Development of a Fuzzy Model for Prediction of Elastomer Properties

Bonato, Jasminka; Tomac, Nikola; Tomas, Vinko

Source / Izvornik: **Tehnički vjesnik, 2019, 26, 1505 - 1509**

Journal article, Published version
Rad u časopisu, Objavljena verzija rada (izdavačev PDF)

https://doi.org/10.17559/TV-20181115140506

ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20181115140506
Preliminary communication

Development of a Fuzzy Model for Prediction of Elastomer Properties

Jasminka BONATO, Nikola TOMAC, Vinko TOMAS

Abstract: Elastomers are amorphous polymers widely used in many applications. Degradability and durability of elastomers are very important properties, which can be strongly influenced by several types of physical and chemical processes such as impact of weather conditions, aging etc. These processes can cause structural changes, which may lead to the destruction of the quality of elastomer materials, like a deterioration of their mechanical and electrical properties, and ultimately a total loss of material functionality. A large number of investigations with various experimental procedures were carried out in order to provide a better understanding of the relationship between the structure of material and its mechanical properties. This paper presents a Fuzzy model, which was constructed for anticipation of elastomers behavior based on experimental research data. In addition, a linear model was made, based on the measured and literature data, for assessing the effect of radiation and deformation on properties of elastomer specimens. The Normalized Roth Mean Square Error (NRMSE) and the Roth Mean Square Error (RMSE) were used to evaluate the results of the Fuzzy model.

Keywords: Elastomers; Fuzzy logic; NRMSE; RMSE

1 INTRODUCTION

Development of new materials are crucial for new technologies that imply to be principal growth domains for the productive power. The efficient use of the computational modeling tools that researchers use to predict properties of materials plays a very important role. The development from new material to product commonly takes one or two decades. In order to reduce that time it is beneficial to apply the computational modeling tools for predictions of the properties of materials [1].

Elastomers are highly nonlinear elastic material with a great energy absorption capability and dynamic damping capacity. The very evident and highly important physical property of an elastomeric material is high elasticity which is demonstrated even when subdued to relatively small stresses [2, 3].

Elastomeric materials may be produced in natural and synthetic forms. Natural rubber (NR) is obtained from the plant sap, most frequently from Hevea Brasiliensis trees [4].

The use of the denomination rubber is not limited to naturally occurring rubber but the term is related to any material having mechanical characteristics considerably alike to those of natural rubber, irrespective of its chemical composition, as Treloar (1975) indicated. Synthetic rubbers are obtained from oil and gas and are attainable in a broad variation. Main rubbers comprise styrene-butadiene rubber (SBR), butadiene rubber (BR) and polyisoprene which include natural rubber (NR) and its synthetic alternative (IR). The extended continuous chain molecules are the usual feature of all polymeric materials comprising rubbers [5].

Mainly, the molecules in a polymer can be organized in an amorphous, glassy, or crystalline form. Elastomers however have unique qualities:

1) The elastomer contains very extended and elastic molecules, which are organized in amorphous elastomers with an unsystematic-winding molecular systematisation.
2) The elastomer has to function over the glass transition temperature, T_g.
3) The elastomer should manifest restricted crystallinity.

The basic chemical component of natural rubber is the hydrocarbon $(C_5H_8)_n$ (n~10^5) or Cis-1,4 polyisoprene (IR) which is a polymer of organic compound isoprene constituted of long chains. The natural rubber is soft and sticky at high temperatures, while at lower temperatures it is hard, brittle and unsuitable for direct use. Therefore, natural rubber has to undergo the networking process. As a result of this process, rubber that is characterized by excellent elasticity and a certain degree of strength [6], is obtained.

Large differences in the mechanical properties of unbroken and crosslinked natural rubber [7, 8] can be readily verified experimentally, for example by measuring the stress strain dependence. Apart from the presence of chemically reactive substances, such as sulfur or organic peroxides, networking can also be carried out by applying high-energy radiation (γ-radiation), as applied in this experimental study.

So called soft rubber, containing 1-3% sulfur, is highly elastic and is used for electro-isolation of conductors and cables and for the production of insulating substrates. From hard rubber, containing 30-35% sulfur, various electro-isolating parts and other rod-shaped products, plates and tubes are produced [8].

