A SYSTEM DYNAMICS APPROACH TO THE MODELLING OF COMPLEX NATURAL SYSTEMS

dr. sc. Ljiljana Šestan
˝Hrvatske šume˝d.o.o.
Zeleni put bb, Novalja 53 291, Croatia
E-mail: ljiljana.sestan@hrsume.hr

prof. dr. sc. Vesna Dušak
University of Zagreb, FOI
Pavlinska 2, Varaždin 42000, Croatia
E-mail: vesna.dusak@foi.hr

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ABSTRACT

The research of complex natural systems is of huge importance, especially considering natural and ecological preservation. However, the problem of studying such systems is exactly manifested in its complexity, which is hard to describe and analyze through classic research methods, mostly based on linear connections between the elements of the observed system. A certain level of insecurity which is always present in the natural processes has to be built into a model. Therefore, the development of a simple and clear model of natural systems is a challenge which demands good knowledge of methodology and system itself. The nature of processes inside the complex natural systems as well as their environmental interactions mostly characterizes nonlinear cause-effect links which could be described and analyzed only within one system dynamics approach. The research of system dynamics approach of modelling and simulation of the complex natural systems will be conducted on the example of phenological phases of forest tree´s leaves.

INTRODUCTION

Phenology (gr:fainomai - to appear, logos – idea, thought, eng:phenology, germ:Fenologie), science which studies biological cycles and their correlation with climate. Whithin phenology the life cycles of plant species are monitored and recorded. The observation of the lenght of the vegetational season can detect climatic changes and contribute to the understanding of carbon cycle (the circulation of carbon between live and unalive nature) which is one of biogeochemical cycles, important for the functioning of the Earth system. The life cycles take place in phases – phenophases. We can discern leaf phenophases and also generative phenophase. Phenological observations are being conducted on the chosen monitoring stations where the specific plant life is observed, and the day of the specific phenophase appearance is recorded. The oldest phenological data comes from the 9th century Japan, while for the European area the beginning of phenology dates from the 15th century.

The study and observation of phenophases which are closely linked to climatic parametres provided opportunity for ecological researches through modelling, analysis and the compilation of the climatic changes study (Jaagus and Ahas 2000). Past researches of this problem area were mosty associated with classic statistical methods, as descriptive statistics, linear regression, correlation, multiple regression (Ahas 2002), and in some cases, canonical correlation analysis (Chmielewski 2002). Previous studies are based on individual studies of phenophases of different plant species and their subsequent comparison (Menzel 2000). Lack of data in time series is largely compensated by interpolation, which brings to multiplication of general trend and reduction of the accuracy of the output data. The most commonly used, linear regression method, presumes linear connections between manifestations, but the relations between complex natural system elements are not always linear, and therefore, the use of linear regression method is not sufficent for development of the complete process model without losing specific components and including the environmental impact.

Relevant outside factor which affects the phenophase system significantly is the air temperature, which notifies significant changes during 20th century. It has been established that during 20th century, mean global temperature in Europe increased average 0.6°C. Fluctuations in air temperatures are especially significant during winter and spring, which influences significantly spring phenophases. The goal of this paper is to develop a model in accordance with the system dynamics methodology, using the example of the phenophases, so to prove that modelling based on system dynamics corresponds natural systems features. The steps of model development in accordance with system dynamics approach :

1. Collecting and organizing data
2. System analysis
3. Verbal and structural model development
4. Mathematical-computer model development
5. Verification and validation of model.

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COLLECTING, ORGANIZING AND PROCESSING DATA

The application of system-dynamic approach to modeling of complex natural systems has been explored in the case of forest trees phenophases of pubescent oak trees (*Quercus pubescens*, Willd.) on the sample plot on island Pag in Mediterranean see (Croatia), where systematic observations have been carried out. The sample plot is located within the protected landscape – special forest reservation „Dubrava-Hanzina“. Data on phenological observations and air temperatures have been collected.

