to the analysis of a sequence of key technologies (see Figure 14).

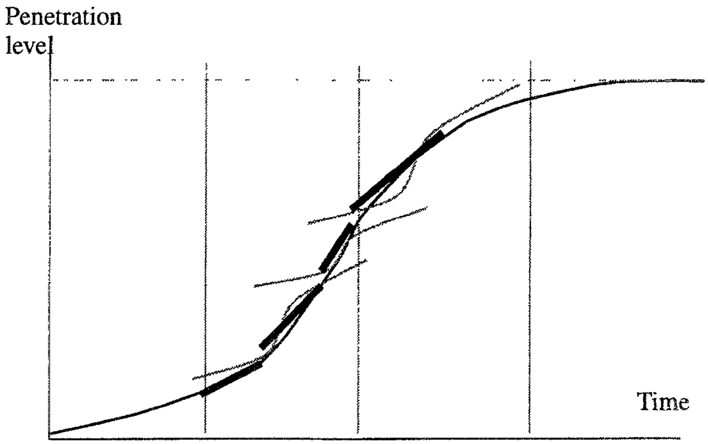

**Figure 14.** Modularity and key technology analysis.

### *6.6. Discontinuity in the progress*

Diffusion models suppose that the progress is regular. The key technology analysis creates a total behavior, which consists of diffusions of a sequence of single key technologies. Where the weight of an old key technology starts to decrease and that of a new one becomes dominant, there exist a*discontinuity* and a *phase dislocation* in the progress (see Figure 15): the *aging phase* of the old technology is replaced by the *growth phase* of the new one in the macro level progress. Correspondingly, a reason for the discontinuity may be caused by sudden changes in the diffusion environment.

In the analysis, background interpretation factors are different before and after the discontinuity. Factors affecting the progress of diffusion are different in all (four) phases. In particular, the expected short-term progress is totally different in the technology moving to its late mature and aging phase than in its early growth phase. At the phase shift, it is important to move from the old progress curve to the new one to avoid wrong forecasts (following the wrong curve in the situation where the old and new curves are overlapping).

Linstone [16] elaborated on the problems of phase shift. First, the mature phase of an older technology is changing to the growing phase of a newer one, and it is sometimes difficult to notice that the driving force of a progress has changed. Second, the phase where the old technology is replaced by the new one always causes a chaos (grey area), in which the behavior of the process is not fully predictable. The predictability can be increased by a careful change in management. Foster [6] emphasizes the importance of a *discontinuity point* with respect to the proper timing for the technology change. The user must know the remaining innovative power of the old technology and the possibilities of benefiting from the new technology. Comparison between these two factors leads to the decision of when to replace the old technology with the new one. For correct timing, the user must

- know the life cycle of the existing technology,
- maintain long-term R&D activities to prepare for the rising new technologies, and
- be market sensible and aware of the right moment for the change.

One part of the successful technology strategy is the ability to *manage the period of change* (this is known as well-managed adoption into the new technology).

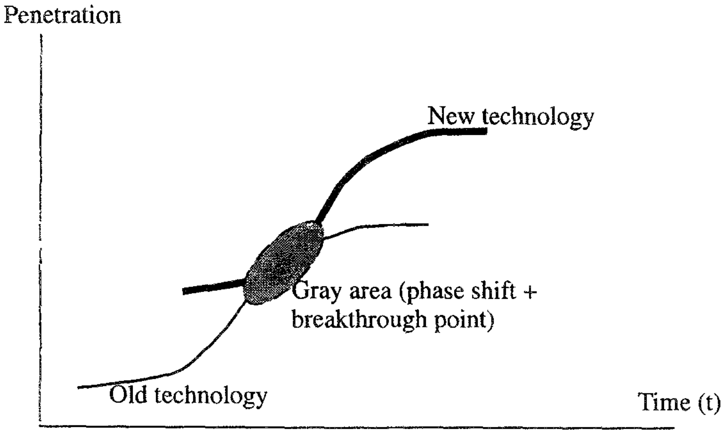

**Figure 15.** Discontinuity in macro level.

### *6.7. Dimensions of the diffusion function*

The diffusion process is typically presented as a one-dimensional function *quantifying* the penetration level (or number of users) as a function of time. The higher the penetration rate in the user potential, the slower the quantitative growth. At the same time, the significance of the *qualitative growth* (*infusion*) becomes higher (see Figure 16). This results from influences such as the following:

- users learn to benefit from all the properties of the technology (learning period)
- because of "ergonomic" changes, the quality of the use increases
- the performance of the equipment in use grows.