Table 1 Properties of natural rubber

Properties	Natural rubber
Density	0,913 gcm^{-3}
Elongation	750-850 %
Glass transition temperature (T_g)	− 72 °C
Tensile strength	17 – 24 MPa
Operating temperature	−50 to 82 °C

Elastomers are also labeled as viscoelastic plastics, referring to their ability to be pulled at least twice the length of the unloaded, and after the release of the strain the material returns to the unloaded length. The reversible rubber elasticity is 5-10 times of its original length, while the reversible metal elasticity is only 0,01-0,001 or 1-0,1%. Some physical characteristics of natural rubber are shown in Tab. 1.

Low prices of elastomer components make the crosslinked elastomeric materials ideal for many varied engineering applications. Elastomers play a very important role in sea transport (marine rubber fenders, engine mount), road transport (car tires, gaskets, bearings, hoses, sealing elements), rail transport (constructional parts, vibration isolators) and electrical engineering (as insulating parts) and many other applications.

The use of mathematical models in many areas of science and technology is increasingly important part of the research. Especially, if the experiment is expensive and time consuming, mathematical models give insight into the behavior of the problem. Fuzzy logic enables the analysis of approximation model [9], while the FISI (Fuzzy Inference System) allows estimating some of the properties within the model itself. The Mamdan algorithm was chosen for the processing of experimental data, and Linear model [10, 11] was created with the fuzzy logic.

Investigations of fuzzy logic applications in the field of shipping can be seen in the MZOS project, through a European Society for Fuzzy Logic and Technology or International Conference on Fuzzy Logic, which provides knowledge and results in theory and application of fuzzy systems [12, 13, 14].

2 FUZZY LOGIC

Fuzzy logic is a logical system in which the truth of some statement can assume any value between 1 (true) and 0 (untruthful). Such an approach is much broader than the binary logic of Boolean and allows mathematical modeling of inaccurate data. In recent times, the amount and diversity of applications of fuzzy logic have enlarged remarkably. The applications are extensive; from products such as photo cameras, DVD camcorders, and washers to production process control, medical devices, investments acceptance, and determination-assistance systems [15].

In classical theory, the sets are clearly defined sets of elements (numbers, symbols, etc.) and are called certain sets. The elements of all the sets we observe in a given situation belong to the invariable, constant set, called the universal set.

Such a definition is often not applicable, particularly in defining the terms such as high temperature or low radiation dose. In these examples, as well as in many others, you cannot always exclusively answer the question (yes or no). The values of linguistic variables represent fuzzy sets, which offer the possibility of interpretation of the ambiguities of spoken language. Fuzzy set is determined by membership function. The method of assigning membership functions depends on the properties of the data being grouped, i.e. the type of the domain for which they are set. If the domains are continuous, they are set by a function expression. For the discrete domains, on the other hand, certain degree of belonging is joined to each data element. Membership function is represented by the curve that shows the way in which each point is assigned the membership of a fuzzy set, and can range between 0 and 1.

Some forms of membership functions in Matlab: triangular (trimpf), trapezoidal (trampf), gaussmf, zmf, sigmf, dsigmf, psigmf. In applications in which we have a small number of data or inaccurate information, fuzziness allows the user to solve and explain the given problem.

The theory of fuzzy sets is the basis of fuzzy logic, introduced by Lotfi Zadeh 1965. Fuzzy logic is appropriate to reality more than classical logic [9]. In recent times, the amount and diversity of applications of fuzzy logic have enlarged remarkably. The applications extent from customer products such as photo cameras, DVD camcorders, and washers to industrial production process control, medical devices, investments acceptance, social researchers, and determination-assistance systems.

Fuzzy inference system – FIS can be described in four steps [11]: fuzzification, inference, aggregation and defuzzification. Fig. 1 shows the fuzzy conclusion structure for the selected input variables and the output variable.

