THE RELIABILITY MODELING OF URBAN TRANSPORT SYSTEMS USING ELECTRICALLY DRIVEN TRAMS

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Abstract: **This paper is dedicated to specific reliability evaluation prediction of an urban transport systems using electrically driven trams (UTSUEDT). The first part refers to topicality, justifying the need UTSUEDT treatment as a result of interconnection of three subsystems. The second part details the application of the concept model parametric UTSUEDT reliability. UTSUEDT states are detailed in part three of the paper, detailing the significance of six states and express the probability of state and transition. This paper contains references to reliability forecasting modeling of the three subsystems of the structure of UTSUEDT Company "Oradea Local Transport" (OTL). In the last part of the paper one presented the conclusions of the analysis.**

Key words: reliability prediction, electric traction, modeling.

1. INTRODUCTION

Applying the concept of sustainable development [1] is one of the most important priorities of modern society. In this context, in large urban areas, urban transport of people is a priority area of great importance and implications. Special contribution of transport, mainly urban public transport (UPT) to the environmental pollution is well known [2]. Pollution in big cities is a major problem and by sharpening it may decide even fate of transport strategies, implicitly the UPT. In these conditions, in terms of sustainable development, local city fathers are required to seek:

• Developing priority of UPT will reduce car traffic with all their implications

• Developing, especially of the urban public transport system operated by electrically driven trams, a transport system that is much cleaner than the car s, is relatively quiet and safe in circulation.

Specific problems of urban public transport systems are largely reflected in the literature. Much of the work aimed at UPT performance systems (urban public transport), performance measured by efficiency, service quality, environmental impact. In [3]on can identify the factors that influence the demand for UPT insisting mainly on service quality, and in [4] proposes and illustrates a methodology for the elaboration of UPT systems quality. A detailed assessment methodology of the transport service quality is in [5], appealing to the decisive impact factors such as availability, comfort and convenience. Availability of transport is examined in terms of hourly service frequency and service coverage. For an UPT system using buses, comfort and convenience are analyzed. Effectiveness of a specific UPT systems is analyzed in [6,7] Thus, in [6] one analyzed the effectiveness of 7 out of 12 UPT systems from Europa and 7 from Brazil. Based on these results the authors conclude that only nine cities in Europe and one in Brazil have an efficient UPT system, the inefficiency is due mainly to a social cause. Using data taken from 15 European UPT systems in [7] one aims to answer three questions identifying essential performance of transport systems: the impact of design methodology, the impact of organization and the performance of UPT systems size.

This paper is part of the concerns mentioned above, but on can distinguish it categorically, being dedicated to the forecasting of reliability modeling for an (urban transport system operated by electrically driven trams (UTSUEDT). Forecasting the reliability of modeling is essential to treat UTSUEDT's rigorous quality and efficiency. Functional aspect of UTSUEDT can be viewed and treated as a result of the interconnection of three subsystems (Fig. 1), [8,9].

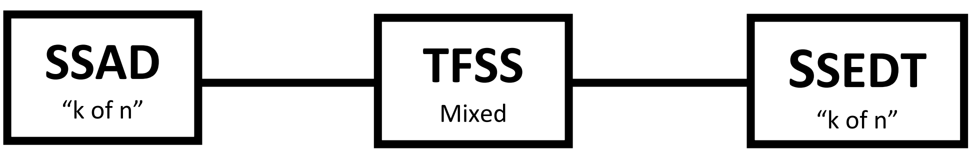

Fig. 1 – The structure bloc of an UTSUEDT

Where:
SSAD - subsystem of adaptation for electrical values of the electroenergetic system levels (EES), the electrically driven trams (EDT) need;
TFSS-transfer subsystem (distribution) of electric energy (EE) between SSAD and EDT, including: bars of recovery stations (RS) and DC power supply grid from

