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LOGISTIC SUBSTITUTION MODEL AND TECHNOLOGICAL FORECASTING

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Abstract

In this paper the application of several models, based on the logistic growth function (simple logistic, component logistic and logistic substitution models) in the context of technology change forecasting is discussed. The main idea of this paper is to revise existing models and arrange working hypotheses for future research. First, the features of a simple logistic model are presented, different types of competition are discussed and a component logistic model is briefly presented. Second, logistic substitution models in the context of long-term technological forecasting are reviewed. Third, some hypotheses about how to improve the reliability of the logistic substitution model for studying the technological future are proposed.

Keywords

Bi-logistic; multi-logistic; logistic substitution model; resource limitations; technology future study; logistic S-curve; socio-economic cycles.

1 INTRODUCTION

The whole purpose of science is to find meaningful simplicity in the midst of disorderly complexity.
Herbert A. Simon, *Models of My Life* (1991)

The main objective of scientific study is to reveal and describe regularities which can be used to predict the future. Among his many achievements, inventor and researcher, Galio Galilei (1564-1642), called the "father of modern science", made an excellent forecast about the periodic return and nature of a comet. That forecast was based on observations and a mathematical model. In fact, forecasting plays a significant role in the development of science as soon as it is employed as a method to verify proposed theories and hypothesis.

Our research on long-term technological forecasting is inspired by the description of "the lifeline" of technological systems from Altshuller [1] where contradiction models, S-curves, and the limitation of resources play important roles. Our former paper (2005) focuses on problems with stages of the generic forecasting process. The distinction between short-, medium-, and long-term forecasts, based on three phases of S-curves is also proposed [2]. One S-curve is typically divided into 3 phases as in figure 1: before point α , between points α and β , and after β . A short-term technological forecast is about one phase of an S-curve, while a medium-term forecast considers two phases. The scope of study for a long-term forecast is usually beyond one technology, since it studies at least three phases on an S-curve and may consider several growth processes and more than one system.

Our article for the ICED'07 conference [4] depicts theoretical and practical results from two forecasting projects. A critical-to-X feature merges qualitative and quantitative natures of long-term forecasting. This paper illustrates through case studies for energy technologies how the prediction of technological barriers can be facilitated by mapping the contradictions in combination with assessment of limiting resources.

In our paper for the TFC-2007 conference [3] emphasis on the definition of the growing parameters for many logistic growth models is made. To address the issue when there is no data for emerging technologies, the naïve and causal methods for long-term forecasting are discussed. The causal method is applied to adopt quantitative models for predicting the diffusion of new technologies. In particular, as a growing parameter for

consecutive logistic growths it is proposed to apply the amount of knowledge in percent of readiness for the transition from exploration to experimentation towards exploitation phases.

In the present paper we develop the applications for reliable and reproducible long-term technological forecasting using the naïve method and logistic growth function. After revising the component logistic (CLM) and logistic substitution models (LSM) some hypotheses for improving their reliability are proposed. According to our findings these models can help cope with the problems of qualitative-quantitative forecasting described in previous publications [2, 3, 19].

The following section is a short history of particular logistic models and concepts of competition. The section 'Logistic Substitution Model' focuses on the questions: "How does LSM work?", "What are the known difficulties?", and "What can be done in order to improve reliability of forecasting with LSM?". The concluding remarks propose possibilities for further work.

2 LOGISTIC MODELS AND FORECASTING

"... with enough parameters anything can be fit..."

Most of the studies of technological changes are based on the application of logistic models and S-curves. However, not all S-shaped curves are logistic ones. Furthermore, there are symmetric and non symmetric logistic curves which are consequently classified as simple logistic functions or complex ones.

In the scope of our research, we apply the simple logistic S-curves due to the ease in interpreting the meaning of their parameters and the simplicity in estimating the parameters from their observed phenomena. Moreover, in numerous publications it was concluded that the other models of non-symmetric growth have limited application due to their complexity and low efficiency for technology forecasts [6, 7, 8, 9, 10].

The widespread practical application of the logistic function as a means to depict growth processes started with *An Essay on the Principle of Population* by the English economist Thomas Malthus (1766-1834). In 1825 Benjamin Gompertz published work developing the Malthusian growth model for demographic study (the law of mortality). The first reference to the logistic curve as a model of population growth can be found in the work of Pierre-Francois Verhulst (1838, 1845, 1847). In 1923 T.

Brailsford Robertson suggested using the function to describe the growth process in a single organism or individual. Raymond Pearl rediscovered the function (1924, 1925) and used it extensively to describe population growth, including human ones. During 1925 and 1926, while working independently, Alfred J. Lotka and Vito Volterra generalized the growth equation to quantify competition among different species and coined the predator-prey equations.

One of the earliest studies about technological substitution described by S-curves was done in 1957 by Zvi Griliches. Using concepts of Griliches in 1961, Edwin Mansfield developed a model to depict the rate at which firms follow an innovator. In the early 1960s, S-curves were regularly employed for technological forecasting [8]. The diffusion of the innovation theory, formalized by Everett M. Rodgers [18] in 1962, postulated that innovations spread in society in an S-curve.

