A System Dynamics Model of Forest Management

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Abstract. *In terms of a dynamic system, the state of any forest greatly depends on the respective forest management model. Commercial forests, aimed at producing timber, ought to be managed in such a way as to ensure not only the sustainability of income, but also of all the other general benefits to be yielded from such forests. In order to determine whether the current management of a forest's dynamic system complies with the principle of sustainable development, simulation modelling has been applied, including the system dynamics method. Owing to it, the state of the forest as a dynamic system upon implementing a certain management strategy can be forecast.*

Keywords: simulation, modelling, system dynamics, even-aged forest, mathematical computer model.

1. Introduction

Simulations and system dynamics method make it possible to describe and solve complex dynamic problems, including forest-related problems, as well as those concerning forest resources management. Over the last few decades, due to the increasing environmental awareness, the importance of the forest ecosystem has been acknowledged at the global level, which in turn enabled it to become a topic of relevance to the general public. Sustainable forest management, that is, the achievement of long-term economic, social and environmental goals has thus become the basic forestry principle. "Forest management is a problem of increasing controversy and difficulty. [1]" However, in spite of numerous initiatives, sustainable forestry, as of yet, has not been totally implemented in practice. According to the European Forest Institute's annual report, consistent efforts need to be made if sustainable forest management and the multifunctional role of the forest are to be fully introduced into the free-market economy [4].

Changes in the forest management approach have led to changes in the modelling of forest development. The advantage of implementing simulations in the modelling of forest development is the fact that experiments are not conducted on a real system, which makes it possible for undesirable effects which may arise during the experiment to be avoided. Additionally, the possibility of incorporating certain undesirable – albeit probable – modifications into particular simulation models is provided, with a view to determining their potential impact on managing forest resources in a given area.

The object of research presented in this paper is the development of the model of Beech management class system. The Beech management class encompasses mixed stand, the most prevalent among which is the beech. Apart from being the most widely represented tree species in Europe, the common beech (*Fagus sylvatica* L.) is widespread in Croatia as well, where it covers around 30% of the total forest area. It is generally found in mixed forest cover type, the most common among which are beech forests consisting of trees of similar age, height and circumference. Such forests are called even-aged forests, made up of management classes. By means of the model developed simulation experiments were carried out. The system dynamics was observed in relation to sustainability principle, with an emphasis on the potential impact of various management approaches. The analysis of the current management approach is aimed at identifying the critical spots within the system. Dealing with these spots effectively might result in improved management and thus enable the system to attain the state of equilibrium implied in the concept of the normality of an even-aged forest.

2. Difficulties inherent in the system observed and how they can be dealt with

A complex dynamic system of the Beech management class, made up of age classes, is observed through its age structure. Disruptions in the age structure, as shown in figure 1, owing to which the sustainability principle cannot be fully implemented, present the crucial problem in managing such systems. In fig. 1 the discrepancy between the actual state of the measured growing stock and the normal state of the observed Beech management class is shown.

