STOCHASTIC RELIABILITY MODELING OF RENEWABLE ENERGY SOURCES - APPLICATIONS TO ELECTRO-GEOTHERMAL GROUPS

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Abstract – Geothermal energy resources (GER) can be used for both electricity generation and direct uses depending on the temperature and the chemistry of the resources. Being included in regenerative energy sources, GER was not been developed to its full potential. Given the fact that the measurements used to assess reliability indicators exploitation of geothermal energy have a random character, stochastic approach to these assessments is well-founded. This paper presents an evaluation methodology of stochastic approach regarding the geothermal energy reliability and a case study where this method was applied to. The conclusions are presented in the final part of the analysis of the evaluation.

Keywords: reliability, modeling, random variables, geothermal systems.

1. INTRODUCTION

As it is widely known [1], the Renewable Energy Directive 2009/28/EC is designed to ensure the achievement of the 2020 renewable energy targets Both national and European targets being presented in different strategies [2,3,4]. In this context, the efficient exploitation of the geothermal energy resources has a significant importance globally, variable from country to country [5]. For Romania the efficient exploitation of GER has a significant level, placing itself as an economic exploitation potential right after the renewable resources from the following categories: hydraulic, wind and solar [6]. For proper operation of GER in effective economic conditions, it is necessary to develop and implement systems for geothermal energy (SGEE) to be effective as well as reliability, efficiency and economics. The present paper points to the SGEE reliability shaping and rating.

A stochastic approach to the subject is claimed by the following reasons:

- the reliability indicators of the equipments in the system structure are random variables (RV);
- the factors which have an influence on the operational reliability of the equipments in the system structure (the load level, the impact factors on environment, the impact of the physic and chemical content of the geothermal water, the operational conditions etc.) are RV;
- for certain settlements and in certain exploitation conditions, the parameters of the geothermal resource can be variable.

The stochastic nature of the systems is underlined in abounding publications [7,8,9,10] and is in a continuous development under the form of applications dedicated to production, transport and distribution systems of the electric energy (EE) coming from classical [11,12] and renewable sources [13, 14, 15]. The model described in [12] is dedicated to describe the relationship between the supplier and the consumer of the EE, through the evaluation of some continuity indicators.

Various papers [13] are dedicated to the development and application of stochastic models and techniques for the evaluation of reliability in case of EE generating systems out of classical resources, as well as wind and solar type renewable resources – resources for which the variable random character of the power displayed in the settlement is obvious. In [14] the random variable character of the wind power is shaped using the time series through which are stimulated the speed per hour of the wind. For the adequate management of the hydraulic hybrid systems generating EE out of renewable resources there were developed solutions customized to the stochastic character of the initial resources. A management solution for hybrid systems with sources using the wind and photovoltaic energy is described in [15].

This paper intends to present the application of the stochastic approach in shaping the reliability evaluation of the SGEE. Knowing the structure and the role of system, considering the fundamental indicators of reliability for the components in the system structure and RV measure we can determine the reliability indicators of the system, which will as well be random variables.

At the same time is analyzed how the level of the components reliability affects the reliability of SGEE. The evaluation methodology is fit for any type of SGEE [16], intended for the conversion of geothermal energy in EE or/and in thermal energy TE. Under these aspects, the presented paper came in addition of the previously presented information's in a recent publication [17], thus achieving full implementation of the results obtained on this topic.

2. WORKING METHOD

On the basis of structure and role of the SGEE there is represented the equivalent reliability bloc diagram (RBD) or the event arbor (EA) [7, 8, 9, 10].

For some SGEE there might be necessary to present several RBD and EA, different according to the functional levels which they have [9,10]. Considering the values recommended in specialty literature, for the supplying companies or identified through operational reliability studies [16] for the basic reliability indicators (failure intensity - λ, and repair intensity - μ) of the structural components of SGEE, generates the distribution of these indicators as being RV.