A significant achievement was accomplished by J. C. Fisher and R. H. Pry (1970) in formulating the model for binary technological substitution as an extension of Mansfield's findings [12]. C. Marchetti proposed a logistic substitution model for describing technology substitution in the dynamics of long-run competition (1976-1979) by extensively using the Fisher-Pry transform [7]. In 1994 P.S. Meyer proposed the component bi-logistic growth model [5]. Later on, a component logistic model with multi-logistics generalises this bi-logistic growth model [6]. The application of bi- and multi-logistics makes possible the description of complex growth processes through a family of simple logistic curves.

Logistic substitution and component logistic models in combination with the Fisher-Pry transform technique provide clear and suggestive outputs for supporting medium- and long-term forecasting of technology change [5-8, 11, 13-16].

2.1 Simple logistic model (SLM)

The natural growth of autonomous systems in competition might be described by logistic equation and logistic curve respectively. In the context of our proposed research, natural growth is defined as the ability of a 'species' (system) to multiply inside finite 'niche capacity' (carrying capacity [5], a physical limit of resources [1]) through a time period.

As soon as the function parameters can be calculated using a partial set of data (e.g. the efficiency of changes in the internal combustion engine over the last 20 years) it is possible to use the equation in a predictive mode (i.e. how much that efficiency will grow and when). Nevertheless, the availability of a reliable set of data is a principal limiting factor for S-curve model application in the technological forecast of emerging technologies.

For socio-technical systems the three-parameter S-shaped logistic growth model (1) is applied to describe continuous "trajectories" of growth or decline through time.

$$N(t) = \frac{\kappa}{1 + e^{-\alpha t - \beta}} \quad (1)$$

Where $N(t)$ – is the number of 'species' or growing variables in question; κ – is the asymptotic *limit of growth*; α – specifies¹ "width" or "steepness" of the S-curve (e.g., $\alpha=0.19$ means approximately 19% growth per time fraction); it is frequently replaced with a variable that

qualifies the time required for the "trajectory" to grow from 10% to 90% of limit κ : $(\Delta t)^2$ – is *characteristic duration*; β – specifies the time (t_m) when the curve reaches 0.5κ : *midpoint of the growth trajectory* (t_m implies symmetry of a simple logistic S-curve).

These three parameters κ , α , and β are usually calculated by fitting the data. The method used to fit S-curves on data aims at minimizing the next sum:

$$\sum_i \frac{(N_i - D_i)^2}{W_i} \quad (2)$$

Where N_i , D_i and W_i are respectively, at times t_i , which is the value of the function, the data value and the weight we may want to assign to the data.

The function is originally evaluated by assigning arbitrary starting values to the parameters of N . After that, an iterative search is performed to determine those values for which the sum becomes as small as possible.

There are diverse fitting techniques. For instance, the asymptotic limit of growth κ can be estimated such as expert judgment, when α , and β are optimized to minimize residuals.

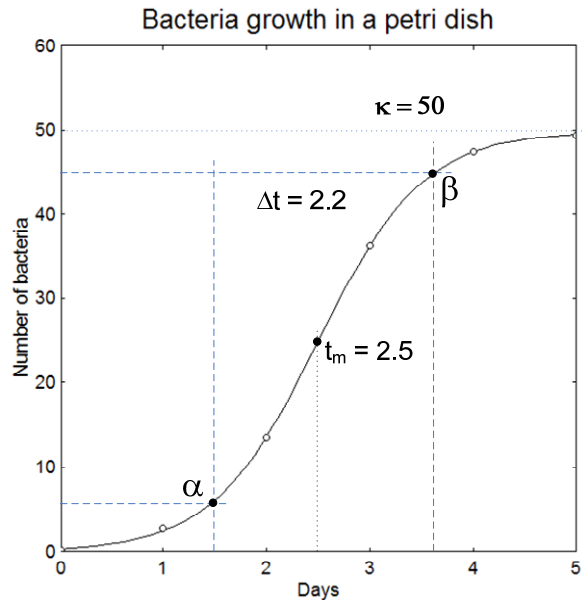


Figure 1: Growth of a bacteria colony consuming sugar and minerals in a closed Petri dish fitted to a logistic curve: limit of growth $\kappa=50$ species, characteristic duration $\Delta t=2.2$ days, midpoint $t_m = 2.5$ days.

For case $N(t) \ll \kappa$, the logistic model closely resembles exponential growth (3):

$$N(t) = e^{\alpha t + \beta} \quad (3)$$

An equivalent form of logistic equation (1) for practical application can be defined as:

$$N(t) = \frac{\kappa}{1 + \exp\left[-\frac{\ln(81)}{\Delta t}(t - t_m)\right]} \quad (4)$$

Empirical studies have shown that the characteristic S-shaped curve is present in thousands of growth and diffusion processes [7, 11]. Therefore, this model can be

¹ Where e – the base of the natural system of logarithms, having a numerical value of approximately 2.71828

² The decline can be described by a logistic with a negative Δt .

applied to both systems where the mechanisms of growth are understood and growing principles are hidden.