Phenological observation data

Phenological observation data are collected by „Croatian Forests“ d.o.o. Observations were carried out in a period 1.4.1993. till 31.12.2005. at seven days intervals and performed 666 in that period. Ten trees have been observed. Collected data are systematized and integrated in ways that are grouped into 6 stages - phenophases marked with F0 to F5 and presented in Table 1.

Table 1: Designation, interpretation and average time performance of the phenophases

Phenophases		
Mark	Meaning	Month
F0	Rest, all leaves fallen	4
F1	Blooming	4-5
F2	Leaves fully developed	10
F3	Leaves begin to change colour	10-11
F4	Leaves completely changed colour	11-12
F5	Leaves begin to fall	12

On the bases of systematized data of phenological observations, the transition frequency of trees from one phenophase to another, were determined as the differences of the state of the neighbouring phenophases. Transition frequencies are expressed in number of trees in a week time unit. In accordance with the terminology of system–dynamic approach the speed transitions are named and marked BPO-1, BP1-2, BP2-3, BP3-4, BP4-5 and BP5-0. The transition of trees takes place at various intervals, the annual cycles. The trees pass from one phenophase to another when conditions arise, that is, when an event from the environment initiate it. In this case, under the influence of certain air temperature values. After all trees step into the next phenophase, for example, from F0 to F1, the speed of transition F0 to F1 (BP0-1) is 0 which means that trees do not step into next phase until next year. Based on the collected data the speed of transitions greater than 0 have been isolated, and calculated average number of trees stepping weekly in such intervals. It was showed in table 2.

Table 2: Average transition speed

The speed transitions					
BP0-1	BP1-2	BP2-3	BP3-4	BP4-5	BP5-0
BS/wk	BS/wk	BS/wk	BS/wk	BS/wk	BS/wk
3.17	3.71	3.25	3.1	2.7	7.5

Data on air temperatures

Data on air temperatures were obtained from Central Weather Bureau. Central Weather Bureau is the fundamental institution for Meteorology and Hydrology in Croatia. It provided data on average daily air temperatures in the area of Pag for the period from 1.1.1993. to 31.12.2005, for the purposes of this study. Total of 4748 data on mean daily temperatures was collected. Mean daily air temperatures are the basis for calculating the mean weekly air temperatures (timestep in model is one week) which dynamics is shown in Figure 1.

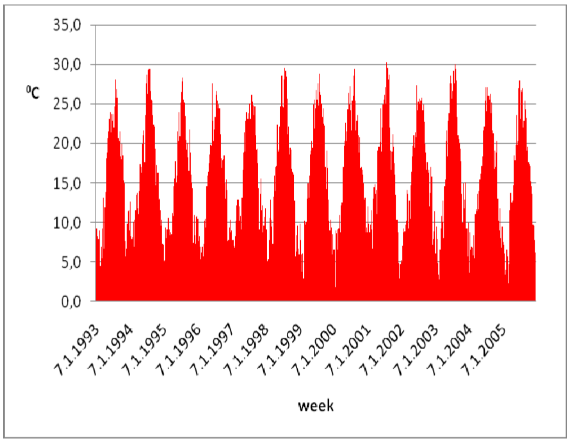

Figure 1: Average weekly air temperatures

Based on the collected data it has been calculated that the average air temperature in the period since year 1993. to 2005. was 16.2°C, and that there were no major fluctuations in average annual air temperature within the studied period. The procedure for determining characteristic distribution was carried out for average weekly air temperatures (TZ) for all phenophases when they are present, which means when their values are greater than 0. Specified values of the air temperatures of associated phenophases were marked as it follows: TZF0, TZF1, TZF2, TZF3, TZF4 and TZF5. By using programe Statistica 7 it has been established if the distribution of the real data matches normal distribution (´goodnes of fit´). Tests Chi-sqaure and Kolmogorov-Smirnov were used with the significance level 0.05 or 5% (Table 3).

