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Application of Logistic Growth Curve

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Abstract

Efficient design of new processes and products requires not only an effective problem solving, but reliable forecasts of coming and distant changes. Decision making about investments into emerging technologies and strategic planning activities also rely upon consistent forecasts of technological substitution. There is a long record of applying different extrapolation techniques and, in particular, the logistic growth curves (S-curves) for studies about future changes. However, inappropriate use of S-shaped curves often leads to strange and inadequate results. Thus, among others, it is important to well define the system to forecast and provide an interpretable model from data.
The paper illustrates the use of single logistic curve and logistic component analysis focusing on the coherence be- tween model, data and interpretation. Directions for improving these techniques are discussed and a process for un- ambiguous definition of system is introduced.

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Keywords: simple logistic S-curve, component logistic model, laws of evolution of technical systems; Researching Future method;

1. Introduction

Efficient design of new processes and products requires an effective problem solving, but also reliable forecasts of coming and distant changes. Decision making about investments into emerging technologies and strategic planning activities also rely upon consistent forecasts of technological substitution. The logistic growth curves (S-curves) is a popular model for studying and forecasting future changes [1]. However, unsuitable application of S-shaped curves frequently leads to odd results [2]. Thus practitioners have to know when this model can be used, how to define system to forecast, how to identify relevant growing variable(s) for long-term forecast, how to improve the coherence of model and data, and provide an interpretation of the obtained curve.

The paper illustrates and discusses the use of simple logistic curve and logistic components analysis with two examples; and proposes a process for clarifying boundaries of a system the evolution of which is to be forecasted. After a short theoretical background, the simple logistic S-curve identification process is provided and then discussed

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on the example of growth of the cumulative number of TRIZ publications. As this example was introduced at TRIZ Future 2007 conference [3], we can now compare past projection to what did really happen since 2006 and provide additional methodological feedbacks by analyzing its components. Then, data from an industrial project for inventive problem solving is applied for illustrating the use of logistic component model when components are unknown at the beginning of the study. Final- ly, some directions for further improvements of reliability of this technique are discussed.

For all the examples of this paper the same software1 as in 2007 is applied.

2. Theoretical background

First describe THEN explain. –scientific maxim

Any study of data sets aims at extracting meaning from data. The statistics is about learning the unobvious facts from data. In border of our research we apply and develop just several models and rules from study of quantitative data for improving interpretation about qualitative changes in future.

As a prediction model we apply the *simple logistic S-curve* and its extensions: the *component logistic model* and the *logistic (multiple) substitution model*. We presented the origin, mathematical characteristics, and history of application for S-shaped curves in [3]. Three major parameters applied for fitting the simple logistic S-curve, are sketched in Fig.1. Multiple models are suggested for description of growth in interaction with a limiting environment [4]. Our presented study focuses mostly on three models which have found the wide spread application in the description of technological change and in economic modeling. More details and mathematical characteristics of diffusion and substitution models can be found in [4, 5, 6, 7, 8, 10, 11, 12].

When fitting data the model function usually represents the data tendency curve. It is taken as an optimized phenomenological description of the time behavior for quantities expressed using empirical time series. It is necessary to notice that the *simple logistic S-curve* as fitting model represents the pattern of natural growth in interaction with environment. Meanwhile, this relatively simple (three parameters) model was applied for trend analysis through study of time series for decades. Quantitative representation of law of Nature and long history of application are two weighty arguments for selecting a model for the purpose of methodology for distant forecasting the changes in socio-technological systems. The example of projection about number of TRIZ-publications with simple logistic is presented below in section 3.2 to illustrate how authors apply *S-curve model*.

When studying long range time series of evolutionary S-shaped processes for socio-technical systems it is necessary to manage the questions of dual or multiple processes operate; changing the limits to growth within one S-curve; impact of various super-system factors to the same system; cyclical nature of any evolutionary process [5, 6, 12]. For this reason, in 1994 the bi-logistic model was suggested by Meyer [8] in modeling systems that contain complex growth processes not well modeled by the simple logistic, for situation where dual processes operate. Later on, in order to simulate the growth and diffusion processes with more than two sub-processes, the bi-logistic model was generalized to a component logistic model [5, 6] where growth is the sum of *n* simple logistics. For studying the evolutionary processes with arbitrary number of phases the application of *component logistic model* provides reliable simulation of future changes [6]. The example of application the component logistic is given below in sections 3.3 and 4.