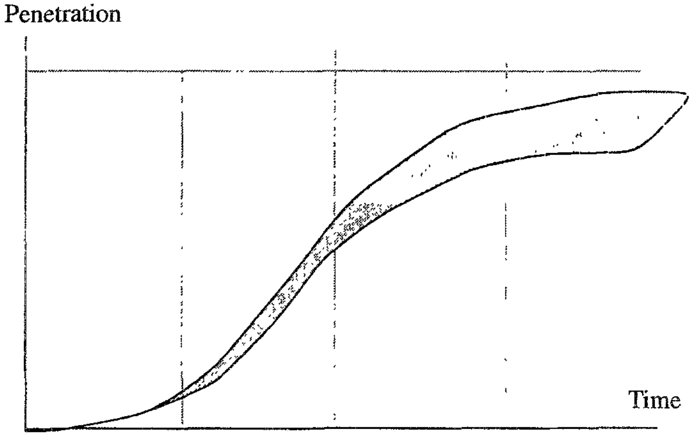

**Figure 16.** Quality dimension.

The quality of use becomes better when the technology starts to reach its maturity and the stage of solid solutions. After that the changes in the technology start to concentrate on the *usability*. *Qualitative diffusion* is an abstract concept and is more difficult to measure. An example of qualitative changes is the diffusion of PCs. This can be described as a one-dimensional quantitative function describing the number of professional PCs (numbers are available from market research and some supporting statistics). The period of existence of PCs has witnessed a number of improvements in the performance of computer equipment, user interfaces, programming tools, utility software, etc. All these factors have increased the usage of the PC from the late 1970s to the present.

## 7. Case study—Mobile telephone diffusion in Finland

### *7.1. More about the data*

The data analyzed is shown through time plots. Such plots, however, tend to hide essential information. This may be caused by the scaling (scaling may not display all inferences in the progress), or by using macro-level analysis instead of the sum of module analyses, etc. The mobile telephone data discussed earlier in this paper includes hidden information useful for a more in-depth analysisof the one made earlier in the paper.

Figure 17 shows the data components. The macro-level progress of the adoption of mobile phones is driven by four sequential module processes. The first and oldest generation, the manual ARP in (curve (1)) reached its full penetration (35,500) in the middle of the 1980s. Since then it has been replaced by the new generation of analog telephones, the analog NMT 450 (curve (2)) and NMT 900 (curve (3)). (The designations 450 and 900 refer to the frequency in MHz.)

Since the early1990s, a new digital telephone system, the European GSM (curve (4)), has started to overtake the market. At the end of 1996, GSM licenses had almost reached 900,000 users, and they had already approached the number of users of the earlier dominating NMT 900 network in 1995 (in just four years). However, the figure shows that, during the first half of the1990s, both NMT and GSM networks have not yet reached their inflection points, and there exists a series of exponentially growing processes interacting with each other. The behavior of the four diffusion processes includes a large number of explanative factors not moldable in the model: changing user potential, network coverage, network capacity problems, license and call prices, monthly fees, services, etc. Short time series make impossible the mathematical analysis of individual processes, which seem to fit the properties of the theory of competing and replacing technology generations. The following example shows the difficulties encountered in performing a practical analysis of fast-changing technologies.

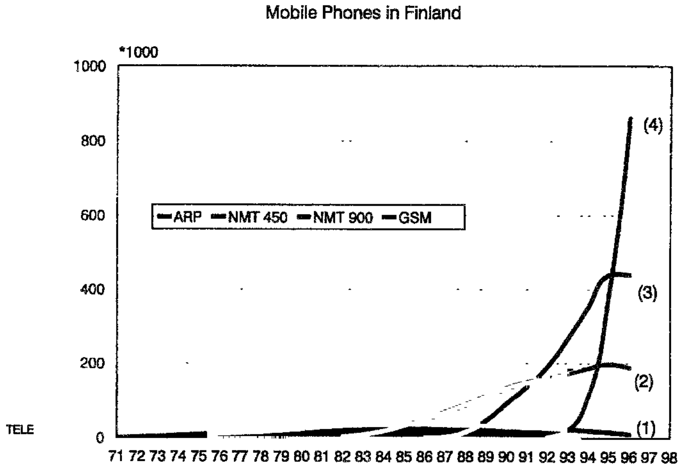

**Figure 17.** The diffusion of component technologies.

### *7.2. The heuristic analysis*

The diffusion of mobile phones follows the curve in Figure 3. The curve actually represents the sum of the licenses of the semiautomatic analog ARP network, analog networks NMT 450 and NMT 900, and the digital GSM networks of two operators (Figure 17).

