# STOCHASTIC EVALUATION ON THE RELIABILITY OF THE THERMOELECTRIC POWER PLANTS

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**Abstract - Reliability of basic aggregates has an important role in safe operation of thermoelectric power plants (TEPP). For this reason a reliability study has been made using simulation software @ Risk. Using this program has been made a stochastic modeling of assessing reliability of basic TEPP aggregates. After a brief justification of the need to assess the reliability of TEPP, is presented the working methodology. Further, are presented the results of a case study followed by conclusions.**

**Keywords**: reliability, random variables, indicators, thermoelectric power plants.

## 1. INTRODUCTION

Assessing TEPP reliability in design and operating phases, it's justified at least by following reasons [1÷6]:

- Importance that, in current state of human civilization development, fossil fuel power plants still have. For instance, in EU 52% of electric energy demand is supplied by fossil fuel thermoelectric power plants (TEEP);
- Impact of burning fossil fuels by releasing greenhouse effect gasses and particles, impact that increases along with decrease of structural power equipment performances and reliability;
- Reliability analysis results are used to determine strategies for maintenance and development of these energetic objectives and for feasibility studies, which implies comparative analyses with other, electricity and/or heat producing solutions;
- Reliability indicators of the equipment within TEPP structure are random variables (RV).

Factors influencing operational reliability of the equipment within TEPP structure (load levels, environment factors, fuel quality, operating conditions) are RV.

Stochastic modeling of energetic system reliability is based on specialized treaties [7÷10] and it's permanently evolving by dedicated applications for electric energy production, transmission and distribution systems (EE) in classical sources [11,12] and renewable sources [13,14,15]. Thus, in [11] is developed a probabilistic model for assessing the reliability of the EE generating systems, based on convolution technique, comparing the two RV (power output and the load required) and determining the adequacy of system indicators. Informational model described in [12] is dedicated to characterize the relationship of provider and consumer of electric energy by assessing some of continuity indicators. A significant number of papers such as [13] are dedicated to develop and apply stochastic models and techniques for evaluating reliability of EE producing systems based on classical sources and renewable sources as solar or wind - which has the power available on settlement an obviously random variable character. In [14] nature of random variable of available wind power is shaped using a time model which simulates hourly wind velocities. For an adequate management of hybrid electricity generating system was developed solution adapted to stochastic character of primary resources. A solution for management of hybrid systems that use solar and wind power is described in [15].

This paper aims to apply stochastic modeling to assess the reliability of TEPP. Knowing the TEPP structure and functions, considering the fundamental reliability indicators of TEPP structure components, the RV, the reliability indicators of TEPP can be determined, which will also be, RV. Assessment methodology is suitable for any type of TEPP used to convert primary fossil fuels energy to heat and / or EE.

## 2. WORKING METHODOLOGY

Based on structure and functions of TEPP, Reliability Block Diagrams (RBD) or events arbor (EA) is prepared. For some TEPP it may be necessary to prepare several RBD or EA based on the functional levels they have [9, 10]. Considering the values recommended in specific literature given by the manufacturing companies or identified by operational reliability studies [7, 16, 17, 18, 22] for the fundamental indicators of reliability (λ, μ) of the structural components of TEPP, we may presume distribution of these indicators to be RV.

The following types of distributions are used: exponential, normal, Pert and triangle. As we know fundamental indicators of elements (λ, μ), we can calculate two, frequently used reliability indicator: reliability function (probability of proper operation) – R and non-reliability function, (probability of failure) – F, used expressions being well known [7÷10, 16]:

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

$n$– number of elements within TEPP structure identified in RBD or EA

These indicators (R,F) will also be RV. As follows, reliability indicators of TEPP wil be analytically expressed and evaluated using well known expressions [7÷10, 16].

Considering specific function and reliability level of TEPP structure components, for expressing reliability indicators of TEPP ($\lambda_s$, $\mu_s$, $R_s$, $F_s$) and structural components, we admit that:

- Components (structural elements) are independent in terms of reliability;
- It's omitted the probability of multiple faults.