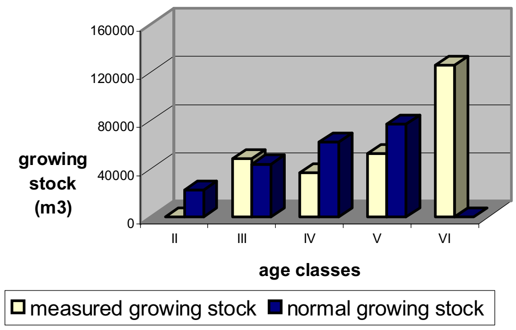


Figure 1. Ratio between measured and normal growing stock in 2002

Major problems in forest management generally arise from the fact that long-term natural processes tend to be paralleled by short-term planning. For instance, whereas forest management is based on the Principles of Management, in which a detailed description of all the regulations regarding the following ten-year period are given, it is evident that this period – when compared to the expectation of life of a forest – is a relatively short one indeed. The normal forest area of an even-aged forest is monitored by analyzing the age class state and dynamics. Distinction should be made between the normal forest area and the normal distribution of the growing stock according to age classes. The number and range of age classes depend on the age until which a forest is to be grown. In beech forests, for instance, which are on average grown until they are a hundred years old, a normal beech forest would contain 5 age classes ranging up to 20 years, respectively. The age class dynamics is conducted naturally, since in the course of time, owing to the aging process, the stand is shifted into a higher age class. Therefore the only intervention carried out is thinning, aimed at increasing the quality. Once the rotation has been completed, which in case of the beech occurs when age class VI has been finalized, the old stand is felled completely. This is known as regeneration harvest, intended for enabling a new forest – age class I stand – to sprout from the seeds of prime trees in the place of the old one. The lifecycle of a forest is thus completed.

However, due to irregularities in the age structure, regeneration harvest is sometimes either postponed or conducted before the projected rotation has ended. It is due to those irregularities in the age structure that considerable oscillations in age classes among trees felled in the course of thinning cutting will arise. Intervention harvests, which may be seen as resulting from both natural processes and measures accounted for by economic reasons, can also have a great impact on the system. Such a harvest is carried out whenever there are indications of drying, disease or damage among timber, so as to gain at least minimum economic benefit from felled timber.

A model of even-aged forest management involving the monitoring of the state and dynamics of age class areas, in the context of various regeneration harvest policies, was already attempted [2]. The normal growing stock is determined for each management class in a particular management unit and is calculated on the basis of the normal forest area (the total management class area distributed evenly into all age classes) and volume tables specifying the norm for even-aged forests [5]. In harvest planning the following parameters ought to be considered: the state of the growing stock by age classes as affected by the regular and intervention harvest done randomly, as well as the growing stock dynamics between different age classes. The transition of growing stock from one age class to another does not have a uniform character owing to the varying age structure of the stand within one age class. In other words, since the transition speed is variable, it is unlikely that the same amount of the growing stock will be transferred between classes. Besides, resulting from changes in the management approach or natural changes, transition between age classes can be induced externally. Within a system, growing stock dynamics is affected by regeneration harvest policies. Namely, the higher the frequency of such harvests, the more considerable the outflow of the growing stock contained within the system. However, such outflow implies a larger area transferred into age class I and thus an increase in the growing stock which in a 20 years' time will provide inflow into the system or, more precisely, age class II.

So, the growing stock of an even-aged forest system, apart from being affected by natural processes (through annual increment and aging), is also changed by means of interventions carried out for economic purposes. Since a forest system is dominated by cause/effect relationships, in developing system dynamics models, systems dynamics methodology will be used. While conducting experiment, the current management approach in the observed forest will be analyzed.

Systems dynamics refers to a simulation of a system depending on feedback, in other words, the one in which system input and system output are interrelated [3]. It makes it possible to analyze the dynamics of changes occurring in the state of a system throughout a particular period.

3. Data gathering and processing methods

Developing a simulation model starts with analyzing the state of the observed system, that is, the selected object of research. The basic characteristics of the object of research are shown in Table 1. Research data were obtained by means of field measuring conducted in 2001.

Table 1. The object of research

The object of research	Beech management class
Forest District	Zagreb
Forest Office	Novoselec
Management Unit	Marča
Working period	15/06/2001 to 15/11/2001

Data referring to the period 1982-2002 were isolated and classified according to age classes. The state of the age structure was determined by gathering and processing data on the growing stock, its respective area and the age class increment percentage. For each age class data on the performed regular and intervention harvests (timber harvested by intervention harvest) were gathered. The data on the annual frequency of intervention harvests were processed statistically by means of the Stat::Fit tool included in the Service Model v4.2. simulation package.