*Information hiding.* Because the sum curve in Figure 3 includes data of four different subprocesses, it hides data that is essential for a better understanding of the macro-level process. A more accurate analysis is possible by studying the diffusion of the components (Figure 17). This figure illustrates several viewpoints introduced in this paper:

- *modularity* of the macro-level process;
- *key technology dominance*: ARP (1) until the 1980s, NMT 450 (2) until the end of the 1980s, NMT 900 (3) from the end of the 1980s, and GSM (4) from 1992, when two competing operator networks were started (see Figure 18);
- *technology generations* having growing user potential and faster growth speed compared to older ones.

However, Figure 17 does not support the hypothesis of *replacement*: in practice, there exist replacement and some amount of surrenders of the old technology. Simultaneously, there are new adopters using the old generation technology as a first adoption because of the opportunity to get a cheaper used mobile phone (e.g., small firms, private people). In the long term, lower prices of new models will favor the new product, causing an increase in the number of replacements.

*Scale problems.* Figure 17 contains some inaccurate features that are caused by different scales of the subtechnologies. The ARP network, separated from the total diffusion process, represents a very regular and typical diffusion process of a mature technology (see Figure 19).

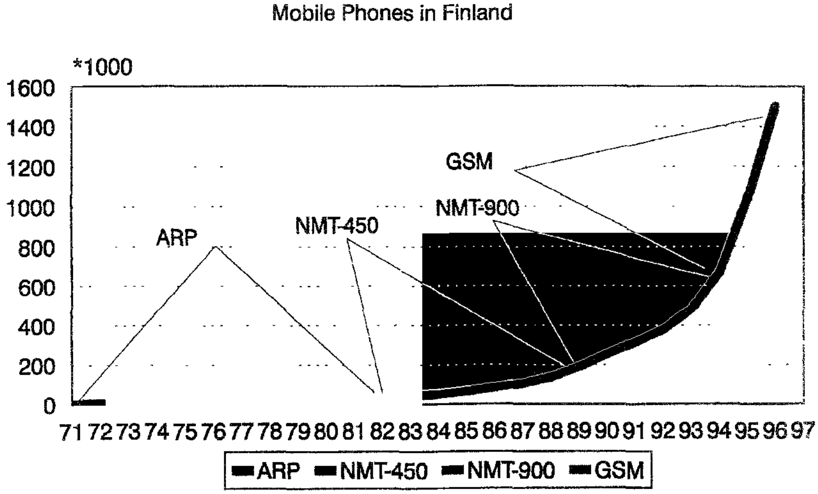

**Figure 18.** Changes in the mobile telephone key technology.

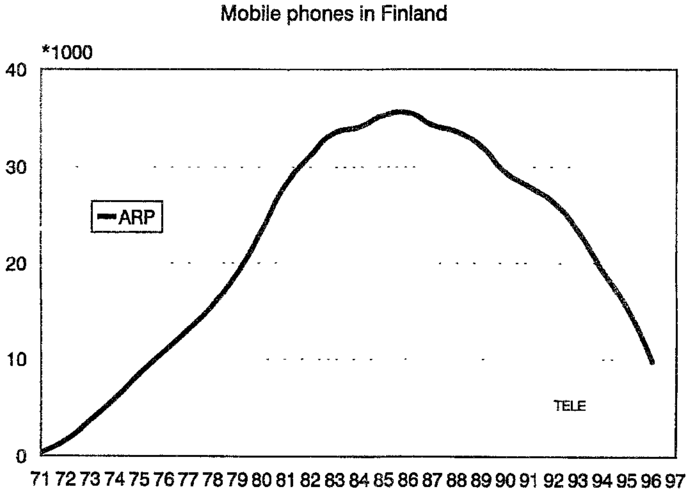

**Figure 19.** The use of ARP telephones in Finland.

*Giving-up phase.* The example of Figure 19 describes the number of licenses of the semi-manual ARP mobile phone. The negative diffusion (decline) started in 1987, and the decrease in the number of users seems to be a mirror image of the growth phase. As seen in Figure 17, the reason for the decline are the competitive networks (NMT 450 in 1982, NMT 900 in 1986, and GSM in 1992). However, in spite of the availability of more advanced mobile phone services, there still exist new adopters of the ARP telephones.