Under these circumstances we do illustrate the indicators expressing mode for CHP plant and it's subsystems if RBD is used:

- For "n" serial component structures:

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

where, MTBFS, MTRS – are average values of "proper operating time" and "fault time"

- For structures with 2 (i,j) parallel components:

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

Knowing the distributions of the above mentioned indicators (RS, FS, λS, mS) we may determinate also other indicators characterizing the level of reliability of TEPP during the analysis time($T_A$), which are also RV, characterized by distribution functions (DF) and characteristic parameters, such as:

$\alpha$ ($T_A$) – total duration of proper operating of the CHP plant;
$\beta$($T_A$) – total duration of the CHP plant fault;
$\nu$ ($T_A$) – number of faults of the CHP plant.

Functions admitted as working hypotheses in case of modeling $RV_{(x)}$ distribution are [7÷10, 19, 20]:

- Exponential:

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

- Triagle:

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

- Normal:

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

- Pert:

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

where,
m – average RV values;
$\sigma$ – standard deviation;
($x_{min}$, $x_{max}$) – minimal and maximal RV value;
B –Beta function;
$B_z$ –incomplete Beta function;
Values of (m, $\sigma$, $x_{min}$, $x_{max}$) are parameters of the 4 DF.

At TEPP level, DF of RV are obtained by composing DF corresponding to structural elements according to the used graphical model (RBD, EA) applying expressions (2,3) to calculate TEPP reliability indicators. In case of some DF is possible to analytically express the resulting DF parameters at the TEPP level [19, 20]. In case of other DF evaluation of resulting DF parameters can be done just numerically, by series expansion.

Currently there are dedicated software packages that make these evaluations in all scenarios and make available to the analyst the DF of the system. This way will be used in this paper, while we use also the testing facilities of the resultant DF at TEPP level by applying tests included by the software package. Obtained results are a measure of compatibility between the empirical distribution (obtained using the input data) and theoretical distribution. Tests used within in this paper [9, 10, 19, 20]: Chi - square (CHISQ), Kolmogorov-Smirnov (KS) and the Anderson - Darling (AD). After applying the tests theoretical DF shall be ranked depending on maximum deviation value from the empirical DF.

Based on results obtained after applying the three tests, most adequate DF will be adopted the one with minimal average deviation value from the empirical function.

## 3. CASE STUDY

Treating method described in Section 2 of this paper was applied referring to the subsystem that converts chemical energy of fossil fuels to heat and mechanical energy within TEPP Oradea (SCTMO).

TEPP Oradea structure has 6 steam boilers, 5 steam turbines - electric generator sets. Primary fuels used are natural gas, coal and fuel oil (support for coal burning). The total installed power in Oradea TEPP is 195MWe and 652 MWt. Operating schemes are set according to (the heating) season, available fuel and technical condition of the equipment, some possible options are shown in Table 1.

**Tabel 1. Operating schemes of TEPP Oradea**

| Season | Operating Variant | Operating equipment |
|---|---|---|
| Summer | $V_1$ | One of the steam boilers C4(400t/h), C5(400t/h), C6(350t/h); one turbo-generator groupTG5 (50MW) |
| | $V_2$ | One of the steam boilers C4, C5, C6; two turbo-generator group, TG1(25MW) or TG2 (25MW) |
| | $V_3$ | One of the steam boilers C1(165t/h) or C2(165t/h) one turbo-generator group, TG1 or TG2 |
| Winter | $I_1$ | Two steam boilers (C4 and C5 or C4andC6 or C5 and C6); two turbo-generator groupTA3 and TA5 |
| | $I_2$ | Two steam boilers (C4andC5 or C4 and C6 or C5 and C6); three turbo-generator group TA3 and TA5 and TA1 or TA2 |

Based on thermo-mechanical structure SCMTO, RBD of each structure in the presented 5 variants are prepared then reliability function is expressed. For example RBD for summer season variant 2 (V2) is presented in Fig. 2.