We deal with the following types of distributions: exponential, normal, Pert and triangle. Knowing the fundamental indicators of components (λ and μ) we can calculate the reliability indicators frequently used:

- the reliability function (the probability of good functioning) – R;
- the non-reliability function (the probability of braking up) – F.

The calculation expressions are well known [7,8,9,10]:

$$R_i = \frac{\mu_i}{\lambda_i+\mu_i}; \qquad F_i = \frac{\lambda_i}{\lambda_i+\mu_i};\ \ i=\overline{1,n} \tag{1}$$

Where:
n – number of components within SGEE structure, identified in RBD or fault tree analysis.

The (Ri,Fi) indicators will as well be RV. As follows, we evaluate the reliability indicators of SGEE, using the well known expressions [7, 8, 9, 10].

Considering the specific role and the reliability level of the components in the SGEE structure, for the reliability indicators of the SGEE structure (λs, μs, Rs, Fs) and some substructures one can admit the following hypothesis:

- the components (structural elements) are independent from reliability point of view;
- the probability of appearing multiple damages is declined.

Regarding this, some examples can be given with reference of the way in which the SGEE and structural subsystems of indicators are expressed when using RBD:

- For structures with „n" components in series:

$$\begin{cases} R_S = \prod_{i=1}^{n} R_i\,;\ \ F_S = 1 - R_S \\ \lambda_S = \sum_{i=1}^{n} \lambda_i = \frac{1}{MTBF_S};\ \ \mu_S = \frac{\lambda_S}{\sum_{i=1}^{n}\frac{\lambda_i}{\mu_i}} = \frac{1}{MTTF_S} \end{cases} \tag{2}$$

Where: $MTBF_S$ – Mean Time Between Failures; $MTTF_S$ – Mean Time of Failure.

- For the structures with two components (i,j) in parallel:

$$\begin{cases} R_{ij} = 1-(1-R_i)\cdot(1-R_j);\ F_{ij} = F_iF_j \\ \lambda_{ij} = \frac{\lambda_i\cdot\lambda_j\cdot(\mu_i+\mu_j)}{\lambda_i\cdot\mu_j+\lambda_j\cdot\mu_i+\mu_i\cdot\mu_j}\,;\ \mu_{ij} = \mu_i+\mu_j \end{cases} \tag{3}$$

Knowing the distribution of the indicators named above (RS, FS, λS, μS) one can determine other indicators which characterizes the level of SGEE reliability in the analyzed period of time (TA), characterized through the distribution function (DF) and characteristic parameters, as:

- α (TA) – the total period of operating time for SGEE;
- β(TA) – the total period of braking time for SGEE;
- ν (TA) – the number of breakings (damaging) of SGEE.

The functions allowed as working hypotheses for (x) RV distribution modeling are [7÷10, 18÷20]:

Exponential:

$$F(x) = 1 - e^{-x/m} \tag{4}$$

Triangle:

$$\begin{cases} F(x) = \frac{(x-x_{min})^2}{(m-x_{min})(x_{max}-x_{min})} & x_{min} \le x \le m \\ F(x) = \frac{(x_{max}-x)^2}{(x_{max}-m)(x_{max}-x_{min})} & m \le x \le x_{max} \end{cases} \tag{5}$$

Normal:

$$F(x) \equiv \phi\left(\frac{x-m}{\sigma}\right) = \frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x} e^{-\frac{(x-m)^2}{2\sigma^2}}dx \tag{6}$$

Pert:

$$\begin{cases} F(x) = \frac{B_z(\alpha_1,\alpha_2)}{B(\alpha_1,\alpha_2)} \equiv I_z(\alpha_1,\alpha_2),\ \ z = \frac{x-x_{min}}{x_{max}-x_{min}} \\ \alpha_1 = 6\left[\frac{m-x_{min}}{x_{max}-x_{min}}\right];\ \ \alpha_2 = 6\left[\frac{x_{max}-m}{x_{max}-x_{min}}\right] \end{cases} \tag{7}$$

Where:
m – average (mean) of RV;
σ – standard deviation;
(x_{min}, x_{max}) – minim and maxim value of RV;
ϕ - the standard normal distribution;
B –Beta function;
B_z – incomplete Beta function;

Magnitudes (m, σ, x_{min}, x_{max}) are parameters of the distribution functions.