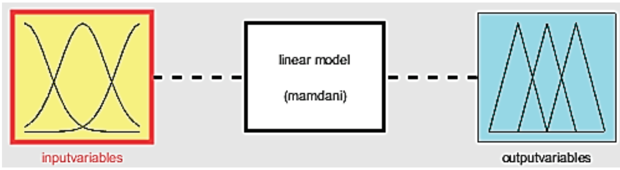


Figure 1 Configuration of fuzzy inference system (FIS) [16]

3 FUZZY INFERENCE SYSTEM

In the first step, fuzzification for the input variables (the deflection primary radiation dose and a second dose of radiation) a number of fuzzy sets and membership functions are selected. In the second step, inference, IF - THEN rules are formed by assisting expert knowledge. Using these rules, distinct values (eng. crisp) of all input variables are joined to as many values of membership functions of each output variable as the number of the selected rules. In the third step, aggregation, each output variable (length, width and number of damage) is matched to one fuzzy set with defined membership function.

Table 2 Samples labels

Sample number	Sample label
1	1-0-1
2	1-0-2
3	1-1,5-1
4	1-2-1
5	1-2,7-1
6	2-0-1
7	2-0-2
8	2-2-1
9	2-2,7-1
10	2-2,7-2

Defuzzification is the process of converting linguistic results from the rule base to numerical values.

The gravity method [17] is most often used to estimate the output value of the output variables. This means that the sum of the areas under the coefficient of affiliation for each individual linguistic set is summed up into a new fuzzy set and the center of gravity is calculated. Calculating the numerical values of linguistic output variables can be seen in Fig. 6 [18, 19].

4 MATERIAL AND METHODOLOGY RESEARCH

Latex natural rubber, produced by The Rubber Research Institute of India, is diluted with 0.6% ammonia solution and the latex thus prepared is subjected to γ-irradiation. As a source 60Co is used. The radiation was carried in Laboratory for Radiation Chemistry and Dosimetry Institute "Ruder Boskovic" in Zagreb [15].

Different primary and secondary radiation measure and streching strains are shown in Tab. 3.

Table 3 Different radiation measures and stretching strain [20]

Primary dose kGy	Degree of deformation $\varepsilon = \dfrac{l - l_0}{l_0}$	Secondary dose kGy
100 or 200	1,0 1,5 2,0 2,7	0 100 or 200

5 RESULTS

The results of determined dimensions, damage lengths, elastomer specimens, Fig. 2 and number of damage per surface unit, Fig. 3.

These measured and calculated values were used for definition of input-and output sets of fuzzy logic.

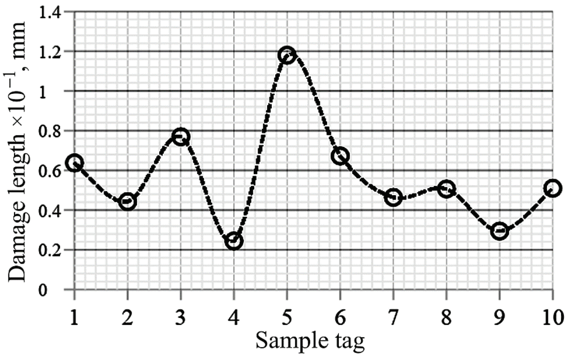


Figure 2 The results of measured dimensions, damage lengths [20]

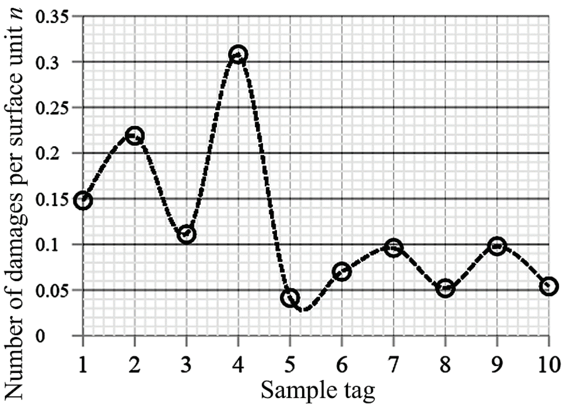
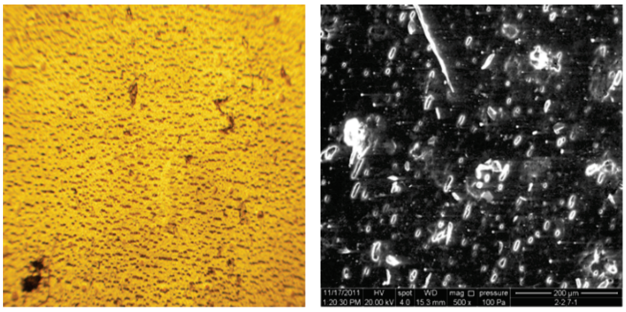