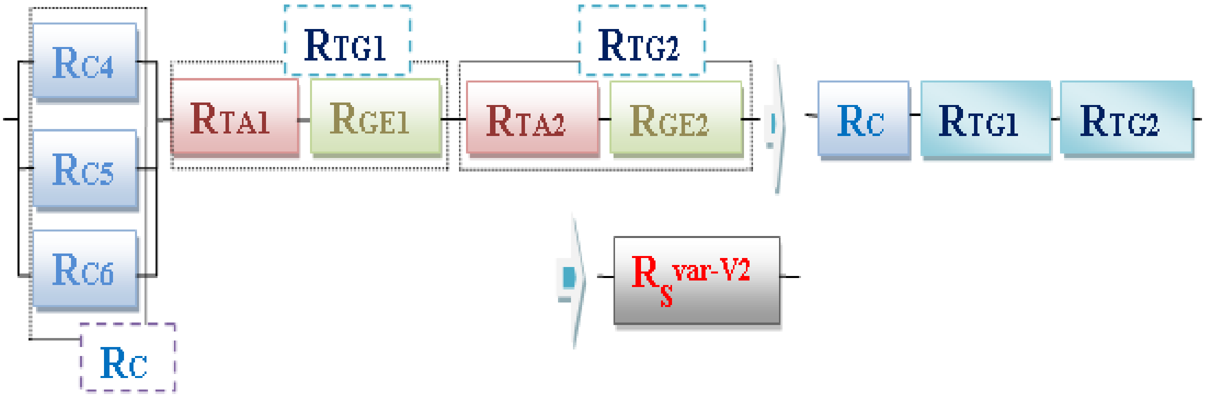


**Fig. 2. RBD of CHP plant Oradea for variant V2**
**C4, C5, C6 – steam boilers on solid fuel with fuel oil burning support;**
**TA1, TA2 steam turbines; GE1, GE2 electric generators**

According to the results obtained in the operational reliability study [21, 22], we have (the following values):
$\mathbf{R_{C4} = R_{C5} = 0,96063; R_{C6} = 0,96968;}$
$\mathbf{R_{TA1} = R_{TA2} = 0,95009; R_{GE1} = R_{GE2} = 0,93333;}$

Average value of reliability function for subsystem $R_C$ which composes the parallel system is:

$$R_e = \frac{R_{C4} + R_{C5} + R_{C6}}{3} = 0.96365 \qquad (8)$$

$$R_C = \sum_{i=1}^{3} C_3^i \cdot R_e^i \cdot (1 - R_e)^{3-i} = 0.99995 \qquad (9)$$

Considering RBD presented in fig 5.22, forecast reliability of CHP plant Oradea structure for variant 2 /summer is expressed as :

$$R_S^{var\,V2} = R_C \cdot R_{TG1} \cdot R_{TG2} = 0.78628 \qquad (10)$$

where,

$$R_{TG1} = R_{TA1} \cdot R_{GE1} = 0.88675 \qquad (11)$$

$$R_{TG2} = R_{TA2} \cdot R_{GE2} = 0.88675 \qquad (12)$$

For considered analysis period $T_A$ = 1 year = 8760 hours we will obtain:

$$\alpha_{var\,V2}(T_A) = R_S^{var\,V2} \cdot T_A = 6887.81h \qquad (13)$$

$$\beta_{varV2}(T_A) = T_A - \alpha_{varV2}(T_A) = 1872.19h \qquad (14)$$

Compared to the deterministic method of treating SCTMO reliability regarding the considerations mentioned, in the first part of the paper, we proceeded to simulate the reliability of this structure in all five variants of operation.

Assessments were performed using @Risk simulation program, a complex program, developed for risk analysis by Monte Carlo simulation method [23]. The program is used as a library add-inn in Excel, being accessible and easy to use.

To generate normal distributions used reference values (most likely) are the values obtained by processing operation data [21] for the probability of success indicator. A variation of 25% of the indicators is permitted, more specific:

- Maximal value +20% compared to the reference value;
- Minimal value, -5% compared to the reference value.

Within this framework is exemplified application of the procedure for Variant 1, summer (V1) assuming normal distribution for RV.

In table 2 are given indicator $R_{S,}$ values for normal distribution.

Figure 3. present chart for normal distribution for $R_S$ for $V_1$.