At the SGEE level DF for RV is obtained through composing DF, correspondent of structural elements, according to the graphical used model (RBD or fault tree analysis), this are obtained applying ratios (2, 3) for reliability indicators of SGEE.

In the case of DF, there are possible the analytical expressions of the DF parameters being outcomes at SGEE level [18÷20]. In the other case the evaluation of DF parameters can be made only numerical, by series ratios.

Several tools and software packages can be found, which are able to make these evaluations in any of the ways and provide the DF of the system. This manner will be used in the present paper, using as well the DF testing facility resulting at the SGEE level, from applying some tests included in the software package. The results obtained after testing, provide the measure of compatibility between the empirical distribution (obtained with the data entry) and the theoretical distribution. The tests used in the present paper are [9, 10, 18÷20]: Chi – square [CHISQ], Kolmogorov- Smirnov [KS] and Anderson – Darling [AD]. After testing we proceed to ranking theoretical DF acting according to the „Fit ranking" value (the maximum deviation from the empirical DF).

For example, in figure 1 there are presented the DF of RV for the components of the simplest system (series, with two elements) and DF resultant.

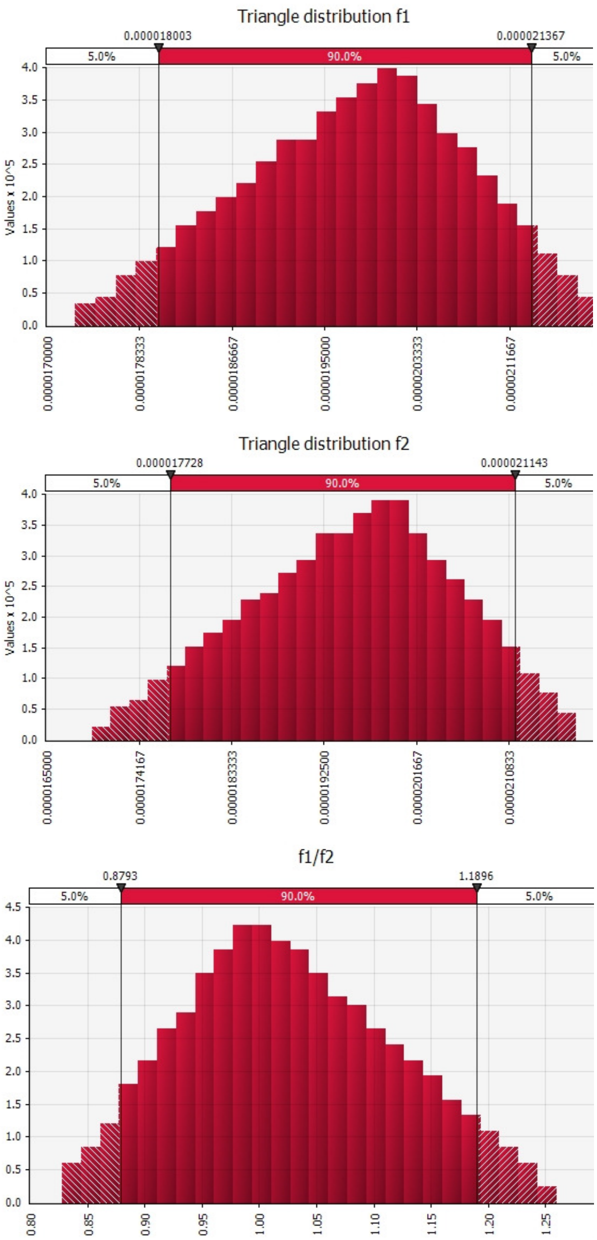

Fig. 1. Exemplification of DF's composition

On the basis of the results obtained after applying the three tests the most adequate DF will be chosen, thus the one for which the medium value of the „Fit ranking" is minimum.