Figure 3 The results of measured dimensions, number of damage per surface unit [20]



a) b)

Figure 4 a) Light optical microscope (LOM) micrograph of sample 9; b) Transmission Electron Microscopy (TEM) micrograph of sample 9

The data collected by optical and electron microscopy made it possible to create a model using fuzzy FIS. Samples were taken with a transmission light microscope BIM 312 T and Scanning Electron Microscope QUANTA 250 FI in the Research Center of Metals in Pula [20, 21]. Elastomer specimens are shown in Fig. 4.

5.1 Presentation of the Results Obtained in Measurement

Total primary doses of 100 kGy and 200 kGy were applied. The degree of deformation was varied, then the samples were irradiated with a secondary dose of 100 kGy or 200 kGy. Sample labels were introduced with the intention that the primary dose (first digit), deformation (second digit) and secondary dose (third digit) could be read from them.

6 LINEAR MODEL

Based on the measurement data from Figs. 2 and 3, behaviour of elastomer material is analysed, when subdued to the influence of strain force, as well as to the effect of primary and secondary dose. According to these conclusions, membership functions and fuzzy mechanism rules are defined. In defining the model for input variables, two fuzzy sets (small, large) are specified. Simultaneously, for the input variable deformation three fuzzy sets: small, medium and large are defined. Each output variable is determined by three fuzzy sets (small, medium, large). For example, three areas of value are established to estimate the amount of damage. The first area of damage is assigned the linguistic denotation little, the second is labelled as middle and the third is big.

$b_{\text{small}} = [0{,}0414;\ 0{,}064\ ]$
$b_{\text{medium}} = [0{,}096;\ 0{,}111]$
$b_{\text{big}} = [0{,}148;\ 0{,}308]$

For each of these areas trumpf function is defined in Matlab program package. The name of the model is Linear. Fig. 5 shows the shape of membership function for output parameter for damage number.

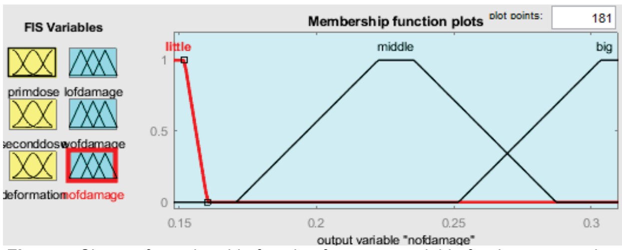


Figure 5 Shape of membership function for output variable for damage number

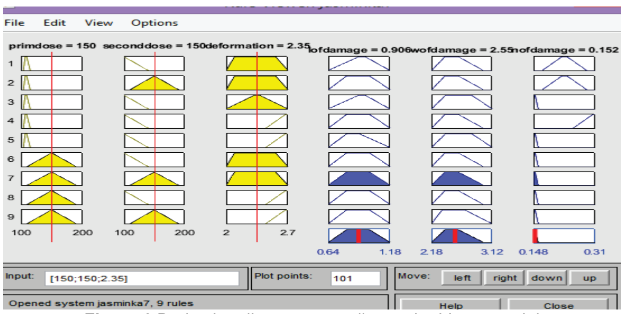


Figure 6 Deduction diagram according to the Linear model

To estimate the value of output parameters, Mamdani model is applied, because of a little input – output data. That is one of the fuzzy logic parameters. It is used as the estimation model in cases when rather small number of input-output data is available. The FIS rules for evaluating values of the output parameters are also defined, Fig. 6.

7 EXAMINATION AND ASSESSMENT OF THE MODEL'S EFFECTIVENESS

Mamdani fuzzy logic algorithm was chosen for data processing. After selecting the algorithm for the measured data set, the results of the model performance evaluation are compared by comparing the measured value with the value provided by the model. The check is made possible by the Matlab software package [16, 17].

Examined measurements and results acquired from Linear model are represented in Fig. 7.