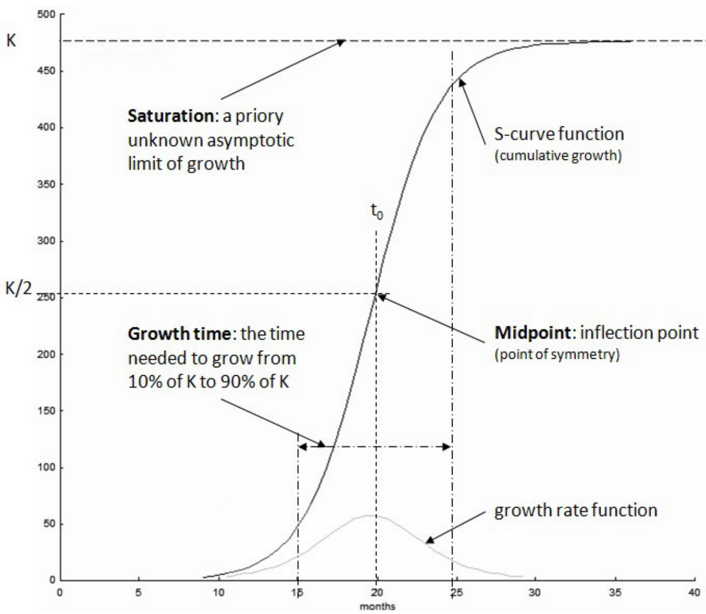

Fig. 1. Schematic diagram of a *simple logistic S-curve*, defined by three parameters: (1) Saturation, (2) Growth time, and (3) Mid- point. The *growth rate function* is represented in scale on the same plot by "bell" shape curve.

3. Simple logistic S-curve. System and components

In this section we use the example of TRIZ-publication dynamics to illustrate application of simple lo- gistic S-curve. We mainly explore the evolution of the system composed of TRIZ-journal, TRIZCON and of ETRIA publications together and separately. We conclude by proposing a process coupling TRIZ- based techniques and logistic model that improves the definition of the system to forecast when perform- ing long-term technology forecast.

3.1. How to develop a simple logistic S-curve?

In practice for developing an S-curve model using time series data we apply the following five steps procedure:

Step 1. Define what is necessary to predict (What is the question that should be answered?). Step 2. Define growing variable (How do we evaluate the evolution of the studied system?). Step 3. Select time-series data to be applied:

a. gather data;
b. refine data;
c. adapt and arrange data;

Step 4. Fit logistic curve(s) to the data:

a. estimate the upper limit (ceiling) for growing variable;
b. fit and bootstrap logistic S-curve to data using fitting rules;
c. examine and reduce the data-to-model residuals;

Step 5. Build a consistent and reasonable interpretation of obtained extrapolations for answering the initial question.

3.2. Application to TRIZ-publications in English

How do we employ the suggested procedure for studying the dynamics of TRIZ publications in Eng- lish?

Step 1. How many TRIZ-articles will be presented at www.triz-journal.com, in TRIZCON pro- ceedings, and in ETRIA TFC proceedings in coming future altogether and separately?

Step 2. Number of original publications.

Step 3. Raw data were collected from three major sources (1) The TRIZ Journal Article Archive[2];

(2) Annual Altshuller Institute for TRIZ Studies International Conference[3]; (3) Annual TRIZ Future Conference of European TRIZ Association[4] for period 1996-2011. The ob- tained lists of articles were analyzed at the level of title and abstracts and recurrent publica- tions were excluded from the count. At the end of this step, yearly data was summarized in order to obtain the cumulative number of publications for each source and the three sources altogether. The results are presented in Table 1. When refining and adapting time-series da- ta we did not distinguish the scientific and the industrial papers as well we included in the total number of publications the materials of workshops (e.g. TRIZCON in 2008-2009).