**Table 2. Values of $R_S$ indicator for SCTMO equipment for normal distribution**

| Equipment | $R_S$ Indicator [-] | | |
|---|---|---|---|
| | Minim | Value from operation | Maxim |
| **Boiler C4, C5** | 0.951024 | **0.96063** | 0.962551 |
| **Boiler C6** | 0.959983 | **0.96968** | 0.971619 |
| **Turbine TA5** | 0.977585 | **0.98746** | 0.989435 |

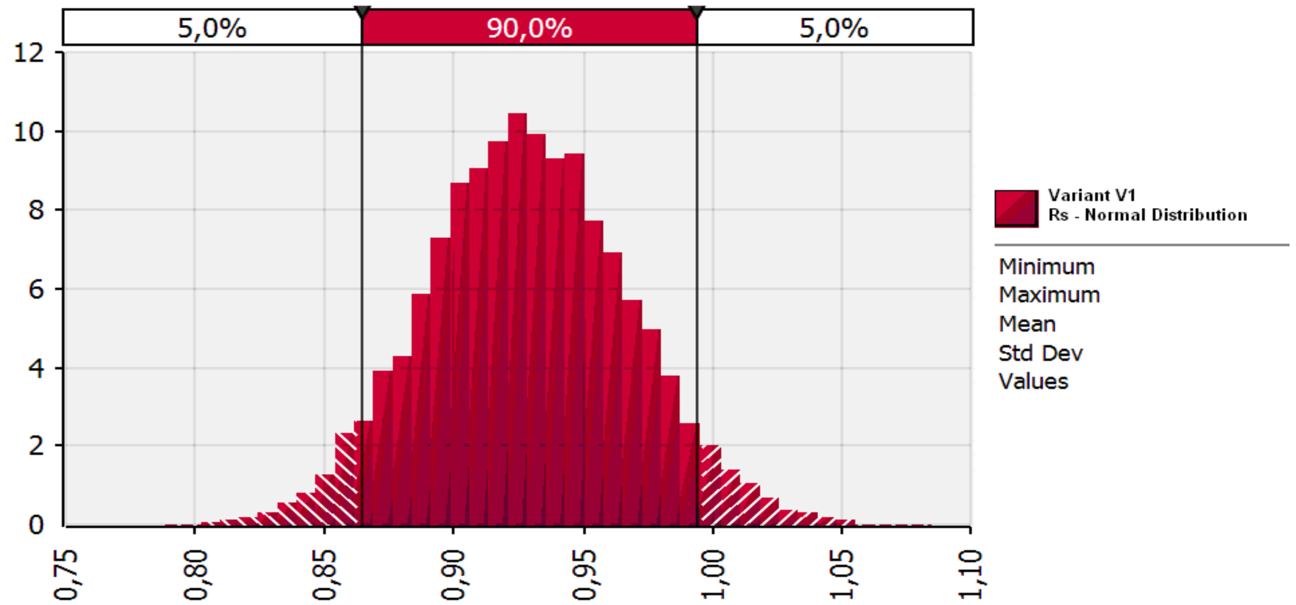


**Fig. 3 –Distribution for reliability function Rs for $V_1$ within SCTMO**

After determination of distributions for $R_S$ and $F_S$ indicators, were generated distributions of total operating time $\alpha(T_A)$ and total non-operating time $\beta(T_A)$ functions, results being presented in fig. 4 for $\beta(T_A)$ indicator.