Table 3: ´Goodnes of fit´ - results

	Chi-sqaure-TEST		Kolmogorov-Smirnov TEST		H_0 or H_1
	Chi-sqaure max	Border (critical) Value Chi-sq. for 0.05	D max	Border (critical) Value D for 0.05	
TZF0	0.990	9.49	0.029	0.086	H_0
TZF1	1.149	9.49	0.068	0.155	H_0
TZF2	12.78	12.6	0.068	0.073	H_0
TZF3	1.867	9.49	0.082	0.151	H_0
TZF4	8.466	12.6	0.122	0.158	H_0
TZF5	5.182	7.81	0.139	0.177	H_0

In accordance with the data in Table 3, it has been determined that the distribution of variables TZF0; TZF1; TZF2; TZF3; TZF4; and TZF5 correspond normal distribution. Collected, organized and processed information of phenological observations and air temperatures movements are the basis for analysis of the system phenophases. It is not possible to start the process of model development without a detailed analysis of the observed system.

SYSTEM ANALYSIS

The basis of the system analysis is the systematically pre-processed data that allow the identification of the character of the variables that represent system elements and also general definitions of relationships between certain variables explored through simulation modeling.

The results of the analysis are as follows:

- The relations between phenophases are of a linear character.
- Relations between phenophase conditions and air temperatures are of non-linear character, because of the temperatures fluctuations which are not followed by the movement of the phenophases.
- Air temperature is a continuous independent, random variable.
- States of phenophases, because of the way they have been noted, have a descrete, dependable variable character.
- The flows between phenophases are continuous because the natural proceses are continuous.
- The system of phenophases involves continuous processes and also events which cause system discontinuity which demands development of the mixed continuous discrete model.

DEVELOPMENT OF VERBAL AND STRUCTURAL MODEL

Before developing structural model it is necessary to formally define the boundaries of the observed system, that is, to determine the first level of the system, and lower levels of the systems – subsystems.

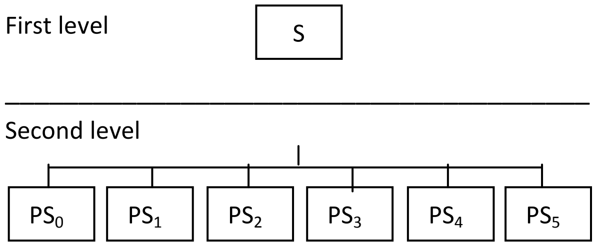

Figure 2: Hierarchical diagram

The boundaries of the observed system are shown by hierarchical diagram in Figure 2. The observed system is broken down to next lower level. The first level system (S) is the system of vegetation cyclus of the sample plot, and phenophases are subsystems (PS). System can be further divided to lower levels. For example, each tree can be observed. In that case phenological observations should be conducted at the level of the tree. Given that the collected data relate to the surface on those observations, it is not possible to obtain information on dynamics of each tree.

Phenophase dynamics, subsystem of the observed system, is under the air temperature influence. All phenophases, all subsystems, have a common structure, shown in Figure 3.

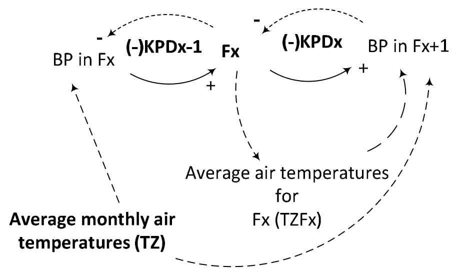

Figure 3: Structural diagram phenophase F_x

The transition from the previous phenophase (BP in F_x) and the transition to the next phenophase(BP in F_{x+1}) affects the condition of the individual phenophase (F_x). The transition to the next phenophase depends on the mean monthly air temperature (TZ) and the average air temperature of the previous phenophase (TZF_x). Therefore, if certain conditions are met, regarding the values of the mean monthly air temperatures and average air temperatures of previous phenophasese, the transition into the next phenophase happens. It is important to emphasize that the values of air temperature (continuous random variables) oscillate, which means that the relationship between temperature influence and the phenophases is not of a linear character. In addition, there is a relationship between the average air temperature specific for the individual phenophase and its condition. When the phenophase is present, there is TZF as well, and when the phenophase equals 0, there is no average air temperature of specific phenophase.