Step 4. The applied software uses the Levenberg-Marquardt method of nonlinear least-squares re- gression for estimating the parameters of logistic curves. No expert's assumption about the Saturation level was provided. When fitting the S-curve we analyzed the values of residuals for the difference between data and model. Preliminary analysis of residuals and bootstrap- ping of the developed model did not call for tuning the initial values of Saturation, Growth time and Midpoint parameters. It is out of the scope of this paper to introduce the detail rules and recommendations for fitting time-series data and for analysis of residuals. This is a very plentiful and interesting domain where most of useful knowledge can be learned from the statistical methods applied in scientific research (e.g. in physics or in biochemis- try). For practical purpose of understanding the evolutionary processes for socio- technological systems one can start from [5], continue with [12], and scan about recent ad- vancement in [2, 6, 7]. The results of this stage can be seen on Fig. 2. Crossed points repre- sent data that was not available in 2007. Saturation, midpoint and growth time are given with confidence intervals at the confidence level of 90%.

Let's comment this result. The S-curve model, obtained in 2007 suggested that the cumulative number of TRIZ-publications from three referenced sources would reach a saturation level about 2018 the value of which has 90% of chance to be within the range [1430, 1730] when midpoint is 2003 and Growth time

8.9 years. Moreover, with this model, the expected value of 2011 publications should be within the range [1400, 1700] but the observed value is 1788, which is even higher than the expected saturation. There- fore, the model of 2007 provided about 12% of underestimation of the cumulative number of TRIZ- publications in English from three selected sources. Is it a significant deviation from S-curve or it is an adequate one? This example is representative of results obtained when using this kind of approach and simple logistic curves: short term result is more or less accurate but significant deviations may happen from logistic model when the upper limit of growth is approached [2, 12].

One way to address the question is to ask whether the simple logistic model is a relevant model for de- scribing the evolution. When watching at the coefficient of determination R^2 given in Table 2 we can see that the simple logistic model is from a mathematical point relevant in 2007 and in 2011 (see also Fig 4). Thus, for short term forecast, we can update the model yearly and apply the 4 steps of the process.

Another approach to address the previous question and to improve the accuracy of S-curves for transi- tion phases is to exploit the component logistic model [8, 5, 6]. Some details about application of compo- nent logistic model in scope of the Researching Future methodology for long-term forecast were present- ed in [15]. One of the basic assumptions behind the component logistic model[5] is that the components of a system (sub-systems) may also be described by simple logistic models and that the system results in a sum of S-curves. The link between systems and sub-systems may provide relevant information that could be purposefully used to improve the description of system and the sub-systems. This is applied in step 5.

Step 5. In this step we have to verify if we are able to interpret and accept the results obtained in step 4. By applying simple logistic decomposition model to the 3 sources of publication separately we obtain 3 logistic curves similar to the one of Fig. 4. Their R^2 values do not push us to reject the S-curve model for the components.

The curve resulting from the sum of these 3 curves is not given here because it is so similar to the curve of Fig. 3 that at the size of the picture of this paper we cannot see the difference.

Let's interpret these results. In our case, the aggregative curve (resulting from our known component) fit and the simple logistic S-curve are congregated. (Q1) Can we interpret that we are at saturation level for this system and that there will be almost no new papers in the future within this system of 3 publica- tions sources? (Q2) Since we are at plateau for the 3 sources of publications, are we also at a saturation phase for ETRIA-publication? (Q3) Can we interpret that we are at a saturation level for the cumulative number of TRIZ-publications in English? Section 3.3 shows to what extent the logistic component analysis of data from Table 1 contributes for answering the questions Q1, Q2 and Q3.

3.3. Evolution of ETRIA publications

When using the only data from the last column of Table 1 for fitting the 3 components logistic curves, some inconsistencies with what we already know about our 3 sub-systems were observed. Thus, we included the following information in order to perform the logistic component fit:

- First we used qualitative information like the fact the publication at www.triz-journal.com is arrived at the plateau (since 2010 publications were stopped) in order to get a realistic simple logistic fit of TRIZ-journal publications (diagram is not presented).
- We also decided to use the simple logistic S-curve for fitting TRIZCON publications (diagram is not presented).

With assumptions above, 6 among the 9 parameters of the 3 logistic components model are hold on. The values of parameters (Saturation, Midpoint, and Growth Time) for TRIZ-journal and TRIZCON that were used for developing the logistic component model are given Fig. 4. The logistic component model then discloses the 3 parameters of ETRIA logistic evolution model (see Fig. 4).