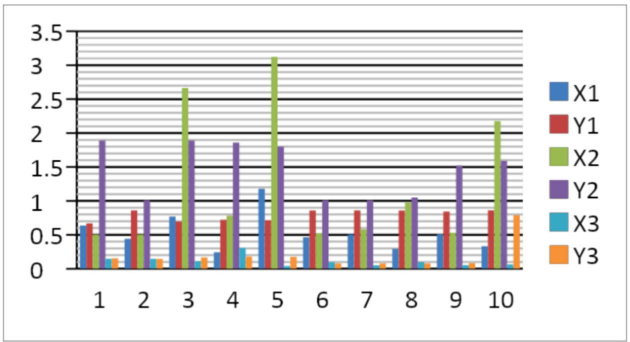


Figure 7 Examined measurements and results

In statistical modeling and particularly regression analyses, a common way of measuring the quality of the model is the RMSE. The predicted values should be compared with the observed data when computing the NRMSE. Values were calculated as well, using the following Eqs. (1)-(4):

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N}}}{\sigma} \tag{1}$$

$$NRMSE = \frac{RMSE}{\sigma} \tag{2}$$

$$RMSE = \sqrt{MSE} \tag{3}$$

$$MSE = \frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N} \tag{4}$$

Based on the data from Fig. 7, for every of the output values Normalized Roth Mean Square Error, Roth Mean Square Error and Mean Square Error were computed:
Linear model damage number = RMSE/std(X1)
Linear model length = 1.4597
Linear model width = 3.1973
Linear model damage number = 0.8797

Effect of different radiation measures on specimens reaction are showed in 3D study, Fig. 8.

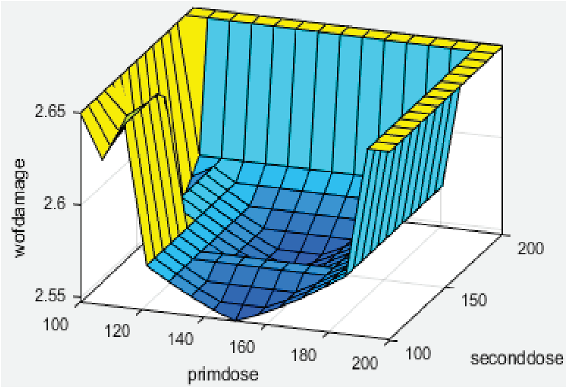


Figure 8 3-D reaction functions: effect of primary and secondary dose on damage width [16]

From study of 3-D reaction functions, it is feasible to recognize the effect of utilized deterioation on specific elastomer specimens (Fig. 9), and the effect of detoriation that was not experimentally tested.

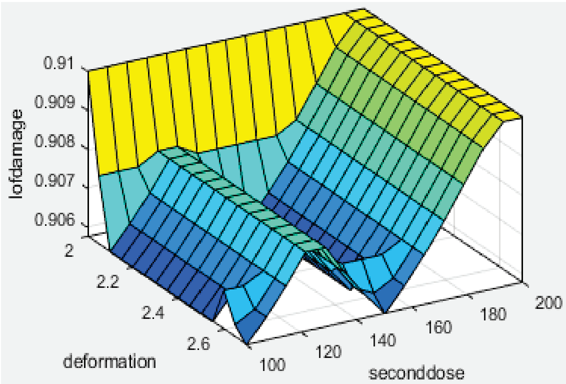


Figure 9 3-D reaction functions: effect of secondary dose and deformation on damage length [16]

8 CONCLUSION

In this investigation, fuzzy logic was used to determine the values of length, width and number of elastomer damages of samples due to the different radiation dose. In addition, the deformation effect on different elastomer samples is also estimated. Linear model was created using a FIS, based on the data collected by optical and electronic microscopy.

The influence of the primary dose on elastomer samples for which deformation is not applied can be analyzed by comparing the measured values and the values that the model gives. Based on the measured values it can be concluded that with the same primary radiation dose of 100 kGy, the increase in secondary dose decreases the width of the sample damage, while the number of damages increases. The behavior of elastomeric material was also investigated by applied stress. After the total dose of 150 kGy according to the linear model with deformation increase the length of specimens also increase. Based on the experimental part of the work it can be concluded that the primary and secondary doses do not have the same effect on the behavior of the elastomer samples.

By analyzing 3D response functions, a difference in sample behavior at a dose of 150 kGy can be observed. This dose was not applied to the samples.