For ranking the components in the SGEE structure according to the impact they have on its reliability, one will calculate the importance factor of each of the components [10]:

$$K_i = \frac{\Delta R_S}{\Delta R_i}; \quad i = \overline{1, n} \tag{8}$$

Evidently the important factors of their components are RV, whose distributions allow sensitive analysis of reliability SGEE [7, 8, 10, 18].

On the basis of information gathered through the named evaluations, the SGEE analyst (designer, investor or manager) can decide, being aware, on the way to follow, with reference to project/investment and to solutions for improving the reliability. Consequently, the matter dealt with in the present paper can be ranged also in the class of basic instruments of decisions through SGEE configuration.

3. CASE STUDY

The methodology from the previous chapter of the present paper was applied in this case study referring to a SGEE, that meets the technological scheme presented in figure 2, and the RBD from figure 3.

The evaluations were made with the aid of @Risk simulation program, a complex one, elaborated for risk analysis through the Monte Carlo [18] simulation method. The program is used as an add-ins library in Excel, being both accessible and easy to use.

For accomplishing the SGEE reliability simulation, we started from the fundamental values of the indicators of the components from (λ, μ) from the RBD of the system. With the aid of Excel and @Risk functions there were generated the reliability indicators for the considered SGEE subsystem presented in RBD. The simulations were run in a number of 10,000 iterations (the maximum of iterations), being also the possibility to decrease the number of iterations to 5,000; 1,000; 500 and 100.

The methodology was applied for the considered SGEE using all 4 distribution functions and the 3 tests, presented in chapter 2 of the paper.

Within this framework there are presented the results obtained with reference to the SGEE, in the hypothesis of Pert distribution of the entrance data and a synthesis of the others DF for SGEE. Details regarding the results obtained we have in [16].

The technological scheme and RBD of SGEE are represented in figure 2. In RBD (figure 3) were presented the components (subsystems) of the SGEE those which have importance for the SGEE reliability.

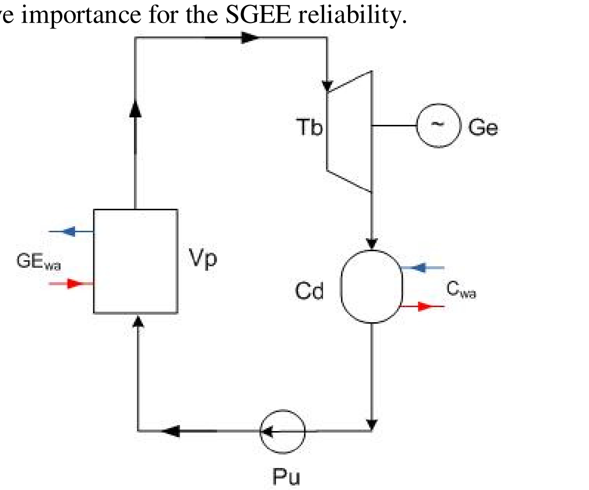

Fig. 2. The technological scheme

Fig. 3. The RBD of the SGEE

Where:
Ge – generator;
Vp – vaporizer;
Cd – condenser;
Pu – pump;
Tb – turbine;
GE_{wa} – Geothermal water;
C_{wa} – Cooling water.

To render the Pert distributions, the reference values taken into account (the most probable ones) the values obtained by processing the exploitation data for basic indicators (λ, μ), accepting a variation of 25% of the indicators value, [18, 19], thus: the maximum value with +10% over the reference value and the minimum value with (- 15%) under the reference value. The obtained results are shown in the table 1.