Let's interpret this result. By considering the ETRIA-publications S-curve we see that it is not yet on its plateau (answer to the question Q2). With the model of Fig. 4 we can see that the number of publications at TRIZ-journal is significantly greater comparing to TRIZCON and ETRIA. Its weight is important and it may let us think on the total curve that we are on a plateau. The answer to question (Q2) pushes us to consider that ETRIA-publication as a system may not have reached a plateau yet.

In order to answer questions (Q1) and (Q3) by using only logistic curves, we should be able to know whether we miss or not some components in our system of TRIZ-publications.

For the purpose of analyzing the emergence, growth, leveling, and decline of multiple competitive systems, the *logistic substitution model* was first suggested by Marchetti and Nakicenovic in 1979 [1]. Some details about authors' viewpoint on application of the logistic (multiple) substitution model for distant forecast of technologies can be found in [9]. Multiple instructive and inspiring examples of application the logistic (multiple) substitution model for long-range forecasting of socio-technological changes can be found in books [10, 11, 12], in the articles of Marchetti [13], as well as in the other sources [14]. Authors applied widely this approach during a recent technological forecasting project. The result was that a good definition of the system is necessary to perform a relevant logistic substitution model.

In section 4 is presented the method we applied for defining the system to forecast by combining component logistic model and TRIZ-based techniques.

Table 1. Number of TRIZ-publications from three sources: www.triz-journal.com, TRIZCON conferences, and ETRIA conferences

Year	***triz-journal***		***TRIZCON***		***ETRIA TFC***		**TOTAL**	
	yearly	cumulative	yearly	cumulative	yearly	Cumulative	yearly	cumulative
1996	5	5	0	0	0	0	5	5
1997	32	37	0	0	0	0	32	37
1998	70	107	0	0	0	0	70	107
1999	68	175	26	26	0	0	94	201
2000	65	240	32	58	0	0	97	298
2001	75	315	36	94	30	30	141	439
2002	86	401	41	135	51	81	178	617
2003	99	500	26	161	31	112	156	773
2004	87	587	27	188	49	161	163	936
2005	90	677	37	225	58	219	185	1121
2006	103	780	34	259	58	277	195	1316
2007	64	844	22	281	49	326	135	1451
2008	59	903	14	295	39	365	112	1563
2009	29	932	11	306	26	391	66	1629
2010	12	944	26	332	55	446	93	1722
2011	0	944	15	347	51	497	66	1788

Table 2: Regression determination coefficient (R^2) values for different data and figures

Curve used for fitting	**R^2**
Fig2: Cumulative publications TRIZCON+TRIZ-journal+ETRIA until 2006	0.9918
Fig5 : Cumulative publications TRIZCON+TRIZ-journal+ETRIA until 2011 obtained with simple logistic	0.9975
Cumulative publications TRIZCON+TRIZ-journal+ETRIA until 2011 obtained with sum of logistic components	0.9981
Fig3 : Cumulative publications ETRIA until 2011 with components analysis	0.9936
Fig3 : Cumulative publications TRIZ-CON until 2011	0.9865
Fig3 : Cumulative publications TRIZ-journal until 2011	0.9965