Verbal model of the phenophase system was defined on the basis of hierarchical presented in the Figure 2 and structural diagram presented in the Figure 3. It is used to define basic structural elements of the system, that is, equation components of the condition changes and cause-effect relationships, through the feedback loop (KPD), which, depending on the sign have (+) accumulation and (-) regulation character. The phenophase system consists feedback loops of regulatory nature. The state of phenophase from F0 to F5 ranges from 0 to 10, because ten trees were observed on the sample plot. It means that state of phenophase cannot be greater than 10 or less than 0. The larger transition into the next phenophase brings to reduction in the phenophase state, which means that cause–effect relationship between state of phenophase and the speed of transition (BP0-1, BP1-2, BP2-3, BP3-4, BP4-5 and BP5-0) from to another phenophase is negative and that closes the KPD of regulatory nature. For example, the condition of phenophase F0 is reduced due to the increase of the next phenophase F1. Because of that negative feedback first KPD1 is negative. The other feedback loops KPD2, KPD3, KPD4, KPD5 and KPD6 are also of the regulatory character. Mean air temperature (TZ) is the independent variable and it represents the external influence on the system, which is reflected in the impact on the speed of transition from one phenophase to another. Average air temperatures with phenophases TZF0, TZF1, TZF2, TZF3, TZF4, and TZF5 present, are also random character variables which affect the speed of transition, and are connected with the phenophase condition. With the phenophase present, the average phenophase temperature is present as well.

With this verbal model the observed phenophase system was described. On its bases the structural model of phenophases system was developed (Figure 4).

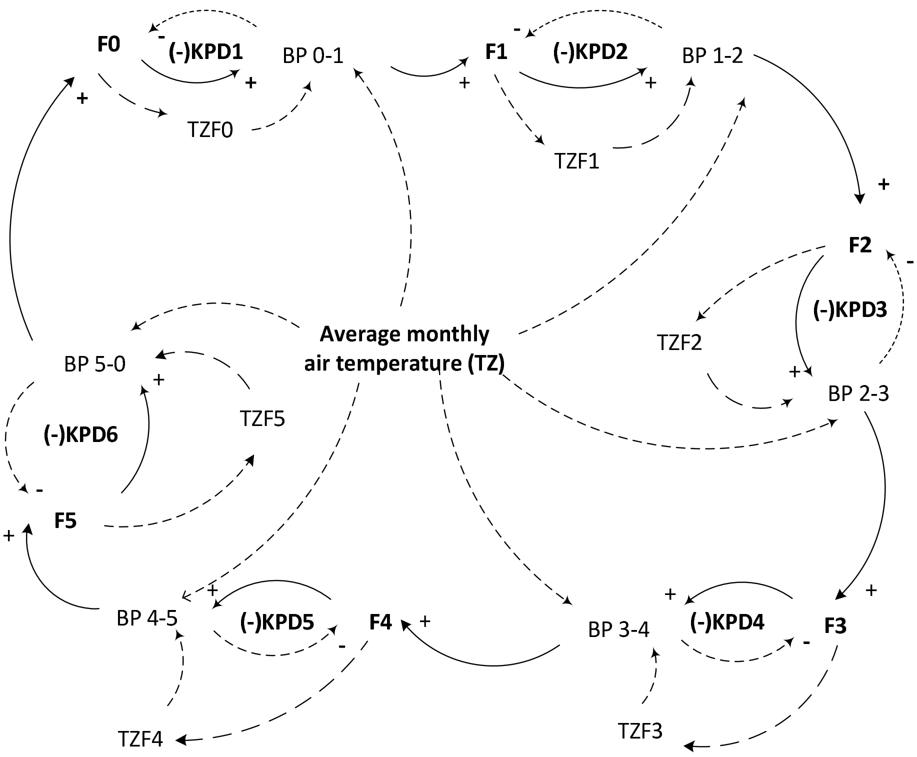

Figure 4: Structural diagram

In the structural diagram, all feedback loops from KPD1 to KPD6 are shown. The most important material flows are drawn at full line, and information at dashed line. Informational flows represent the impact of the external factor, air temperature, on the system: average weekly temperatures when the phenophases are present (TZF0…TZF5) and average monthly temperatures (TZ) in period since 1.1.1993. to 31.12.2005.