2.2 Technology diffusion and competition

Our working definition of *technology diffusion* is the following: technology diffusion is the process of obtaining (new) technology adapted through practical use. In the context of long-term technological forecasts, technology diffusion can be presented as a process of transition from invention to innovation [17, 18]. Therefore, such a transitional process from the first feasible prototype to the first regular product and new market creation takes time. For photography it took 112 years, for the steam locomotive – 55, for rolled wires – 47, for the lead battery – 79 and for arc welding – 49 years [17].

In the framework of the present research *invention* is defined as the result of engineering activities in a technological context which resolves contradictions between specific needs (how it was perceived) and known laws of nature. The output of the invention process is a feasible solution and working prototype, but not necessarily a patent³. *Innovation* is the result of socio-economic and technological activities. It produces added value because of an uncommon way of doing business. Thus, it seems meaningless to compare invention and innovation. They result from different activities and their values are measured by different parameters.

From invention to innovation, technology diffusion is a long and bumpy road full of uncompromising competition. It is a fact that hundreds of thousands of inventions have never become innovations. Furthermore, when innovation occurs, the long delay from invention to innovation makes it difficult to study the causality of the innovation process. Unfortunately, these facts are frequently ignored in studies about invention-innovation relationships.

Moreover, it is evident, that competition among emerging technologies plays a crucial role in technology diffusion. One of the basic assumptions for long-term forecasts that we apply is: all systems (super-systems, sub-systems) evolve under competition according to the law of logistic growth. Thus, mechanisms of competition should be divulged and purposefully applied for technology forecasting in a reproducible way.

In his paper on the scientific approach of managing competition, T.Modis describes⁴ six ways that two competitors, can influence each other's growth rate [13]: pure competition, predator-prey, symbiosis, parasitic (win-impervious), symbiotic (loss-indifferent), and no-competition.

Pure competition is when both species suffer from each other's existence because they use the same resources to survive. The traditional example of this occurs between rabbits and sheep. Each one decreases the growth of the other but at a different rate (sheep multiply more slowly than rabbits but eat more grass).

Predator-Prey competition is a relationship in which two 'species' interact as 'predator' and 'prey'. The predators flourish when there are abundant preys. However, ultimately, predators surpass their 'food supply' and decline. When the predator population is low, the prey population will increase once again. These dynamics go on in cycles of growth and decline. The classical example

is the case of rabbit (prey) and fox (predator) populations. The Lotka-Volterra equations are usually applied to simulate the dynamics of this kind of competition.

Symbiosis is a situation where both species benefit thanks to their association. For instance, mobile phone sales trigger the increase of operators and new services and this escalation provokes sales of the latest mobile phone models.

Parasitic (win-impervious) is a relationship between two species in which one obtains some benefit while the other is unaffected. The classic example is from biology: remoras, which attach themselves to sharks and feed on their leavings without hindering their hosts. A market example is the increase of digital cameras and computers sales which prompt growth in the external hard discs market. However, the sale of external hard disks does not influence the sale of digital cameras.

Symbiotic (loss-indifferent) is a situation when one species suffers from the existence of another, which remains insensible to what is happening. A textbook case from biology is the shading out of one plant by a taller and wider one.

No-competition is a relationship between two species when there is no overlap in using resources to evolve. For instance, sales of coffee do not affect sales of tea in the same supermarket. Sales depend on seasonal variation rather on competition between two products.

In addition to two-competitor cases, the competition of one 'species' for resources (*Malthusian case*), such as *multiple competitors*, as well as a model of *indirect competition* (e.g. spatial competition when A interacts with B, and B with C, then C affects A through B) are revealed.

Given the number of various competition models it is not easy to subsequently build a practical instrument. Such a study becomes inadequately complex and time-consuming, with multiple opportunities for hidden errors and biases.

Therefore, problem can be formulated: it is necessary to take into account competition mechanisms that occur within technology diffusion among multiple competitors in order to consider intrinsic processes; but it is necessary to avoid the analysis of competition mechanisms, because it complicates applied models, and increases study costs. In addition, the complex models leave room for hidden errors, biases, and as a result, cause inadequate output.

2.3 Component logistic model (CLM)

If the data do fit well a large section of an S-curve, then one can argue for logistic growth... "if it walks like a duck and quacks like a duck, it must be a duck." T.Modis

As soon the logistic S-curve had been extensively applied to and studied in a wide range of socio-technical systems, the necessity of a feasible model to describe systems that experience two or more phases of growth became vital (medium and long term forecasting).

Starting with the assumption that the standard logistic S-curve describes one period ("pulse") of growth for a particular system, then obviously multiple growth pulses depict many systems [5]. Meanwhile, defining a system is a difficult task in itself. One of the fundamental ideas in the system approach is that all systems interact with their environment. In order to portray this phenomenon the system operator (multi-screen schema) must link super-systems, systems, and sub-systems as well as past, present, and future dimensions.

Indeed, a system is a demarcated part of the universe which is separated from the rest by an imaginary border. These artificial borders are unavoidable since to perceive

³ "A patent is a government grant to an inventor assuring him the sole right to make, use, and sell his invention for a limited period." (Collins English Dictionary. 8th Edition first published in 2006 ©)

⁴ It is referenced to the study of Kristina Smitalova and Stefan Sujan (1991).

or know anything, one must make this distinction. Nevertheless: How can we be sure about our delineation of a system? What are the criteria that justify the location of an artificial boundary?