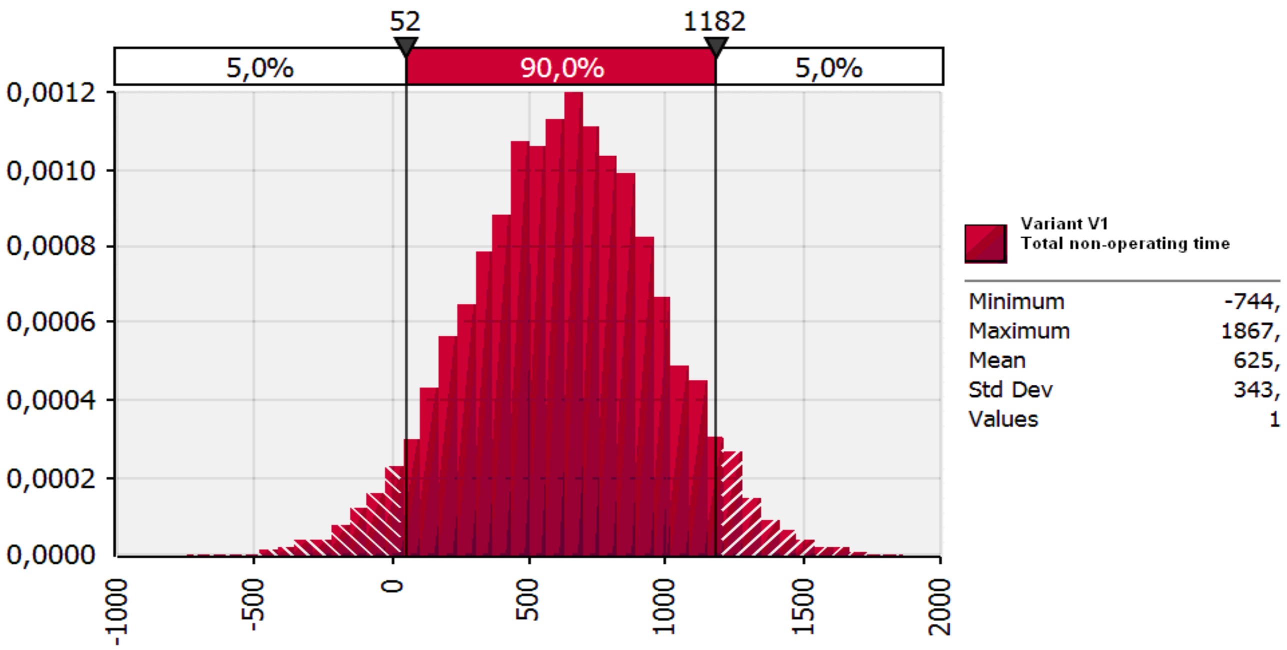


**Fig. 4. – Distribution for variable $\beta(T_A)$ for $V_1$ within SCTMO**

Reliability function of the system was tested with CHISQ, KS and AD tests. Figure 5 and 6 presents results of testing reliability function ($R_S$) with AD and KS tests.