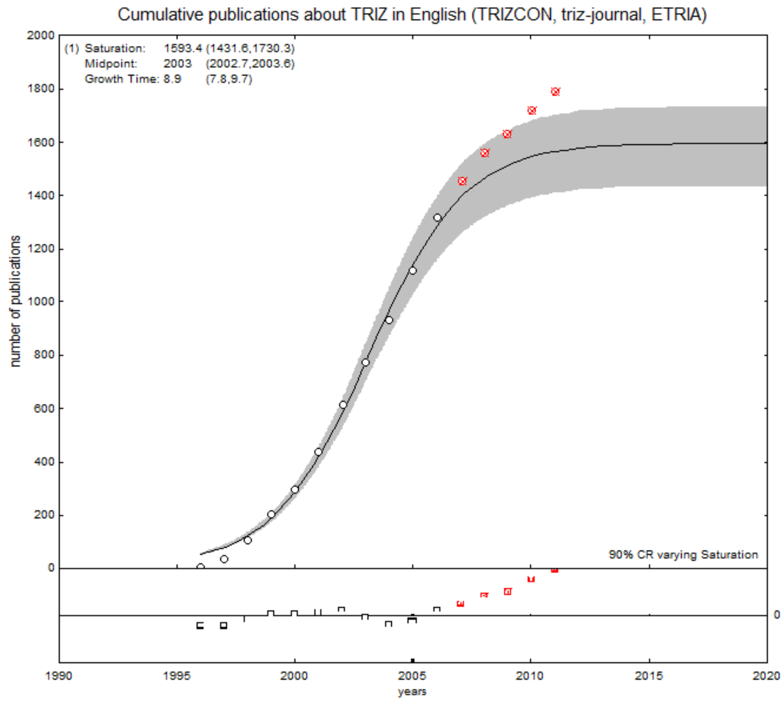

Fig. 2. Cumulative number of TRIZ publications in English from www.triz-journal.com, from TRIZCON proceedings, and from ETRIA conferences. Projection of 2007, updated with recent data from 2007 to 2011 when crossed data points after 2007 present deviation between the trajectory extrapolated in 2007 and actual data.

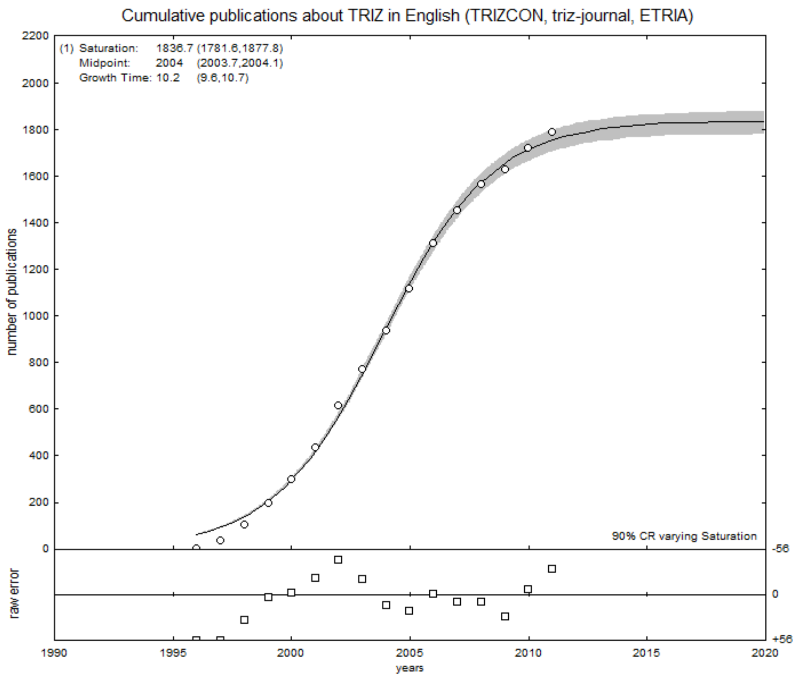

Fig.3. Cumulative number of TRIZ publications in English at www.triz-journal.com, TRIZCON and ETRIA. Projection based on recent data.

Long-term tendency (Fig. 3) is leaned by number of publications on triz-journal.com, therefore the midpoint of growth S-curve is about 2004 when characteristic duration of growth (the time interval needed to grow from 10% to 90% of Saturation) is about 10.2 years. The values and pattern of residuals (differences between data a model) can indicate the cycling nature of publications. When time-series data fitted separately, the "cycles" for two conferences correlate when waves of deviation for internet publications are different.