In order to convey the pattern of behaviour of this parameter into a computing model in as trustworthy a manner as possible, characteristic distributions in each age class were determined. The significance level of the obtained results was 5%. The degree of freedom was determined in accordance with the number of frequency distribution classes and the curve rank. The 'goodness of fit' – distributional adequacy – between parameter and its respective theoretical distribution was determined by using the Kolmogorov-Smirnov test (K-S test).

The following hypotheses regarding the frequency of intervention harvests in each particular age class were tested:

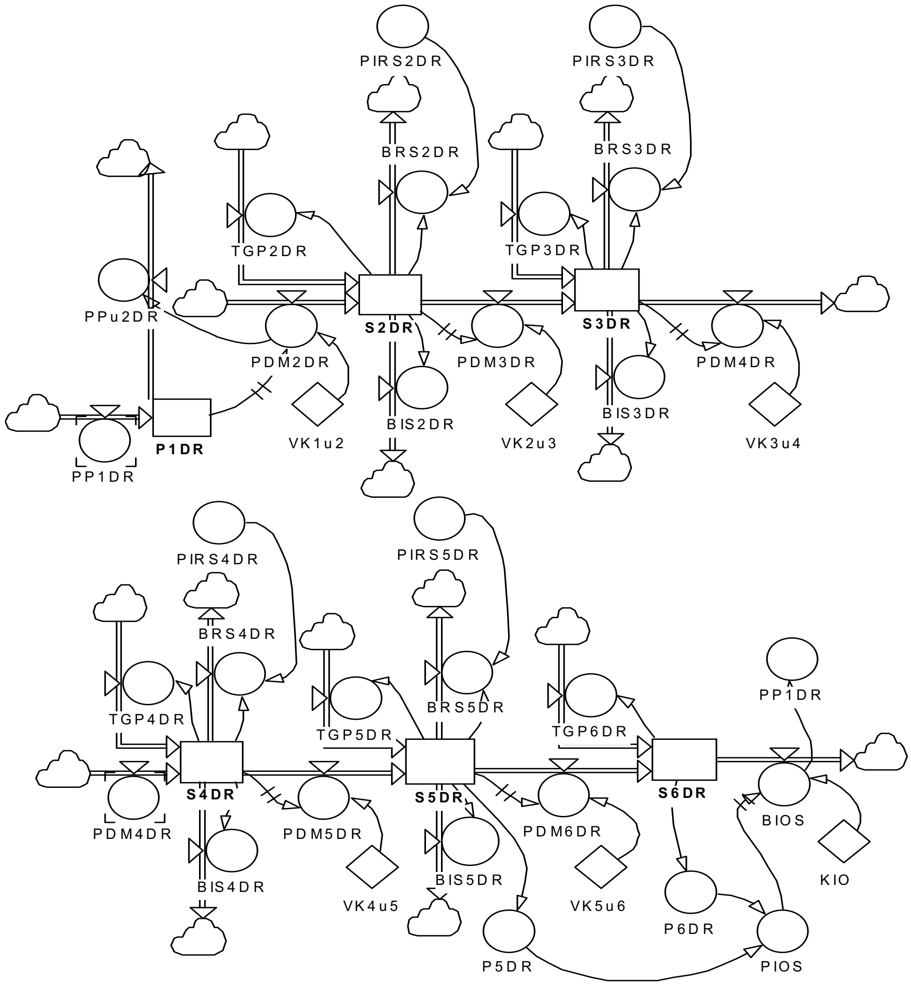
H_0: The observed data can be displayed by means of theoretical distribution at the 5% significance level.
H_1: The observed data cannot be displayed by means of theoretical distribution at the 5% significance level.
The selected distributions as well as their respective parameters are shown in Table 2.