To develop a system definition it is necessary to situate the boundaries and describe the characteristics of the system, the features of universe which affect the system outside of the system (super-system), and the interactions between universe and system.

Frequently, due to difficulties with the definition of the system, the time-series data cannot be cleaned and split properly. This leads to problems with fitting logistic S-curves to data. Before Perrin Meyer proposed bi-logistic and multi-logistic⁵ models, complex multi-parameters functions were applied for the extrapolation of this sort of data [5, 6].

Problem

Prior to discussing the component model, let us appreciate the problem. The evolution of systems should be described by multi-parameter complex functions and curves, since the systems rarely follow a single S-curve trajectory due to *indigenous* complexity (e.g. systems including sub-systems and sub-processes; the irregularity of system parts evolution, etc.) and *exogenous* complexity (e.g. quasi-random behaviour thanks to multiple interactions with other systems, etc.). However, the evolution of systems should be described by (symmetrical) simple three-parameter logistic functions, to provide clear physical interpretations, to be comparable with other system evolutions, to decrease errors during forecasting, and to be applicable in practice.

Solution

The component logistic model describes the complex growth processes using a combination of simple three-parameter functions by applying bi-logistics [5] or multi-logistics [6]. The mechanism of combination resembles the 'nested doll' principle [1] and once again confirms the fractal feature concept of natural growth [20].

For instance⁶, to study the dynamics of US Nuclear tests (source of data [21]) a single simple logistic does not provide an adequate level of residuals, while a bi-logistic growth curve fits data with acceptable residuals (see Figure 2).

Such a result was interpreted the following way: "...the fastest rate of growth (midpoint) of the first pulse occurred in 1963, following the Cuban missile crisis. While the first logistic pulse was largely the race to develop bombs with higher yields, the second pulse, cantered in 1983 and nearing saturation now (1994), is probably due to research on reliability and specific weapons designed for tactical use. The Bi-logistic model predicts that we are at 90% of saturation of the latest pulse. Processes often expire around 90%, though sometimes processes overshoot. The residuals show the extraordinary, deviant increase in U.S. tests after the scare of the 1957 Sputnik launch..." [5]

When reasonable interpretation is done, the application of component models provides suggestive and attention-grabbing results. However, our practical experience shows that experts might need several weeks to propose a realistic interpretation for obtained fits.

One of the remarkable characteristics of the component logistic model is its self-adjustment to a proposed definition of a system. Through the reduction of residuals

and decomposition of an initial set of data by multi-logistic ones the initial definition of a system can be corrected and refined. In the proposed example (Figure 2) the initial system for nuclear tests was decomposed to nuclear tests for aircraft and for missile delivery and indeed they demonstrate different features and interactions.

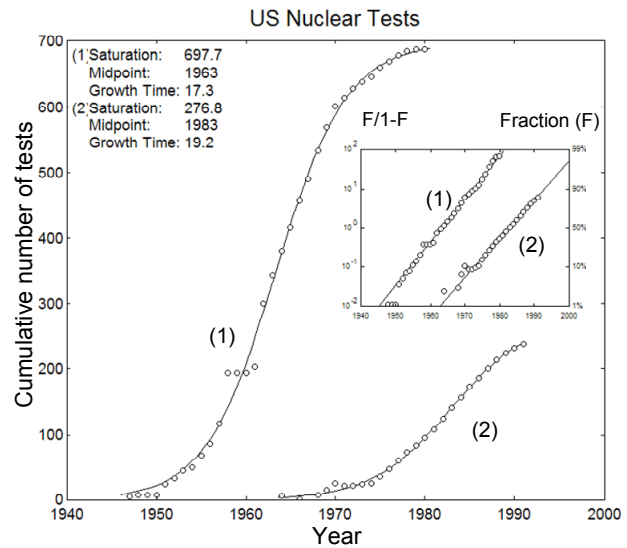


Figure 2: US nuclear weapon tests with a decomposed bi-logistic growth curve. The inset shows the component growth curves after using the Fisher-Pry transform.

Source: [24].

3 LOGISTIC SUBSTITUTION MODEL (LSM)

"...no two people, working independently, will ever get exactly the same answer for an S-curve fit..." T.Modis

In their classic paper Fisher and Pry [12] proposed the substitution model of technological change based upon a simple set of assumptions. It was suggested, that the model could be applied for "...forecasting technological opportunities, recognizing the onset of technologically based catastrophes, investigating the similarities and differences in innovative change in various economic sectors, investigating the rate of technical change in different countries and different cultures, and investigating the limiting features to technological change." At first, proposed mathematical transform, decreases the number of parameters defining logistic growth and second, allows the comparison of growth processes with very different absolute values (e.g. growth of total length (for US) for canals - 7×10^3 km, and for roads - 6×10^6 km).

Most of the sources for LSM refer to the publications of C. Marchetti, and N. Nakicenovic [7, 22] issued in 1979. However, early traces of an application of the Fisher-Pry transform to study technology substitution under long-term competition are already in a 1976 publication [23].

The logistic substitution model *describes the competitors' niche market* (e.g. fraction of market share). The life cycle of competitive technologies is subdivided into three periods: growth, saturation and decline, where the growth and decline stages are logistic growth processes.