Table 1. The characteristic value of (λ, μ) indicators of considered SGEE components, using triangle DF

Equip ment	Indicator λ $[h^{-1}]$		
	Min. $\lambda\cdot 10^5$	Most likely $\lambda\cdot 10^5$	Max. $\lambda\cdot 10^5$
Ge	1.70926	2.01090	2.21199
Vp	1.68835	1.98629	2.18492
Cd	1.69983	1.99980	2.19978
Pu	1.68802	1.98590	2.18449
Tu	1.69127	1.98973	2.18870
Equip ment	Indicator μ $[h^{-1}]$		
	Min. $\mu\cdot 10^3$	Most likely $\mu\cdot 10^3$	Max. $\mu\cdot 10^3$
Ge	1.32605	1.56006	1.71607
Vp	34.0000	40.0000	44.0000
Cd	2.32900	2.74000	3.01400
Pu	56.6666	66.6666	73.3333
Tu	7.58923	8.92850	9.82135

Forward there are presented results obtained through simulation with @Risk program. In figure 4 and 5 is presented the Pert distribution for fundamental indicators of the SGEE (λ_S, μ_S).

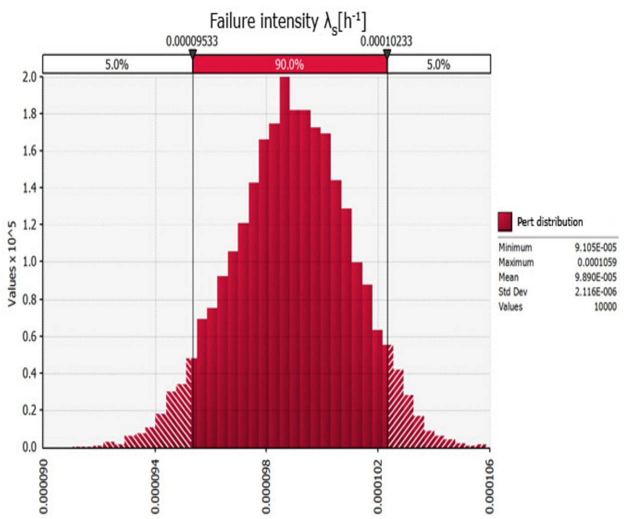

Fig. 4. The Pert distribution of the indicator $\lambda_S[h^{-1}]$

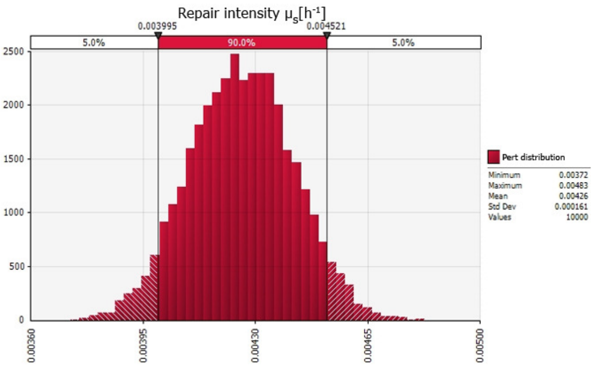

Fig. 5. The Pert distribution of the indicator $\mu_S[h^{-1}]$

Based on the determined distributions of the fundamental indicators (λ_S, μ_S) the reliability function distributions can be generated as it's shown in the fig. 6.

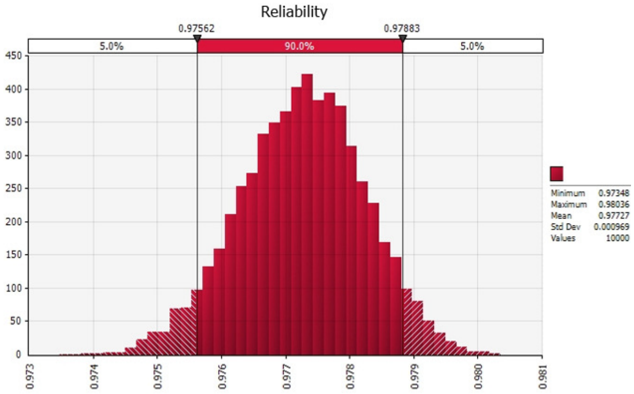

Fig. 6. Distribution of reliability function R_s"

The reliability function of the SGEE was tested with KS, CHISQ and AD. Distribution for SGEE with KS is presented in figure 7.