In further research, this developed model can allow estimation and prediction of the properties of the material, with the change of the values of same parameters. Benefits of applying are flexibility, tolerance to data inaccuracy, as well as the use of language concepts in a fuzzy approach, enabling the improvement and implementation of human (expert) knowledge and experience.

Acknowledgements

The authors acknowledge the support of the Ministry of Science, Education and Sports of the Republic of Croatia for this work. Authors express appreciation to Julije Skenderović for the contribution in this investigation.

9 REFERENCES

[1] Janović, Z. (1987) *Polimerizacije i polimeri.* HDKI - Kemija u industriji, Zagreb
[2] Klarić, I. (2007) *Karakterizacije polimera*, http://www.ktf-split.hr/bib/karakterizacija_polimera. pdf
[3] Kolumbić, Z. & Tomac, N. (2005). *Materijali - podloge za diskusiju*. http://mapef.ffri.hr/~zvonimir/2005.
[4] Kovačić, T. (2010). *Struktura i svojstva polimera*, Pomorski fakultet, Split
[5] *An analysis of European plastics production, demand and waste, Plastics – the Facts 2012*, Retrieved from https://scholar.google.hr/scholar?q=%5B1%5D%09An+analysis+of+European+plastics+production,+demand+and+waste,+Plastics+%E2%80%93+the+Facts+2012&hl=en&as_sdt=0&as_vis=1&oi=scholart
[6] See http://www.mzos.hr/svibor/2/15/224/proj_h.htm
[7] Charlesby, A. (1960). *Atomic Radiation and Polymers*, Pergamon Press, New York, https://doi.org/10.1016/B978-1-4831-9776-0.50011-5
[8] Von Altrock, C. (1995). Fuzzy Logic and Neurofuzzy Applications Explained, Prentice- Hall Inc.
[9] Marković G., Marinović C. M., & Jovanović V. (2009) The effect of gamma radiation on the ageing of sulfur cured NR/CSM and NBR/CSM rubber blends reinforced by carbon black. *Chemical Industry and Chemical Engineering Quarterly / CICEQ*, 15(4), 291-298. https://doi.org/10.2298/CICEQ0904291M
[10] Jang, J. S. & Gulley, N. (1995). *Fuzzy Logic Toolbox for Use with MATLAB.* The MathWorks Inc., Natick, MA
[11] Tron, E. & Margaliot, M. (2004). Mathematical Modelling of Observed natural behavior: a fuzzy logic approach. *Fuzzy Sets and Systems*, 146, 437-450. https://doi.org/10.1016/j.fss.2003.09.005
[12] See http://www.hrbi.hr/ukf/members_eng.php
[13] See http://www.eusflat.org/
[14] Lotfi A. Zadeh (1965). Fuzzy Sets Information and Control 8. 338-353. https://doi.org/10.1016/S0019-9958(65)90241-X
[15] See http://www.mathworks.com/21383-rmse
[16] Ross, T. J. (2014). *Fuzzy Logic with Engineering Applications,* John Wiley & Sons, U.K.
[17] Waterman, D. A. (1986). *A Guide to Expert Systems.* Addison-Wesley Publishing Company
[18] Hines, Wesley, J. (1987) *Matlab Supplement to Fuzzy and Neural Approaches in Engineering.* John Wiley & Sons, Inc., New York
[19] Bonato, J. (2012) *Contribution to the analysis of the influence of temperature and radiation on the behavior of polymeric materials in maritime*. PhD thesis, Rijeka
[20] Bonato, J., Tomac, N., & Tomas, V. (2017). Assessment of the influence of radiation and deformation on the elastomer deterioration by using fuzzy logic. *Brodogradnja, 68*(2), 63-77. https://doi.org/10.21278/brod68205

Contact information:

Jasminka BONATO, PhD, Assistant Professor
(Corresponding author)
University of Rijeka, Faculty of Maritime Studies,
Studentska 2, 51000 Rijeka, Croatia
bonato@pfri.hr

Nikola TOMAC, PhD, Associate Professor
University of Rijeka, Faculty of Maritime Studies,
Studentska 2, 51000 Rijeka, Croatia
tomac@pfri.hr

Vinko TOMAS, PhD, Full Professor
University of Rijeka, Faculty of Maritime Studies,
Studentska 2, 51000 Rijeka, Croatia
tomas@pfri.hr