Problem

In order to provide long-range (over 50 years) forecasting in areas of the energy market, and energy use, the researchers faced with the problem of applying models which capture and simulate numerous relationships and feedback characteristics (complex ones), to represent, among other things, the activity of an economic system and to report competition phenomena. It was also necessary, however, to apply models with minimum

⁵ For multi-logistic model growth is the sum of n simple logistics.

⁶ This example is adopted from [5].

characteristics (simple ones), in order to provide a clear unambiguous interpretation and satisfy a 50 year forecast horizon.

Proposed solutions and results

For the purpose of dealing with long-term technological forecasting for energy systems, a basic hypothesis was formulated which stated that, "primary energies, secondary energies, and energy distribution systems are just different technologies competing for a market and should behave accordingly." [7]

The authors emphasised three basic assumptions they applied to LSM [7, 22]:

1. New technologies enter the market and grow at logistic rates.
2. Only one technology is in the saturation period at any given time.
3. Declining technologies fade away steadily at logistic rates uninfluenced by competition from new technologies.

Nevertheless, two additional suppositions can be recognized as well:

4. There are n competing technologies ordered chronologically in the sequence of their appearance in the market.
5. A technology in saturation follows a non-logistic path that connects the period of growth to its subsequent period of decline.

A total of about 300 cases were examined from IASA's Energy System Program using LSM for historical periods from 130 to 20 years ago. The report [7] description details the resulting model with comments for nine pages. Additional examples, graphs, and captions occupy sixty pages.

Descriptions of numerical methods for logistic substitution can be found in following publications from C. Marchetti, N. Nakicenovic, P. S. Meyer, J. W. Yung, and J. H. Ausubel [22, 6, 7]. There are also at least two non-commercial software packages [24, 25] for experimentation with LSM without the complications of equations and programming.

3.1 How does it work?

To illustrate how a forecast can be supported with LSM, the data of recording media sales in the US was fitted with the help of Loglet Lab software [24]. The latest data sets can be taken from <http://www.riaa.com/keystatistics.php>. However, in order to recognise the strong and weak points of LSM we will start with an old set of data, from 1998.

At first, initial data in millions of US dollars for vinyl record, cassette, and CD sales is represented as market shares using the Fisher-Pry transform. After that, the years between in which a logistic should be fitted are entered. These years are the assumptions about a period for Δt (see Fig. 1), based on the visual observation of transformed data. Linear behaviour corresponds to logistic growth or decline for the Fisher-Pry representation. In practice, assumptions about Δt and midpoint t_m can be done instead of a period evaluation.

As in any judgment, these assumptions contribute to the accuracy of a fit and future forecast. It was assumed that for vinyl a decline logistic is fitted from 1977 to 1985, for cassettes a growth logistic is within 1977-1985, and for CDs a growth logistic is within 1987-1995 (Figure 3).

Note that the data sets for the early years of the CD and for the later years of vinyl do not follow the model. Based

on the results of thousands of fits, such growth behaviour is usually irregular when a market share is less than 5% [26, 11, 20].

The obtained results strengthen the forecast about the growth of CD and the decline of cassette market shares. To convert this information into an absolute value in millions of US dollars, return to the initial data and fit them with the parameters learned from LSM.

The next step is to make an assumption about the next (new) technology, one for which there is not yet any data. Creating logistics for hypothetical technology demands supplying assumptions about a fourth saturation curve. At least two parameters should be defined: characteristic duration Δt and midpoint t_m to approximate when and how fast the technology will grow.

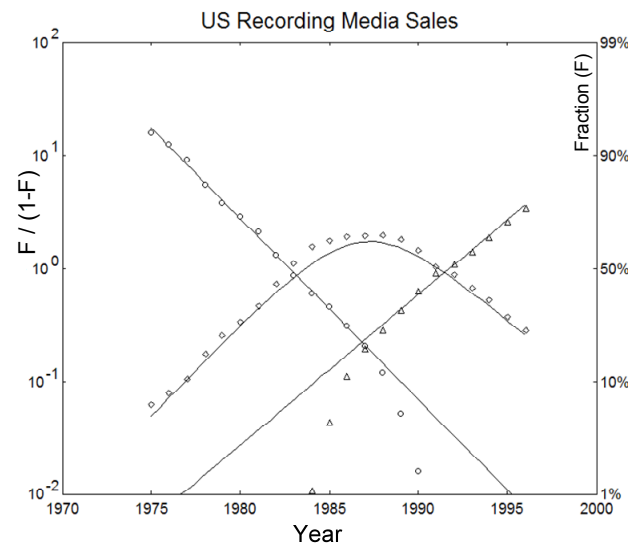


Figure 3: The recording media sales data with the logistic substitution model.

How can these two parameters be predicted? When the technology has already entered the market (passed 10% of market share threshold), the assumption about growth rate is based on the logistics for past technologies. For vinyl, cassettes, and CDs calculated Δt were respectively 12, 13, and 14 years. On Figure 4 the projected result of emerging technology #4 with $\Delta t=14$ and $t_m=2005$ is presented.