Table 2. Selected distributions for the frequency of intervention harvests

AGE CLASSES	DISTRIBUTION	KOLMOGOROV-SMIRNOV TEST	
		K-S	H_0/H_1
II	UNIFORM (0., 6.)	0,2	H_0
III	UNIFORM (0., 12.)	0,183	H_0
IV	EXPONEN. (0., 4.4)	0,215	H_0
V	UNIFORM (0., 16.)	0,225	H_0

4. Development of the Beech management class system model

The fact that in developing the computer model the POWERSIM package was used entails that a flowchart was developed in parallel with the mathematical computer model. In figure 2 flowchart of the process of even-aged forest management is shown.



Key: S2DR,S3DR,…,S6DR – state of the age class, P1DR, P5DR, P6DR – *n* age class area, PP1DR and PP2DR – transition of the area into the first/the second age class, PDM2DR, PDM3DR,…, PDM6DR – transition of growing stock into *n* age class, BRS2DR, BRS3DR,…, BRS5DR – speed of executing regular harvests in *n* age class, BIOS – speed of executing regeneration harvests, PIOS – Regeneration harvest execution plan, PIRS2DR, PIRS3DR,…, PIRS5DR – Plan for executing regular harvests in *n* age class, BIS2DR, BIS3DR,…, BIS5DR – speed of executing intervention harvests in *n* age class, TGP2DR, TGP3DR,…, TGP6DR – annual increment in *n* age class, VK1u2, VK2u3,…, VK5u6 – delay in transition into another age class, , KIOS – delay in the execution of regeneration harvests.

Figure 2. Flowchart of the process of forest management

In the observed system of the Beech management class there are regulatory flows concerning the speed of transition of the stand from one age class to another as well as those concerning regular planned harvests and intervention harvests. The impact of the speed of executing regeneration harvests is also defined by a regulatory flow. Accumulative flows, on the other hand, are those connecting the annual increment of a particular age class with the state of that age class. There is a total of five such accumulative flows and fourteen regulatory flows. Plans for executing regular harvests and regeneration harvests are external factors affecting the system. For the dynamics of the system as a whole to be monitored, the following auxiliary variables were added to the model: the total of age classes (SDR), the total of regular harvests (SRS), the total of intervention harvests (SIS), as well as the total of harvests (SS), none of which were represented in the flowchart in figure 2. Additionally, the system of the Beech management class was observed in terms of normality, that is, of enabling the system to attain the equilibrium state. It is for this reason that both the mathematical computer model and the flowchart were supplemented by relation (1) concerning normality.

NS = STOPRUNIF((S2DR=22000)AND (S3DR=S2DR*2)AND(S4DR=S3DR*1,4) AND(S5DR =S4DR*1,2)) (1)

The dynamics of the observed system was described by means of a system of differential equations:

$$\frac{d(S2DR-15895m3)}{dt} = PDM2DR + TGP2DR - BRS2DR - BIS2DR - PDM3DR \quad (2)$$

$$\frac{d(S3DR-11146m3)}{dt} = PDM3DR + TGP3DR - BRS3DR - BIS3DR - PDM4DR \quad (3)$$

$$\frac{d(S4DR-67359m3)}{dt} = PDM4DR + TGP4DR - BRS4DR - BIS4DR - PDM5DR \quad (4)$$

$$\frac{d(S5DR-258854m3)}{dt} = PDM5DR + TGP5DR - BRS5DR - BIS5DR - PDM6DR \quad (5)$$

$$\frac{d(S6DR-0m3)}{dt} = PDM6DR + TGP6DR - BIOS \quad (6)$$

$$\frac{d(P1DR-0ha)}{dt} = PP1DR - PP2DR \quad (7)$$

In these equations, constants (2), (3), (4), (5) and (6) refer to the initial state of the growing stock of the age classes observed in 1982. In equation (7), the initial state of the first age class is represented through its respective area. The integration of the equations listed above results in a mathematical computer model used for describing the dynamics of the observed system of the Beech management class.