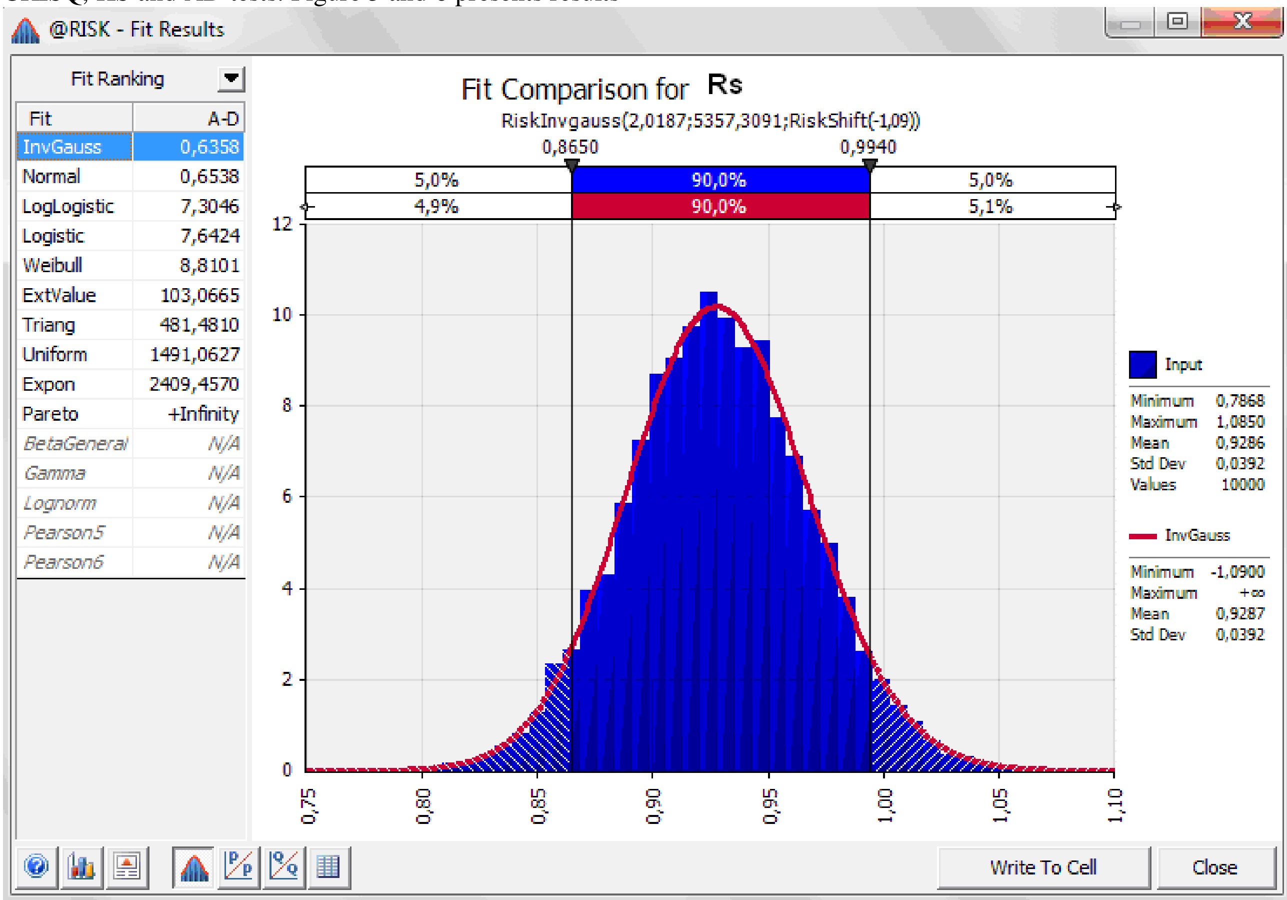


**Fig. 5. Applying AD test for $R_S$ within SCTMO – V1**

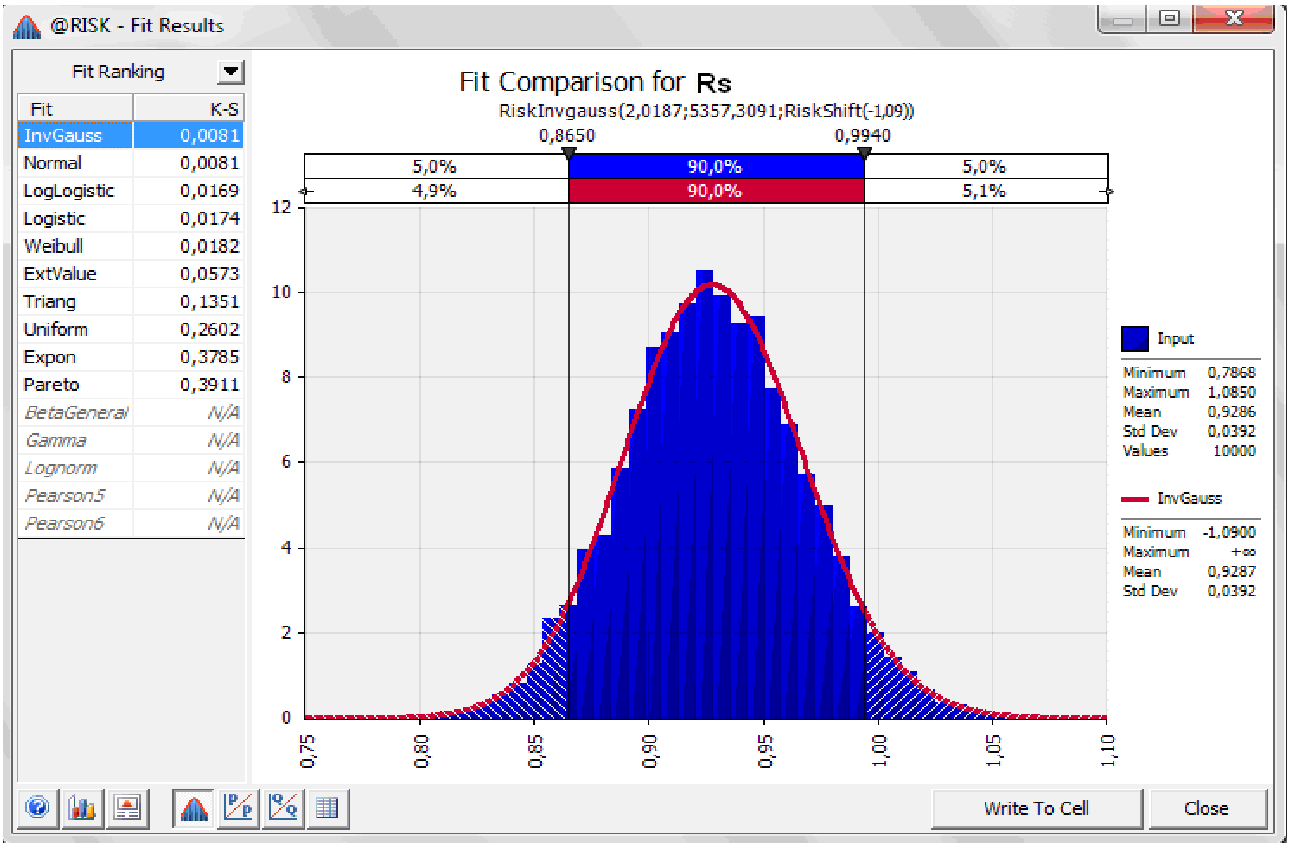


**Fig. 6. Applying KS test for $R_S$ within SCTMO – V1**

Values obtained for reliability function and corresponding hazard for the five variants within SCTMO are presented in table 3

**Tabel 3. Reliability function ($R_S$) value intervals for SCTMO**

| Operating Variant | Distribution type | Interval within 90% of $R_S$ indicator values can be found | Test value | | |
|---|---|---|---|---|---|
| | | | CHISQ | AD | KS |
| **V1** | Triangle | 0.9001 ÷ 0.9536 | 100.3488 | 3.2368 | 0.0151 |
| | Pert | 0.9243 ÷ 0.9583 | 79.5992 | 0.3915 | 0.0073 |
| | Normal | 0.8650 ÷ 0.9940 | 52.7372 | 0.6358 | 0.0081 |
| **$V_2$** | triangle | 0.7065 ÷ 0.7653 | 62.0612 | 0.3032 | 0.00071 |
| | Pert | 0.7391 ÷ 0.7787 | 79.5696 | 0.4389 | 0.0079 |
| | Normal | 0.6662 ÷ 0.8104 | 56.0228 | 0.2344 | 0.0049 |
| **$V_3$** | Triangle | 0.9717 ÷ 0.9819 | 58.9828 | 0.1836 | 0.0053 |
| | Pert | 0.9785 ÷ 0.9844 | 67.5224 | 0.2356 | 0.0055 |
| | Normal | 0.9628 ÷ 0.9878 | 60.8032 | 0.2306 | 0.0041 |