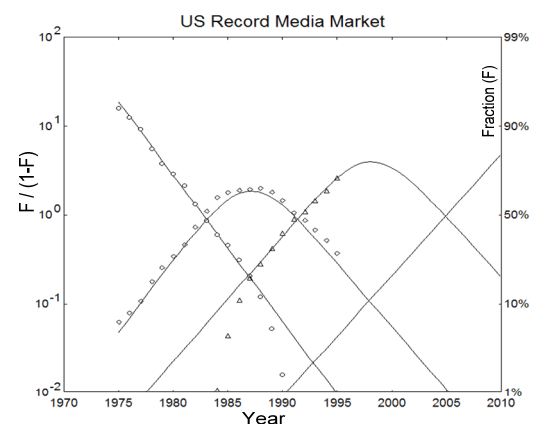


Figure 4: Anticipating the impact of new technology: the recording media sales data with a hypothetical fourth new technology.

In 1998, the DVD was chosen as the new technology and this turned out to be an incorrect prediction.

3.2 Known difficulties

To illustrate some known difficulties and ambiguities, let us compare diagrams reported in 1999 [6, 24, 26] with diagrams reported in 2007 [25] about the same topic.

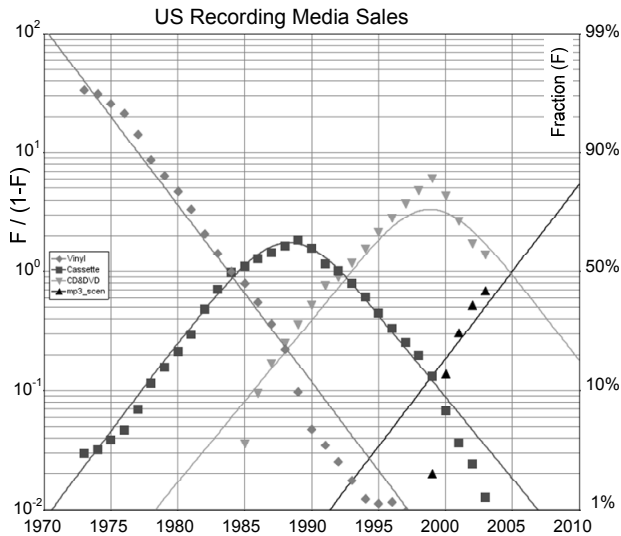


Figure 5: The recording media sales with MP3 data set (up to 2003). Source: [25].

The *first issue* is the definition of parameters for the hypothetical technology. In two papers published by the same authors in the same year, different assumptions were made about characteristic time Δt and midpoint t_m to describe logistic growth of new music technology. In Table 1 the second, third, and fourth columns represent the years of logistic decline / growth which were chosen as parameters for LSM.

	1999 [6]	1999 [26]	2007 [25]
Vinyl	1975-1985	1977-1985	1977-1988
Cassettes	1977-1985	1977-1985	1985-1999
CD	1988-1996	1988-1995	1986-2000
Hypothetic	2005-2018	1998-2012	1999-2016

Table 1: Variation of assigned parameters for logistic growth description.

The analysis of data from Table 1 once again confirms the absence of formal procedure to define the parameters for the given time periods.

The *second issue* is linked to the definition of the new technology itself. How is a prospective competitor defined in advance? In publications in 1999 the digital versatile disc (DVD) was a candidate. However, today MP3 technology is following the predicted growth curve, whereas the DVD is mostly used for video records, and not for music.

Another example to underline the second issue is the famous diagram "World – Primary Energy Substitution" which was made in 1979 [7]. In his 2002 book [11, p.164] Theodor Modis wrote "That turned out to be a most inaccurate forecast..." For instance, according to the world energy statistics [28] the nuclear primary energy supply in 2005 was about 6.3%⁷, and combustible renewable & waste supply represents about 10%. Thus, the trajectory for nuclear energy evolution fell below what had been predicted.

⁷ Fuel share of TPES. Total primary energy supply (TPES) is made up of indigenous production + imports - exports - international marine bunkers ± stock changes [28].

Even if LSM can predict logistic growth and decline, it is a challenging task for naming of a new technology within the long-term.

The *third issue* is about time-series data sets (selection, cleaning, transformation) and the assumptions made to fit logistics into data. In the second and third rows in Table 1 the same data were fitted with different assumptions. The primary question is: How can one have confidence in obtained fits? Unfortunately, the analysis of residuals is not allowed for LSM in referenced software [24, 25].

The *fourth issue* (but not the last) is about the interpretation of obtained results. LSM represents changes in competitor niches (e.g. changes in market share). On the other hand, the trustworthiness of a model depends on the initial estimations of niche capacities (κ) for each technology.

The difficulty for LSM is not building or running a model several times to get the best fit, but the interpretation of those obtained results, for the interpretation of plausible results do not always correspond to the actual future. Therefore, a formal mechanism is required to predict implausible events.

3.3 How to be more reliable

...the system had a schedule, a will, and a clock...

The working hypothesis to answer the *first issue* about the definition of parameters for logistic growth curves is based on studies about cycles in economic, technological and social environments [11, 29-36]. Detailed reviews of long economic cycles-waves, can be found in R. Ayres, *Technological Transformations and Long Waves* [39] and in documents from the NATO Advanced Research Workshop: *Kondratieff Waves, Warfare and World Security*, February 2005, Covilhã, Portugal⁸.