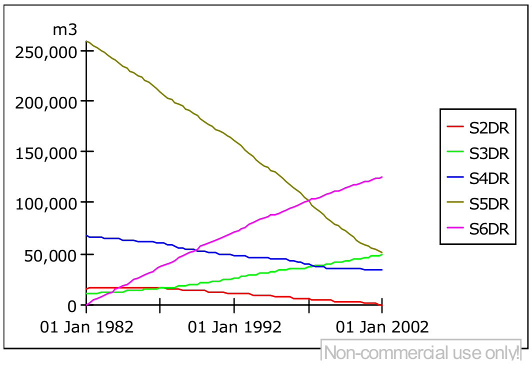


Figure 3. Simulated dynamics of age classes

5. Verification and validation of the computer model

Modelling the dynamics of the developed system was performed by means of the Powersim package. The verification of the developed model included conducting experiments by using different seeds for generating random numbers, as well as repeating the same experiment with the same seed. Replicative evaluation of the simulation model of an even-aged forest was conducted by implementing the developed computer model as well as the previously collected and processed data on the selected object of research. The validity of the model was ascertained through simulation of the twenty-year period between 1982 and 2002. The results of the simulation are shown in the diagram in figure 3.

In the diagram shown in figure 4, the actual dynamics of age classes based on the measuring performed in 1982, 1992 and 2002, is given.

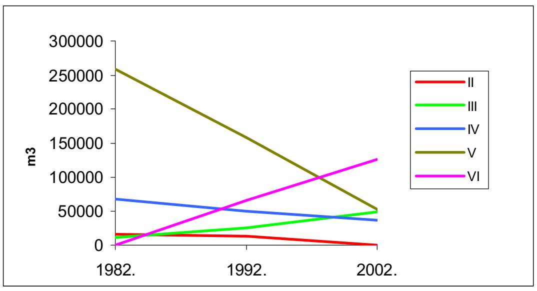


Figure 4. Actual dynamics of age classes

Upon comparing the simulated dynamics of age classes (Figure 3) and the actual dynamics of age classes (Figure 4), the validity of the simulation model can be estimated. Whereas the interval embodied in the model is 0.25 year, measuring was conducted at a ten-year interval, which accounts for the fact that in figure 3, showing the simulated dynamics of age classes, the transition between different growing stock samples tends to be fairly subtle.

6. Planning and conducting the simulation experiment

By changing coefficients in the equations of the mathematical computer model it is possible to create different scenarios. Simulation scenario I is based on the assumption that in the forthcoming period included in the simulation, regular harvests will be executed at the same rate as in the past 20 years. The initial conditions correspond to the state of the system in 2002. PIOS and BIS variables (the approach to planning regeneration harvests and the speed of executing intervention harvests, respectively) also have remained unchanged in relation to the mathematical computer model. Another assumption was that the speed of transition of the stand would also remain the same as that in the past twenty-year period. The dynamics of age classes according to this scenario is shown in figure 5.

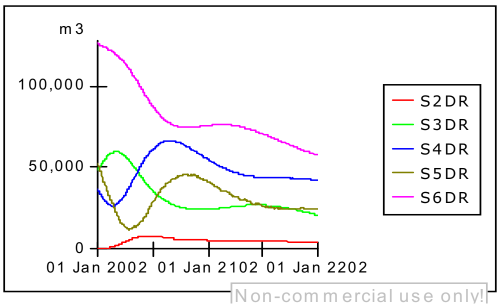


Figure 5. Dynamics of age classes according to scenario I

According to the diagram in figure 5, at the end of the simulated period a decrease in the growing stock is evident in all age classes, with the exception of class IV, which has been slightly increased. In other words, during the simulation the system did not attain the state of equilibrium.