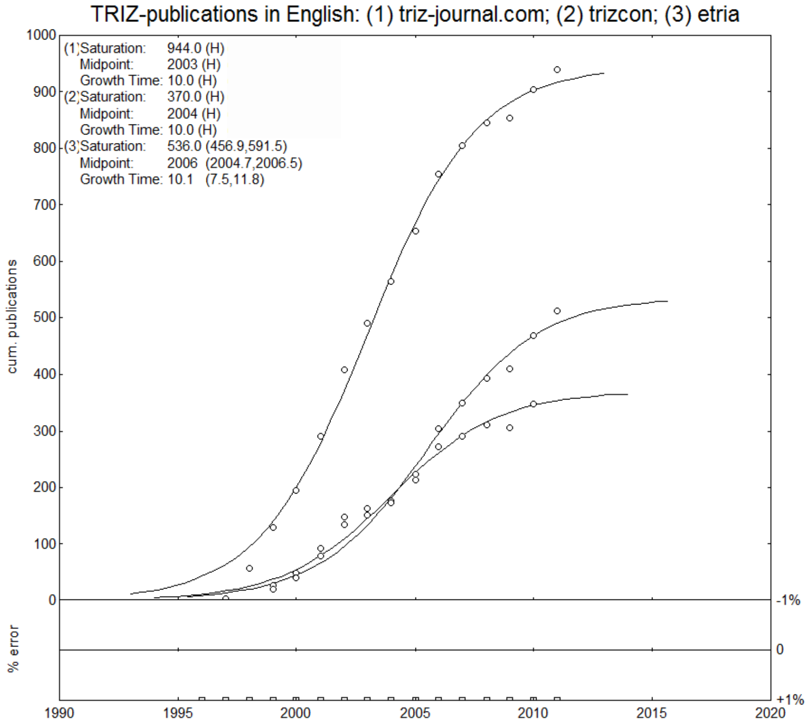

Fig. 4. Component logistic model for three growth processes: initial displacement 5 (publications); holding on the parameters for TRIZ-journal and TRIZCON. The Saturation, Midpoint, and Growth Time parameters for TRIZ-journal and TRIZCON were obtained from separated fits using data from Table 1. After bootstrapping the estimated maximum value of Saturation for ETRIA-publications is about 590 publications.

4. Improvement of system boundaries definition with logistic component model

4.1. 1 Example of application.

With an extract from problem-solving project[6] performed in 2008, we would like to illustrate the ap- plication of component logistic model for defining the boundaries of the system to be improved. At the beginning of the project our partners supposed that their mainstream product is at the end of its growth curve, thus they would like to invent a new solution for boosting the innovation process and to substitute the old technology by a new one.
Using the sales data from marketing department of company, we fitted time-series with simple logistic S-curve model for checking the company hypothesis. First, we discovered that some data from available time-series were not real, but artificially made. It took several days to complete missed time-series. The first attempt for real data confirmed the hypothesis of our colleagues. However, we were concerned when analyzing the residuals (left diagram in Fig. 5). The residuals showed the regular deviations of data from model. Such regularity in residuals usually indicates the combination of growth processes. In order to improve residuals, the component logistic model was applied instead of one simple logistic S-curve. In this example contrary to the example of TRIZ-publications no components of the system was known by the members of the working group. Thus, we had to discover the number of components. The results of the fit for three logistics component showed the adequate residuals (low deviation of data from model and absence of regularities).

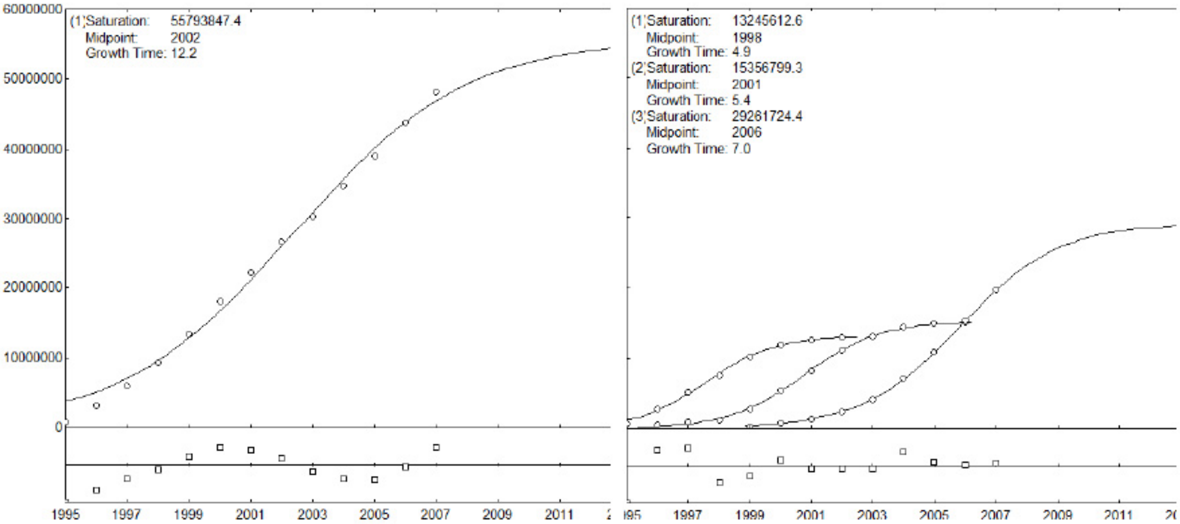

Fig. 5. Growth of sales for Product-X: intuitive projection (at the left side) vs. the component logistics model (at the right)