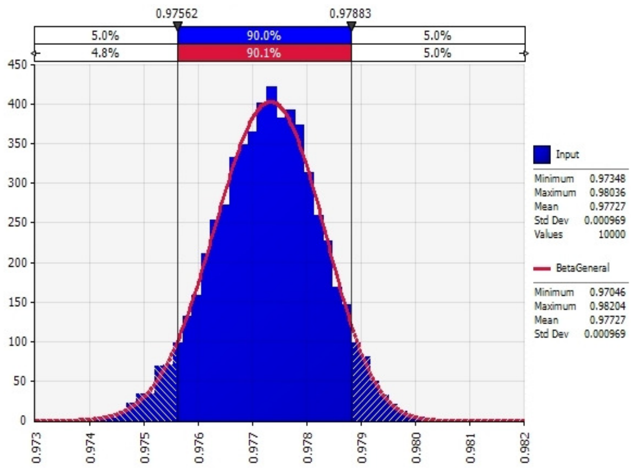

Fig. 7. Distribution of SGEE reliability function / KS

Analyzing the data obtained from all of the 3 tests applied we noticed that the first 3 places in shaping the empirical distribution of the SGEE reliability function are to be found the theoretical distributions BetaGeneral, Weibull and normal. Follow-up the simulation program used allows the representation of Box and Whisker diagrams, in which are underlined the representative values of the reliability indicators (figure 8).

Fig. 8. BW diagram for reliability function of SGEE

Sensitivity Analysis highlights the influence of fundamental values indicators of each component on the reliability function (figure 9).

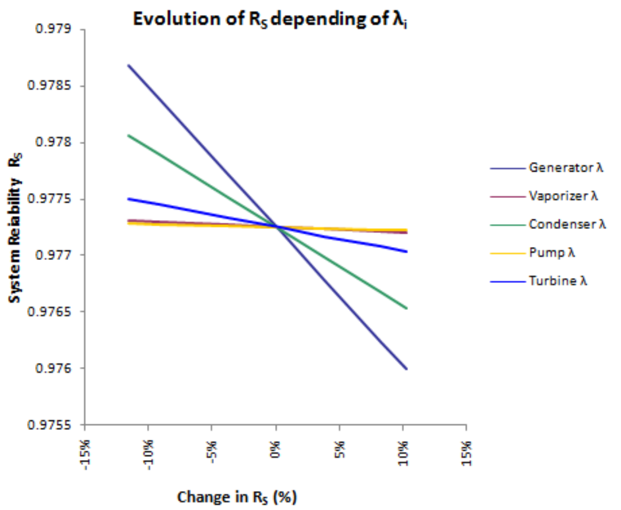

Fig. 9. The variation of SGEE reliability considering the fundamental indicators for components reliability

The second set of charts within the sensitivity analysis illustrates the distribution of importance factor (K_i). In figures 10÷12 there are a few examples.