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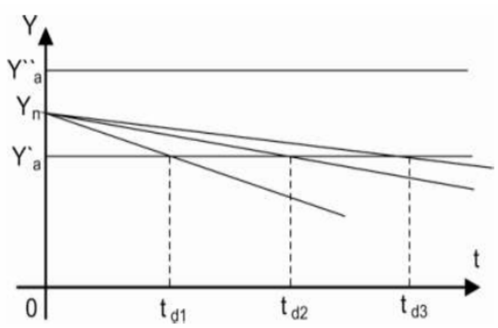
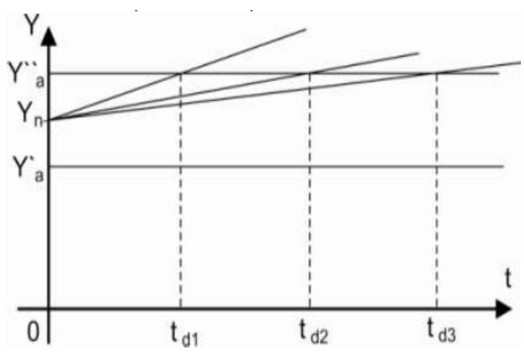
RS, including injection sections (IS), the wires contact system (WCS) and rails (R).
SSEDT-subsystem of electrically driven trams covering the entire vehicle, actuators, with the transfer of EE (pantograph), with speed control equipment (controller, inverter, converter), with own facilities (lighting, thermal comfort) and other specific equipment and facilities.

2. CONCEPT OF PARAMETRIC RELIABILITY ON THE UTSUEDT

A lot of UTSUEDT components failure modes are characterized by parameters derived [9]. Due to wear, aging time, fatigue and other phenomena, certain elements of UTSUEDT structure parameters have a slow evolution over time (Fig. 2.). Moments (t_{di}) are basically parametric failure times. By the treatment of the statistical values of (t_{di}), one can obtain the parametric reliability of UTSUEDT respectively the structural elements referred to.



a) case of a parameter (Y) whose value decreases with time (insulation resistance, pressure, mechanical tension, section, surface contact, et. al)



b) case of a parameter (Y) whose value increases over time (contact resistance, the game, electrical resistance, et. al)

Fig.2 – Time variation of a significant parameter (Y) for elements of UTSUEDT structure (Yn - nominal value of the parameter)

Therefore, the reliability function of UTSUEDT (R_{ST}) can be expressed as:

$$R_{ST} = R_{ST}^{b} \cdot R_{ST}^{p} \qquad (1)$$

R_{ST}^{b} - function of reliability (safety time) assessed against sudden failures statistics
R_{ST}^{p} - reliability function determined by statistical parametric failure events.

If one approximates the evolution of an element of UTSUEDT by a significant parameter (Y) with a straight (Fig. 2.), the equation that gives the momentary value of the parameter is:

$$Y = Y_0 \pm v \cdot t \qquad (2)$$

v - rate of degradation
Y_0 - initial value - can be equal to the nominal value Y_n or can be defined as Y_n, with the condition of being between Y_a' and Y_a'' values.

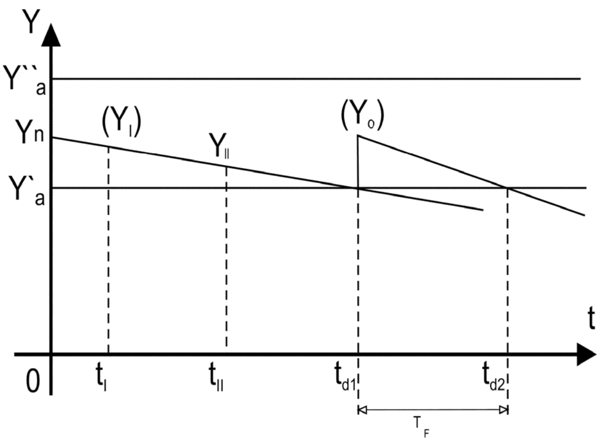


Fig. 3 - The evolution and correction of the Y parameter

Based on (2), by measuring Y parameters, one can determine the essential random values for UTSUEDT diagnose: rate of degradation (v) and proper operation time (T_F) between two preventive maintenance actions designed to make the correction of (Y)parameter- Figure 3 [10].