DEVELOPMENT OF MATHEMATICAL AND COMPUTER MODEL

With regard to the application of methodology of system dynamics to build a computer model of the observed phenophase system, softwer simulation package POWERSIM Studio was selected. Using this programe allows the formalization of concepts of system dynamics in the form of mathematical-computer simulation model. POWERSIM is an object-oriented program in which the program code is generated by creating a flowchart, so that the construction of the flow diagram (the second conceptual model of the system dinamics) runs parallel to the construction of mathematical-computer model.

Flowchart of the computer model is built with the help of symbols: equations of the level state (Level), equations of the change of the level state (Rate), auxiliary equations (Auxiliary), constant equations (Constants) and initial value equations. Levels, constants, equations of the change of state and auxiliary equations are connected by flows and in that way close the feedback loop. Time-step model is 1 week and responds the time interval in which the phenological observations were performed. The bank calendar was chosen and required measure units defined. The state of the phenophases was decribed through the number of trees, so measure unit BS was added.

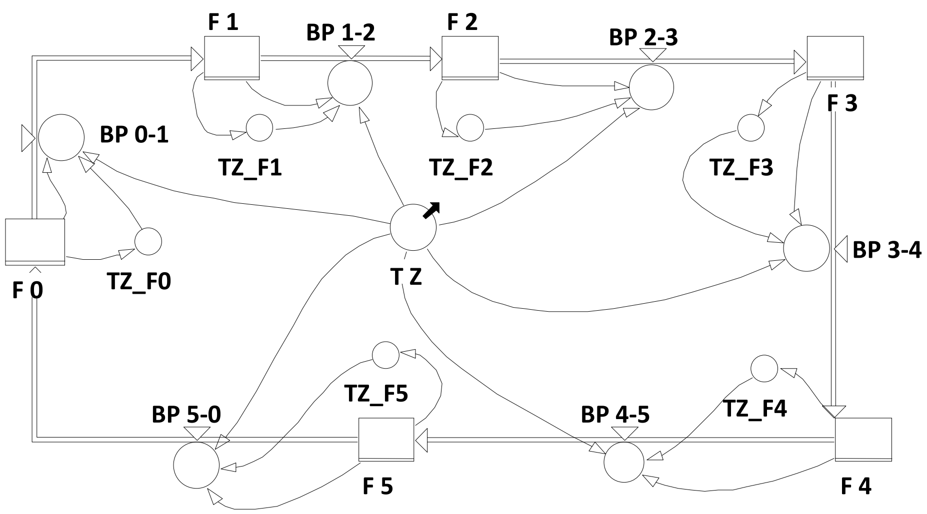

Figure 5: Flowchart model

The flowchart of the phenophase system was developed as shown in Figure 5. One symbol in the flowchart model determines an exact mathematical equation. The model consists six stage levels, which means that it is the model of the sixth degree. The dynamics of the phenophase system has to be described through system of differential equations:

$$\frac{d(F0-10BS)}{dt} = (BP5-0) - (BP0-1) \quad (1)$$

$$\frac{d(F1-0BS)}{dt} = (BP0-1) - (BP1-2) \quad (2)$$

$$\frac{d(F2-0BS)}{dt} = (BP1-2) - (BP2-3) \quad (3)$$

$$\frac{d(F3-0BS)}{dt} = (BP2-3) - (BP3-4) \quad (4)$$

$$\frac{d(F4-0BS)}{dt} = (BP3-4) - (BP4-5) \quad (5)$$

$$\frac{d(F5-0bs)}{dt} = (BP4-5) - (BP5-0) \quad (6)$$

In equations (1), (2), (3), (4), (5), and (6) initial conditions recorded by phenological observations on 1.1.1993. are expressed with the number of trees (BS). Given that it is a dormant vegetation, the initial condition of phenophase F0 is 10 BS, and for the rest of the phenophases it is 0 BS. Phenological observations on the sample plot started 1.4.1993. However, with the aim of closing the full cycle of vegetation, it is safe to say that the trees in the sample plot, on 1.1.1993. were in idle state. Integration of equations (1), (2), (3), (4), (5) and (6) results in mathematics-computer model which is used to describe the dynamics of this system. Working with POWERSIM software allows transfer of data to Excel. In order to monitor system status and compare the dynamics of the average air temperatures and the actual system model, the model has ben supplemented by auxiliary variables. Total state of the phenophase temperatures is defined by following auxiliary equation:

UTZF = sum(TZF0;TZF1;TZF2;TZF3;TZF4;TZF5) (7)

Next equation (8) defines the number of present air temperatures where the function COUNTGT gives the number of elements in a row whose value is greater than 0.

BTZF = COUNTGT({TZF0;TZF1;TZF2;TZF3;TZF4;TZF5};0) (8)

Equation (9) defines average weekly air temperatures of the phenophases:

PTZF = UTZF/BTZF (9)

VERIFICATION AND VALIDATION OF MODELS

During simulation modelling continuous model screening is necessary. To determine whether the model represents the actual system satisfactorily, the process of creating confidence in the simulation model that includes verification and validation of the model is carried out. If the procedures of verification and validation show that the model is not valid, we need to go back to the beginning of the simulation modelling and modify the model.

In the case of the phenophase model development, the procedure of creating confidence in model demanded its modification through change of the model structure and definitions of certain variables in more than one occasion. The application of the POWERSIM software package facilitates the transition from structural to computer model, because the program code is generated parallel with construction of a flowchart. It means that, through parallel building of the flowchart and computer model, which is based on a structural diagram, the verification is done through alignment of the structural diagram, flowchart and mathematical-computer model (Lončar 2005). During model development the verification procedure demanded repeated model calibration. Tuning was repeatedly referred to the way of the defining the influence of the temperature on the phenophases. Verification was carried out by performing experiments with different sorts of seeds to use random numbers, as well as repeating experiments with the same seed. With implementation of the verification of the computer model of the phenophase system it was determined that the model mimics the real system well, and that based on that behaviour it is possible to draw conclusions about the real system. The evaluation process of the model is implemented as replicative evaluation.

Replicative evaluation

The simulation for the period 1.1.1993. to 30.12.2005. was implemented using computer built model of the phenophase system and collected and processed data. The completion of the simulation is 30.12. due to the calendar chosen during model development, and that is bank. The choice of the calendar in POWERSIM was done according to the demands of the model, because Bank calendar enables defining TZ variable as average monthly air temperature value. Table 4 shows average occurence time of certain phenophases obtained by simulation.

Table 4: Simulated average time of the phenophase occurence in observed time

Phenophase	Month
F0	4
F1	4
F2	10
F3	10-11
F4	11
F5	11-12

Comparing Table 4 with data in Table 1 can be concluded that there is some difference in the occurence of phenophases F1, F4, and F5. The spotted difference is related to the chosen time step of the model and the calendar of the simulation project. Based on the forgoing it can be concluded that the simulation model well mimics the real system.

The comparison of variables TZ and variables PTZF was performed by using software Statistica7 and conducting appropriate tests: t-test for dependent samples, Sign test and Wilcoxon Matched Pairs test. All these tests are used for associated samples which meets the needs of comparing differences between variables TZ and PTZF, as these variables come from the same population of air temperatures. T-test for dependent samples enables determining the differences between two related samples, assuming that samples are normally distributed. The results of the t-test for dependent samples, with significance level α=0,05 as shown in Table 5.