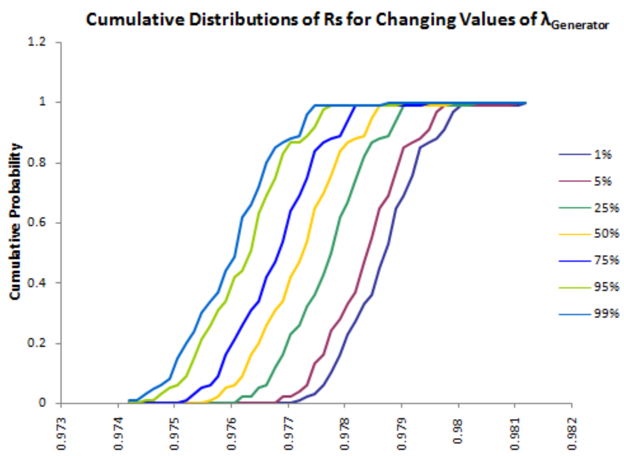

Fig. 10. Evolution of „R_S" depending of λ_{Ge}

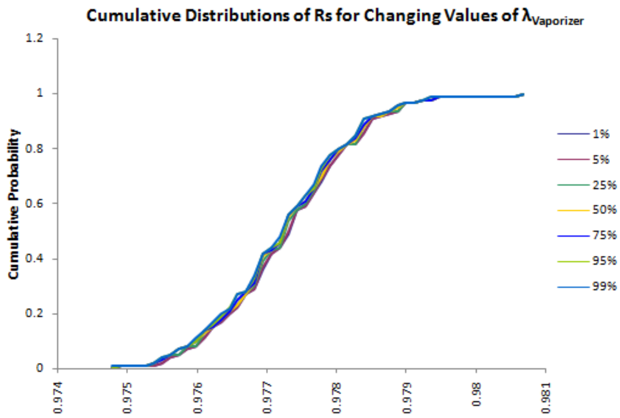

Fig. 11. Evolution of „R_S" depending of λ_{Vp}

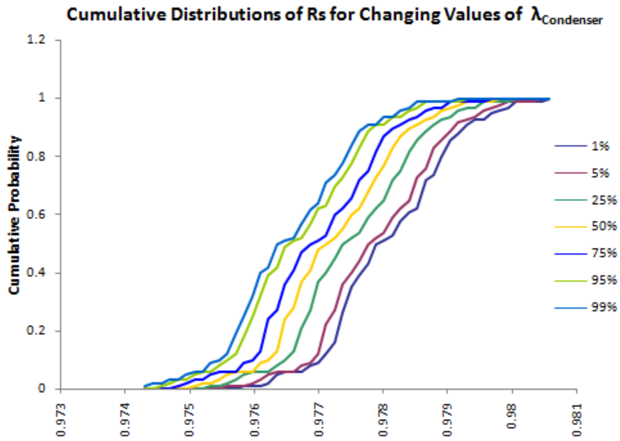

Fig. 12. Evolution of „R_S" depending of λ_{Cd}

The Tornado graph (figure 13) shows a bar for each of the defined elements within the analyzed SGEE, showing the minimum and maximum values of the system reliability, as the values of the input vary.

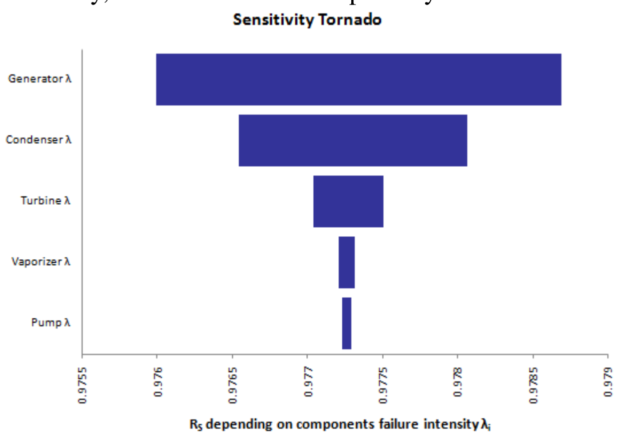

Fig. 13. Extreme values of „R_S" depending on λ_i

In figures 10÷13 we notice that the variation of the fundamental indicator **λ** of two components, generator and condenser (respectively, vaporizer and pump as for the μ) of SGEE significantly influences the reliability of SGEE.

The characteristic values of the most important SGEE reliability indicators, in the hypothesis of the four distributions of entrance data are ranged in table 2.