Theodor Modis proposes a suggestive diagram (see Fig. 6) in his book [11]. A harmonic wave with a fifty-six-year time period in the upper part of the diagram represents deviations of the logistic growth of energy consumption in the US⁹. At the bottom, more than fifty growth processes are shown with their ceiling normalized to 100 percent. Most of the data for curves have been taken from Grubler's *The Rise and Fall of Infrastructures*. [37].

The growing parts of curves coincide with the upswing of the cycle indicating growth and prosperity, while saturation periods correspond to economic recession.

Data sets showing basic innovations [11, 17] represent regularity as well: the peaks in innovation correspond to valleys in energy consumption. Therefore, energy consumption resonates with making basic innovations¹⁰.

The results in Figures 6 and 7 coincide with the conclusions about activities in social systems which were proposed in 1924 [29] and confirmed using extended data sets in 1936 [36] by A. Tchihevsky. These results are also in accordance with N. Kondratieff's concept of long waves in economics [30] and data about basic innovations collected by Mensch [17].

The hypothesis, which we are going to check in the coming future, defines logistic growth characteristics for LSM (characteristic time Δt and midpoint t_m) in accordance with the "schedule" from the nearest environmental, social, and economic super-systems. The

⁸ <http://www.natoarw-kw.ubi.pt/scope.htm>

⁹ The periodicity in energy consumption was first observed by Hugh.B. Stewart [38].

¹⁰ Cesare Marchetti first correlated Stewart's energy cycle with Mensch's basic innovations one [40].

surprisingly accurate predictions made using software based on knowledge about cycles TechSignal [44] give us

confidence in our expectations.

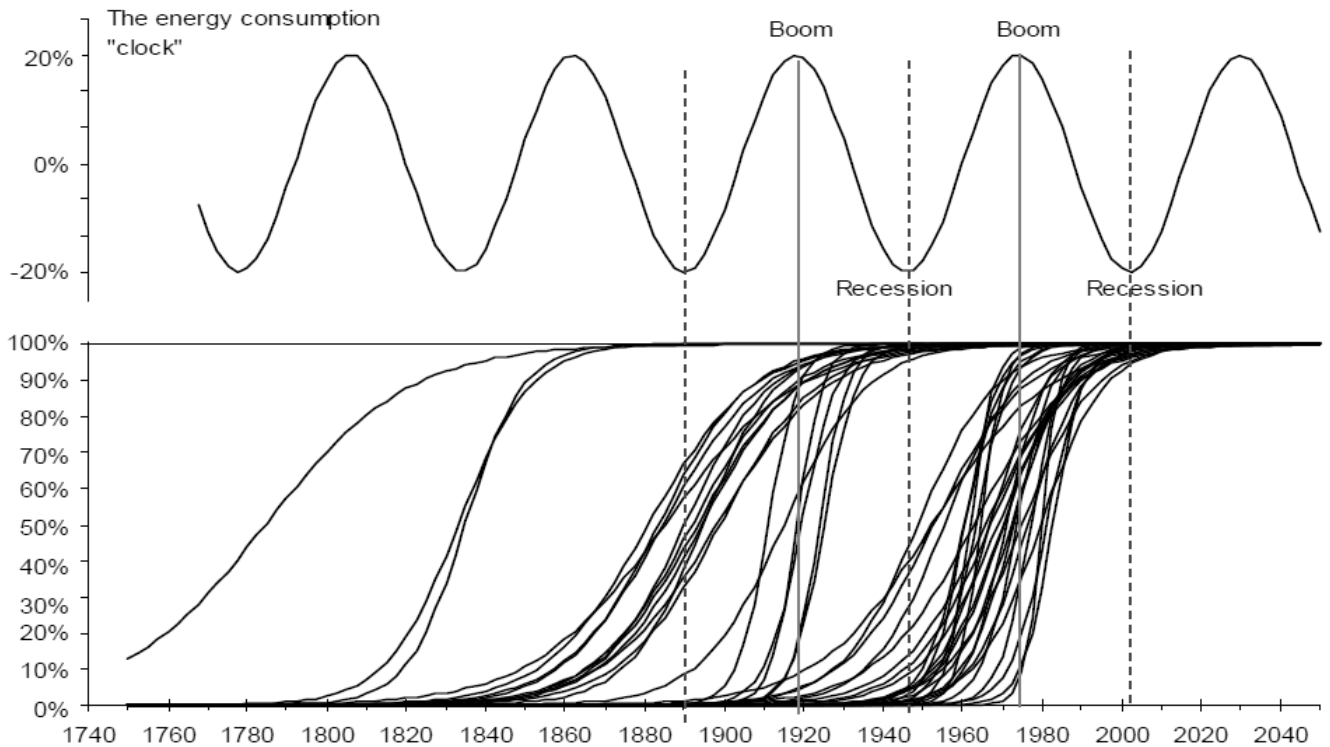


Figure 6: S-curves describing technological growth and substitution processes all normalized to reach 100% when they are completed. Adapted from [11].