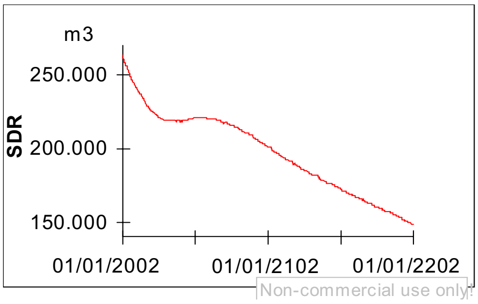


Figure 6. Dynamics of the state of age classes (SDR) according to scenario I

It is evident from the diagram in figure 6 that scenario I has resulted in the decrease in the system's growing stock, wherein a significant decrease is likely to occur in the period after the year 2052.

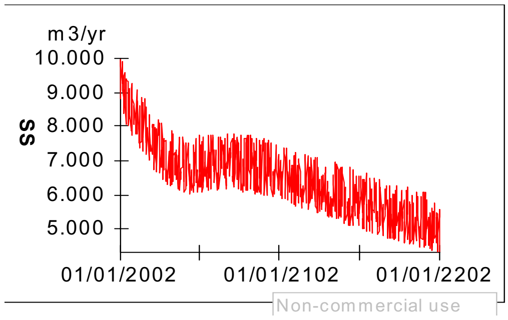


Figure 7. Dynamics of total harvests (SS variable) according to Scenario I

The diagram in figure 7. shows the dynamics of total harvests (SS variable), according to the scenario created. According to scenario I, the value of SS variable oscillates fast, which refers that the rates of the executed harvests are to large. Because of that the total growing stock of the system tends to decrease during the simulation period.

7. Final considerations

The methodology presented in this paper makes it possible to design a model of the dynamic system of an even-aged beech forest on the basis of system analysis and system dynamics. The system developed in such a way may aid the decision-making process concerning the selection of the optimal forest management strategy. Upon developing and evaluating the model, it can be assumed that one of the goals of the research described has been accomplished, namely that of ascertaining whether the system dynamics method indeed enables the development of a quality simulation model suitable for emulating forest management approaches.

A major feature of the described methodology is its applicability to all types of management classes. For it to be applied, it is necessary to merely modify and adjust the given parameters. In the course of planning and execution of experiments it was ascertained that the developed system dynamics model provides an effective means of identifying advantages and disadvantages of the current forest management approach.

In this paper, the problem has been detected according to the system approach (the existing forest management is not consistent with the sustainable management). It is necessary to look into possible ways of system management and choose the optimal through further research of different scenario. In doing so, the optimal way would be the one bringing system to balance as close as possible.

According to the findings of the conducted research, the current management approach ought to be modified and adjusted to system approach, which facilitates long-term planning and monitoring of the state of the system. Simulation based on system dynamics is used for determining the impact of management on the functioning of the system and its overall performance, as well as the consequences of long-term policies on the well-being of the system. By taking into consideration the results of scenario I, it could be argued that the current management approach does not fully comply with the sustainability principle.

Therefore it can be concluded that the implementation of the system dynamics methodology in forest management planning provides an alternative to present management approaches mainly based on linear projections of the future of a particular system. Such an alternative should by no means be disregarded.

8. References

[1] Barkley Rosser Jr, J. Complexities of Dynamic Forestry Management Policies, James Madison University Harrisonburg, USA, 2003.

[2] Čavlović, J. Sustavna dinamika u planiranju gospodarenja regularnim šumama na području Uprave šuma Zagreb. Glasnik za šum.pokuse 33: 109-152, Zagreb; 1996.

[3] Čerić, V. Simulacijsko modeliranje, Školska knjiga, Zagreb,1993.

[4] Flies, R. Forestry Strategy for Europe, 10th Annual Conference of the European Forestry Institute: Forest research crossing borders; Finland, 2003.

[5] Meštrović, Š., Fabijanić, G. Priručnik za uređivanje šuma, Ministarstvo poljoprivrede i šumarstva, Zagreb, 1995.

[6] Seila, A.F., Čerić, V., Tadikamalla, P. Applied Simulation Modeling, Thomson Books/Cole, USA, 2003.