| **$I_1$** | Triangle | 0.8076 ÷ 0.8757 | 89.1304 | 0.3265 | 0.0057 |
| | Pert | 0.8480 ÷ 0.8933 | 73.2056 | 0.4880 | 0.0066 |
| | Normal | 0.7614 ÷ 0.9259 | 68.5436 | 0.2493 | 0.0052 |
| **$I_2$** | Triangle | 0.7914 ÷ 0.8577 | 48.8744 | 0.2745 | 0.0054 |
| | Pert | 0.8348 ÷ 0.8786 | 56.3928 | 0.2619 | 0.0050 |
| | Normal | 0.7449 ÷ 0.9073 | 68.7064 | 1.1654 | 0.0094 |

After applying the three statistical test for each variant and distribution type (results like presented in fig 5 and 6) and comparing obtained values we can conclude:

- *Variant V1*
  - ✓ Distribution with smallest deviation is pert followed by normal distribution and finally triangle distribution.
  - ✓ In normal distribution case, simulations and comparison with other, statistic hypothesis checking tests, shows that distribution InvGauss and Normal ranks the top 2 positions, as exemplified in fig 5.
  - ✓ For triangle distribution, distribution Beta General, Weibull and Normal ranks top 3 positions;
  - ✓ For Pert distribution, top 3 positions ranked are distribution Beta General, Weibull and Logistic.