In Figure 19 the giving-up phase seems to follow the same analytic form (inverted) as the positive phases. In studies on the diffusion processes there is no evidence for the similarity of the positive and negative diffusion phases. The speculative approach may suggest that a mirror image of any of the analytic forms of diffusion models describes the progress in the giving-up phase. A wider study is needed to prove this hypothesis.

Features to notice in Figure 19 include the following:

- the process reaches its full penetration just before the middle of the 1980s; after that, *negative diffusion* starts;
- there seems to be an irregularity in 1984–1985 causing an *unexpected growth* in the amount of licenses; this is due to the technical change from a manually operated system to a semiautomatic one, i.e., it is caused by an *external* factor that is not radical enough to become classified as a new generation in this subtechnology.

*External disturbance.* In Figure 17 there is another irregularity detectable in the beginning of the 1990s. The growth speed of the NMT 450 network (curve (2)) decreased temporarily for a couple of years. This irregularity was caused by the heavy load in the network; as a result, just a few new licenses were available. The operator of both NMT 450 and NMT 900 wrongly believed that the replacement speed would be faster than it actually was, which caused the overload in the old network. A new technology was partially responsible for generating *growth to the demand of the old* one, too. An analogous situation occurred in the beginning of the 1990s when two operators started competing fiercely for the share in the fast-growing GSM market. Unfortunately, the time was too early for GSM equipment: most manufacturers had not yet introduced their phones, and only a small amount of equipment has passed the tests of the national control body. This led to economic losses for some manufacturers, for they were not able to reach their anticipated sales income after losing the benefit of early entry into the market. In this case, the manufacturers were *controlled by external forces* (teleoperators).

*Forecasting by analogy.* Fitting Mansfield's model to the NMT 450 and NMT 900 data corresponding to the "almost" fully-penetrated diffusion, we obtained the following values of the model parameters:

- for NMT 450, $c_1 = -3.0815$ and $c_2 = 0.4818$,
- for NMT 900, $c_1 = -4.3170$ and $c_2 = 0.6521$.

Using the least-squares fit resulted in the plots shown in Figures 20 and 21.

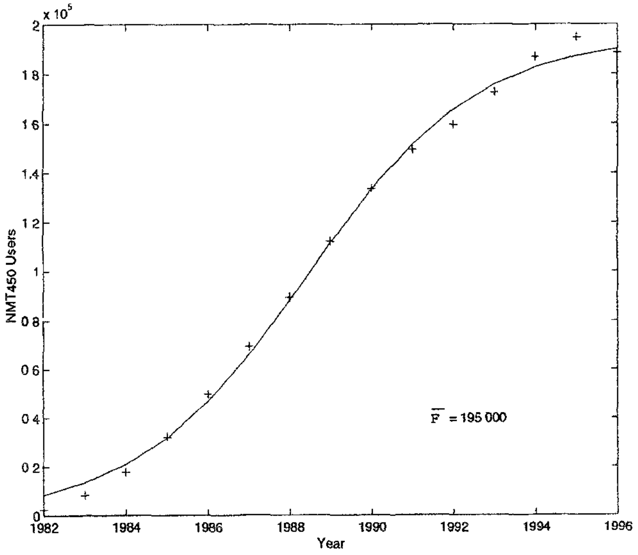

**Figure 20.** NMT 450 Diffusion curve.

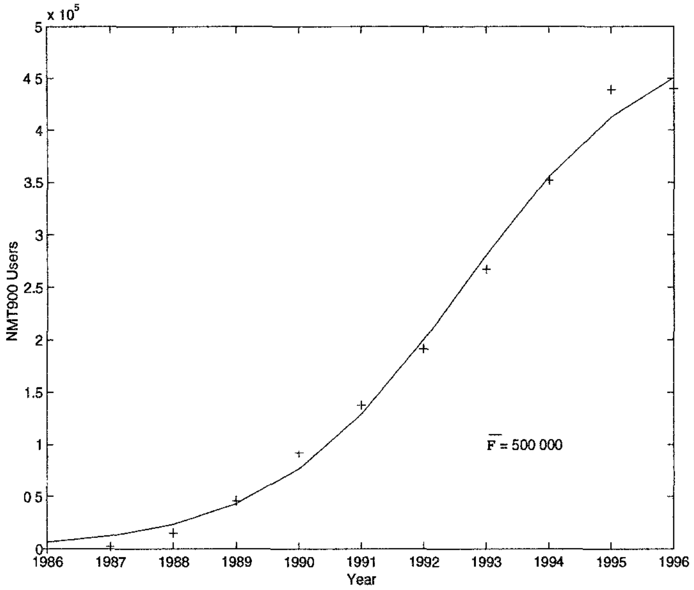

**Figure 21.** NMT 900 Diffusion curve.

From this set of model parameters and based on the curves in Figures 20 and 21, one can draw the following conclusions:

- the exponential growth is faster for NMT 900 compared to NMT 450 (the difference is quantified in parameter $c_2$; whereas,

- the time lag is more important for NMT 900 than for NMT 450 (see the corresponding values for parameter $c_1$). This is due to the fact that at the time NMT 900 was introduced, NMT 450 was undergoing its "growing" phase (see Figure 1).

By analogy, the GSM was introduced in Finland during the "growing" phase of NMT 900 and may thus be expected to diffuse in a similar manner. That is, one would expect an increase in the value of parameter $c_2$ and a decrease in $c_1$. A simple linear extrapolation produces $c_1 = -5.5525$ and $c_2 = 0.8224$. Although these estimates are not accurate, they constitute a good initial guess for the "true" parameter values. Applying a least-squares fit to the available GSM data with an expected total number of user potential, $\overline{F} = 3$ million, we obtained the following values: $c_1 = -5.3152$ and $c_2 = 1.1051$. These values are used to forecast the diffusion of GSM phone users, and the results are shown in Figure 22.

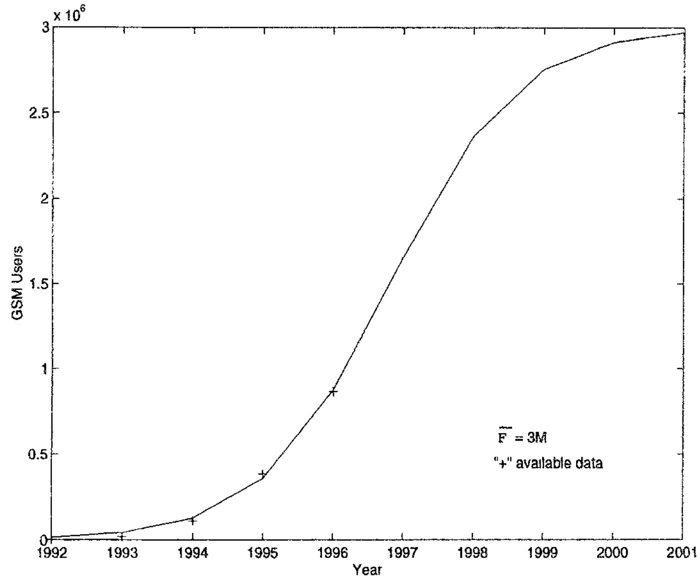

**Figure 22.** GSM Diffusion forecast.

The exponential growth rate turned out to be greater than what was expected through linear extrapolation, but the latter has no rationale in this context. Still, one would expect a nonlinear increase in the growth rate from one generation to the next, especially if the newer generation product offers more desirable services and features (which is the case for the worldwide standard GSM).

Our case study has illustrated the power of the diffusion model and some of the difficulties encountered in setting the parameter values.

## 8. Conclusions

This paper has provided an introduction to the principles of diffusion analysis. In particular, the focus has been on the description of the diffusion of an innovation, called the *first adoption model*. The other approaches include, e.g., *replacement models*, describing the replacement of a product by a new one, and *figure-of-merit* models, describing the changes in the capacity of a technology. Other models include *multiadoption* processes, modeling the diffusion of parallel product *generations*, and *adaptive models*.

A popular mathematical (Mansfield) model was used to model empirical diffusion data. Problems in the mathematical analysis were also discussed, and the optional approach of heuristic modeling was introduced. The analysis based on the principles of heuristic modeling was described in the case study concerning the spread of the use of mobile phones in Finland. The target empirical data was only used for descriptive purposes; however, in many ways several interesting phenomena of technology diffusion were illustrated in the study. The motiva- tion to write this paper was to give the readers of this journal a short overview on the impact of their research work on circuits, systems, and signal processing on real products. This is especially important in the area of high-technology products.

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