Table 5: T-test

Statistica 7	t_{tab}
0.513507	1.98

Given that the calculated t<tab, it can be concluded that the difference between TZ and PTZF is not significant. As an alternative to t-test for dependent samples and as additional confirmation of the results, nonparametric tests Sign test and Wilcoxon Matched Pairs test were conducted. The results in which the

difference between variables TZ and PTZF is not significant are shown in Table 6.

Table 6: Sign test i Wilcoxon Matched Pairs test

Pair of Variables	Sign Test (TZ I PTZF) Marked tests are significant at p <.05000			
	No. of Non-ties	Percent v < V	Z	p-value
TZ & PTZF	156	49.35897	0.080064	0.936186
Pair of Variables	Wilcoxon Matched Pairs test (TZ I PTZF) Marked tests are significant at p <.05000			
	Valid N	T	Z	p-value
TZ & PTZF	156	6026.000	0.171630	0.863729

The simulation model has to meet an acceptable level of reliability so that the conclusions based on the model behavior could be treated as valid and applicable in a real system. Accordingly, it can be concluded that the phenophase system model mimics the real system well and that based on its behavior conducting simulation experiments, conclusions on real phenophases systems could be made.

CONCLUDING REMARKS

System-dynamic approach to modeling natural systems is shown in the example of forest trees phenophases and has many advantages:

1. Studies the system with feedback control, and natural systems are feedback control systems.
2. Includes a system analysis through which the most important factors affecting the dynamics of the system can be detected and through wich can also be observed the relations between system elements and their interaction with the environment.
3. May include random variables which are almost always present in natural systems.
4. It requires interdisciplinary approach which is a prerequisite for modeling natural systems.
5. Synthesis of mathematics, informatics, statistical and biological methods results in interdisciplinary scientific methodology that can be applied to the parametrization and formalization of complex natural systems.
6. Valid model enables experimentation without consequencis and with full control of conditions which is not always possible in nature.

REFERENCES

1. Ahas R, A. Aasa, A. Menzel, V.G. Fedotova and H. Scheifinger. 2002. „Changes in European spring phenology“. International Journal of climatology, 22: 1727-1738.
2. Ahas R, Jaagus J, A. Aasa. 2000. „The phenological calendar of Estonia and its correlation with mean air temperatur“. International Journal of Biometeorology 44(4): 159-166.
3. Chmielewski F-M, Rőtzer T. 2001. “Response of tree phenology to climate change across Europe“. Agricultural and Forest Meteorology 108: 101-112.
4. Chmielewski F-M, Rőtzer T. 2002. „Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes“. Climate Research 19: 257-264.
5. Jaagus J, Ahas R. 2000. „Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia“. Climate Research 15(3): 207-219.
6. Lončar Lj. 2005. „Sustavska dinamika u analizi gospodarenja šumom“, Magistarski rad, FOI, Varaždin.
7. Lončar Lj, M. Hell i V. Dušak. 2006. „A System Dynamics Model Of Forest Management“. ITI 2006 Proceedings of the 28th International Conference on Information Tehnology Interfaces, Cavtat/Dubrovnik.
8. Menzel A. 2000. „Trends in phenological phases in Europe between 1951 and 1996“. International Journal of Biometeorology 44(2): 76-81.
9. Scheifinger, H., A. Menzel, E. Koch, C. Peter and R. Ahas. 2002. „Atmospheric mechanisms govering the spatial and temporal variability of phenological phases in central europe“. International Journal of Climatology, 22: 1739-1755.

AUTHORS BIOGRAPHIES

LJILJANA ŠESTAN was born in Bjelovar, Croatia and went to the University of Zagreb, where she studied forestry and obtained the BSc degree in 1999. She recived she´s MSc and PhD from University of Zagreb, Faculty of organization and informatics. She works from 1999. till present day in „Croatin Forests“d.o.o. She´s e-mail address is: ljiljana.sestan@hrsume.hr.

VESNA DUŠAK was born in Bjelovar, Croatia and went to the University of Zagreb, where she studied informatics and obtained she´s MSc and PhD degree. She is currently a profesor in the Faculty of organization and informatics in town Varaždin in the field of simulation and operations research.