- *Variant V2*
  - ✓ Normal distribution has the smallest deviation followed by triangle distribution and pert distribution;
  - ✓ In normal distribution case, simulations and comparison with other, statistic hypothesis checking tests, shows that distribution LogNormal, Normal and InvGauss ranks the top 3 positions for AD and KS tests, for CHISQ test first 3 positions ranks distribution InvGauss, Normal and LogNormal;
  - ✓ For triangle distribution top 3 positions ranks BetaGeneral, Weibull and Normal distribution for CHISQ and AD tests and BetaGeneral, Normal and Weibull distributions for KS tests;
  - ✓ -For pert distribution top 2 position ranked are BetaGeneral and Weibull distribution

- *Variant V3*
  - ✓ Triangle distribution has the smallest deviation followed by Normal distribution and Pert distribution;
  - ✓ For normal distribution, simulations and comparison with other, statistic hypotheses checking tests, shows that distributions Weibull, BetaGeneral and Logistic ranks the top 3 positions for AD and KS tests, for CHISQ test first 3 positions ranks BetaGeneral, Weibull and Normal distributions;
  - ✓ For triangle distribution top 2 positions ranked are BetaGeneral and Weibull distributions;
  - ✓ For pert distribution top 2 position ranked are BetaGeneral and Weibull distributions.

- *Variant $I_1$*
  - ✓ Normal distribution has the smallest deviation followed by Pert and Triangle distribution;
  - ✓ For normal distribution, after checking the statistic hypotheses , results that distributions InvGauss, LongNormal and Normal ranks the top 3 positions for CHISQ test, for AD and KS tests, LongNormal, InvGaus and Normal distributions ranks the top 3 positions;
  - ✓ For triangle distribution top 3 positions ranked are Weibull, BetaGeneral Normal distributions for CHISQ test , and for AD and KS tests, Betageneral, Weibull si Normal distributions ranks the top 3 positions;
  - ✓ For pert distribution top 2 position ranked are BetaGeneral and Weibull distributions.

- *Variant $I_2$*
  - ✓ Triangle distribution has the smallest deviation followed by Pert and Normal distribution;
  - ✓ For normal distribution, distributions InvGauss, and Normal ranks the top 2 positions for CHISQ test, for AD and KS tests, Normal and InvGaus distributions ranks the top 2 positions;

- ✓ For triangle distribution top 3 positions ranked are BetaGeneral, Weibull and Normal distributions for all three statistic tests;
- ✓ For pert distribution top 2 position ranked are BetaGeneral and Weibull distributions.

## 4. Conclusions

The reliability analysis of TEPP can be done based on systems reliable analysis acknowledged method both in designing phase (forecast reliability) and also in operational phase (operational reliability)

To calculate forecast reliability indicators of TEPP, using analytic and/or Monte Carlo simulation methods are recommended. Results closer to reality are obtained by a stochastic approach assuming that main reliability indicators of TEPP components (λ, μ) are random variables and assessing TEPP reliability indicators, these will also be random variables. To identify the theoretical distribution that is closest to empirical values, for the reliability analysis of TEPP, helped by the @Risk software package, three distribution functions were tested (triangle, pert and normal. For these functions three tests were applied CHISQ, KS and AD. Following the simulations carried out for the five variants of SCTM within TEPP structure, considering the system reliability, results recorded in table 4 were obtained. In terms of obtained values, applying the three statistic tests helped by the @Risk software we can notice:

- For V1, optimal distribution is pert distribution followed by normal and finally the triangle distribution;
- For V2, optimal distribution is normal distribution followed by the triangle and finally the pert distribution;
- For V3, optimal distribution is the triangle distribution followed by normal and finally pert distribution;
- For I1, optimal distribution is normal distribution followed by pert and the triangle distribution;
- For I2, optimal distribution is pert distribution followed by normal and finally the triangle distribution;

Average values of reliability function are the same for all for any hypothesis of RV distribution function.

Assessment based on presented and exemplified methodology, can be applied to any system, including thermoelectric power plants from Romania.

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