From mathematical viewpoint, fitting a set of 12 points with 3 S-curves (9 parameters) will provide a better fit than with one simple logistic S-curve (3parameters). Therefore, a crucial question was to supply meaningful interpretations of received results before applying the projections for decision making. It took several weeks before confirming the consistency of the obtained components model by a retired market- ing expert. Each curve had clear qualitative interpretation and causal link with changes on the market due to new regulations (first S-curve), appearance of strong competitors (second S-curve) and emergence of new demands for existing product (the third curve).
What were the practical results of applying the component logistic model for the company? First, company could improve accuracy of production plans for coming future. Second, time and resources for development of new technology were defined more precisely at R&D department. Third, the specific market and its potential, at which the existing product of company can be sold in coming years, were clearly identified.

4.2. How to define the technical system to forecast?

When studying the distant future changes, the task of defining boundaries of the socio-technical sys- tem to be forecasted can become a stumbling-block. Nevertheless in context of long-term forecasting of technological changes, it is inevitable to clearly define system to be forecasted. For instance, TRIZ law of transition to the super-system [17] postulates that “during their evolution technical systems merge to constitute bi- and poly-systems; in the future the system continues its evolution as a part of the super- system.” After performing several forecasting projects and studying multiple forecasts done by others, we can witness that often the forecast is mistaken just because the system to be forecasted was not defined at all or it was defined indistinctly [19]. In the frame of authors’ method for forecasting the distant techno- logical changes [20], special attention is paid to the definition of the system to be forecasted from the very beginning of the study. It is appropriate to notice here, that just qualitative techniques for defining the boundaries of the system provide results with considerable traces of personal biases.

In order to define the system to forecast, three techniques are applied in complementary style: system operator, laws of the evolution of technical systems and the exploration with logistic models. First, Sys- tem Operator[7] are applied when on the central screen the main function of analyzed system is defined. Second, in order to check the consistency of preliminary description of sub-systems and super-systems, the three first law of technical system evolution are applied [p.p.223-231, 17]. Third, the preliminary version of S-curve model for defined system to forecast is developed and a rigorous examination of resid- uals is performed. If residuals are not well shaped (e.g. they are too big or they present the evident pat- terns in time), the tweaking of parameters (Saturation, Midpoint, Growth time) can be applied. However, the distinctive structure of residuals in most cases indicates that there are several growth processes enveloped in studied time-series data. Therefore, the component logistic model allows describing the processes of growth with improved accuracy. Forth, the final definition of "the system to forecast" is incorporated into system operator representation in consistency with axes past-system, future-system, and anti-system.

The example of the application of logistic models after definition of system with system operator and laws of the evolution of technical systems is presented above in section 4.1. The suggested method can be also applied within roadmapping projects or for problem solving projects.

5. Conclusions

A process of application of the simple logistic S-curve for predicting future changes was introduced in this paper. According to the proposed 5 steps procedure, it is crucial for accuracy of the prediction to define the boundaries of the system and growing variable at very beginning of the study. The rigorous and meaningful selection and preparation of time-series data play an important role for decreasing deviation of projection and real data as well as for reasonable interpretation of results.

The new concept of application the component logistic models for unambiguous definition of system is suggested and tested on two examples from completely different areas: number of publications and mass production. The reliable definition of system to be examined is important for reliable forecast of distant technological changes because poorly defined system boundaries distort the forecast [19].

In order to evaluate the suggested approach the past projection from 2007 is revisited and discussed with recently available data for example about TRIZ-publications in English. In the first case study, the cause of system model inaccuracy was disclosed thanks to the distinction of growth processes for 3 dif- ferent "sub-systems". In the second case study, the importance of meaningful interpretation of obtained results is emphasized.

The strongest point of simple logistic S-curve application is that the model is based on firmly proved law of Nature. S-curve model represents the growth or decline of every system in interaction with an environment (its limited resources). Thus, quantitative study of system transformation in combination with qualitative approach contributes effectively to the reliability of long-term forecasting.

Clearly, more case studies need to be performed for reinforcing weak points of suggested technique and validate its consistency.

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