Table 2. Summary of results obtained. T_A=*50,730[h]*

Indicators	Symbol	Significant values SGEE		
		Min.	Average	Max
Triangle distribution				
Failure intensity	$\lambda_S [h^{-1}]$	8.993E-05	9.806E-05	1.059E-04
Total duration of operation	$\alpha_s(T_A)$ [h]	49390.88	49582.01	49755.95
Number of interruptions	$\nu_S(T_A)$ [nr. Intr.]	4.46869	4.86215	5.23633
System reliability	R_S	0.97349	0.97726	0.98068
Exponential distribution				
Failure intensity	$\lambda_S [h^{-1}]$	5.756E-06	9.972E-05	3.515E-04
Total duration of operation	$\alpha_s(T_A)$ [h]	396.67	46383.20	50661.09
Number of interruptions	$\nu_S(T_A)$ [nr. Intr.]	0.04592	4.56544	17.38184
System reliability	R_S	0.00782	0.91421	0.99852
Pert distribution				
Failure intensity	$\lambda_S [h^{-1}]$	9.153E-05	9.890E-05	1.062E-04
Total duration of operation	$\alpha_s(T_A)$ [h]	49379.68	49582.57	49726.40
Number of interruptions	$\nu_S(T_A)$ [nr. Intr.]	4.54594	4.90343	5.25568
System reliability	R_S	0.97327	0.97727	0.98010
Normal distribution				
Failure intensity	$\lambda_S [h^{-1}]$	9.806E-05	9.806E-05	9.806E-05
Total duration of operation	$\alpha_s(T_A)$ [h]	49585.00	49585.00	49585.00
Number of interruptions	$\nu_S(T_A)$ [nr. Intr.]	-4.23330	4.86256	13.47068
System reliability	R_S	0.97731	0.97731	0.97731

The obtained values for the reliability function and the associated risk are shown for the analyzed SGEE in the table 3.

Table 3. Intervals of function values of reliability (R_S)

System	Type	Range that can be found 90% of R_S indicator values	Test value/ Test
SGEE	Triangle	0.97349 ÷ 0.98068	▪ 65.0360/CHISQ ▪ 0.2896/AD ▪ 0.056/KS
	Exponential	0.00782 ÷ 0.99852	▪ 13084.374/ CHISQ ▪ 785.9229/AD ▪ 0.2334/KS
	Pert	0.97327 ÷ 0.98010	▪ 75.0852/ CHISQ ▪ 0.3957/AD ▪ 0.0054/KS
	Normal	0.97731 ÷ 0.97731	▪ 72.0364/ CHISQ ▪ 0.1795/AD ▪ 0.0054/KS

4. CONCLUSION

To evaluate the reliability of a SGEE, already known methodology can be used for the reliability analysis of the systems. These can be applied in both in designing phase (predictive reliability), and in the running phase (operational reliability).

Reliability analysis of SGEE's represents a necessity, both for the producer of these systems and also for the customers. The number of papers dedicated to this subject in specialty literature is relatively low.

To evaluate the predictive reliability indicators of SGEE's applying analytical and/or simulating Monte Carlo methods are recommended to use. Assuming that the fundamental reliability indicators of SGEE components (λ, μ) are random variables, using the stochastic approach, results obtained are closer to reality in the evaluation of the SGEE reliability indicators, which will be also random variables.

In order to identify the theoretical distribution which accurately reflects the empirical distribution, for SGEE reliability analysis, with the aid of @Risk software package, four distribution functions were tested (triangle, exponential, Pert and normal) applying a number of 3 tests (Chi-square, Kolmogorov-Smirnov and Anderson – Darling). Running the simulations for the SGEE with reference to the reliability function of the system the results are gathered in table 3 was obtained.

A significant dispersion can be noticed for the values within the reliability function, predominantly in the case of exponential distribution and also in case of minimal values. Analyzing the obtained results after applying all three statistical tests available in the @Risk program we can conclude:

- the most appropriate distribution for the analyzed system, obtained with triangle, followed by Pert and normal;
- the exponential distribution found to be unrealistic.

The medium values of the reliability functions are the same in each distribution hypothesis of the random variable; small differences (such as a few hours) were noticed regarding the MTBF and MTTF indicators.

The solution provided by @Risk program offers the possibility to analyze the degree in which the reliability of SGEE's components influences the systems; a thing possible through the sensitivity analysis. The analysis allows the determination of values for importance factors of the components and of „critical" variables of the model. The methodology presented and illustrated in this document applies to any similar system.

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