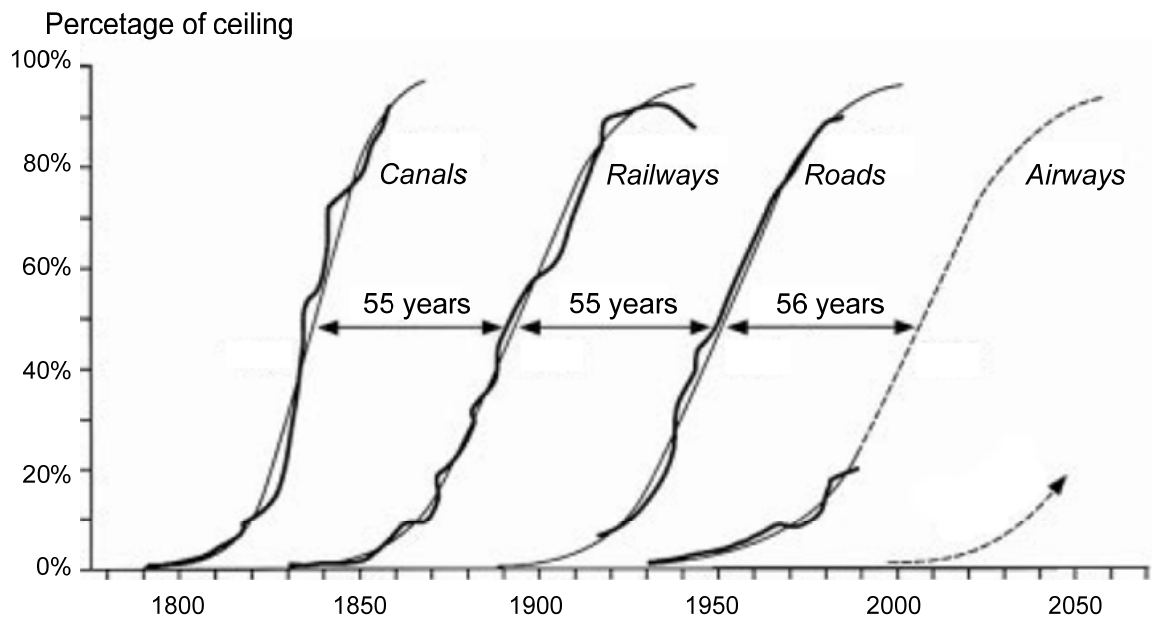


Figure 7: U.S. transport infrastructure. The growth in length of each infrastructure is expressed as a percentage of its final ceiling. The absolute levels of these ceilings in miles are different. Source [11, 37].

The *second issue* concerning the definition of prospective competitive technology can be addressed with the help of a genetic algorithm [41] and problems flow technology [42]. To identify the next generation of technology, techniques and models should be applied which are similar to the ones applied in inventive problem solving: the description of an X-element (ARIZ) [43], the Ideal Final Result (IFR) [1], and the element-name_of_feature-value_of_feature (ENV) model [42].

Progress regarding the *third issue* demands research about logistic growth models and the development of

software which will facilitate LSM construction using a rigorous analysis of data and residuals.

Advancement on the *fourth issue* which concerns the interpretation and initial estimation of a ceiling for S-curves will come from analysis of limiting resources [19] and further development of the network of contradictions approach.

4 CONCLUDING REMARKS

In this paper we introduced the 'direction through super-systems' for problems of long-term forecasting of

emerging technologies using CLM and LSM in the dimension of the naïve method. In further research, we plan to explore the 'direction through sub-systems' using the causal method based on logistic growth of knowledge within the 'invention-to-innovation' process [3].

Based on the application of laws of technical system evolution [1], logistic growth [11], and cycles [39] as main components, we have concluded that the basic patterns of technological changes are invariant. This application of knowledge about cycles and laws of logistic growth models (SLM, CLM, LSM) makes long-term technological forecasting possible as it soon helps resolve an incompatibility between cause-effect description (scientific) and the inadequate complexity of a model (practical).

The multi-screen scheme of thinking [1] in combination with the concept "competition is possible only in a common infrastructure" [37] makes possible the management of complexities of models by the synergy of CLM and LSM. When CLM allows the description of the logistic growth of a system from a viewpoint of sub-system evolution and endogenous competition mechanism, LSM provides a means for depicting technological change and performing long-term forecasting of socio-technical systems from super-systems and exogenous competition factor viewpoints.

For logistic growth models, the critical point for forecasting is the interpretation of results. For instance, in the case of CLM, it is a nontrivial task to recognize the essential underlying mechanism of obtained bi-, or multi-logistic growths. In one practical case it takes more than three weeks to understand the underlying mechanism of the constructed triple-logistic model. In the case of LSM, it is a challenging task to name the next technology. Even the time parameters of growth can be accurately identified.

Another remaining question: What are the regularities of evolution for systems which never show innovation? It is a well-known fact that before 'point α ', systems do not display logistic growth behaviour (see Figures 3, 4, 5).

In conclusion, it is necessary to emphasize the crucial role of forecasters, since they play a decisive one. The reliable forecasting method alone is not enough for accurate long-term prediction. It will never be a "push-button" solution. Like any powerful tool, a method can produce a great outcome in the hands of the intelligent, but it may demonstrate misleading results in the hands of the inexperienced.

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