3. STATES OF UTSUEDT

To analyze the safety performance, availability and efficiency of UTSUEDT is essential to define states and assessing the probability of their existence. Figure 4 and 5 plot UTSUEDT states, emphasizing realistic transitions between them. Theoretically, other ways of transition are possible, but in practice [9] they are not confirmed during UTSUEDT operation.
The significance of the two figures are:
F(1) - normal functioning ≡ 100% availability of UTSUEDT;
AS(2) - waiting (for ex. night waiting, not planned for duty);
C(3) - critical (exposed), because of structural elements and parameter overuse like (used rails, used insulation resistance, lack of contact resistance, brake system damage, etc..);
D(4) - damage ≡ irreversible failure (sudden or parametric), which requires stopping

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CM(5) - corrective maintenance;
PM(6) - preventive maintenance, which can be applied in two ways [10,11,12];

- PPM(7) – programed PM
  → regarding time (de ex.: daily, weekly, monthly, annually);
  → regarding travelling distance (for ex.: la 5.000, 10.000, 50.000, 100.000 km);
- PMO(8) – PM to the object (opportunistic, predictive) by human decision .

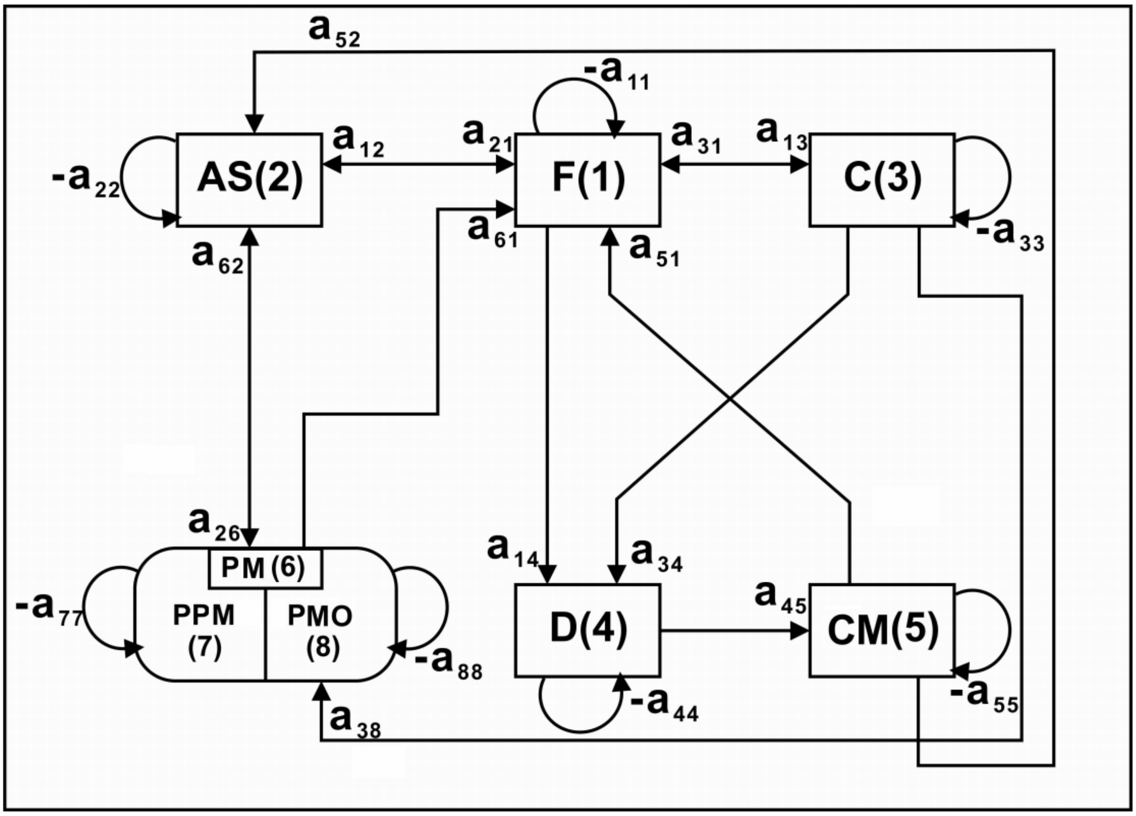

Fig. 4 – States of an UTSUEDT using state intensity indicators (-aii) and transitions (aij)

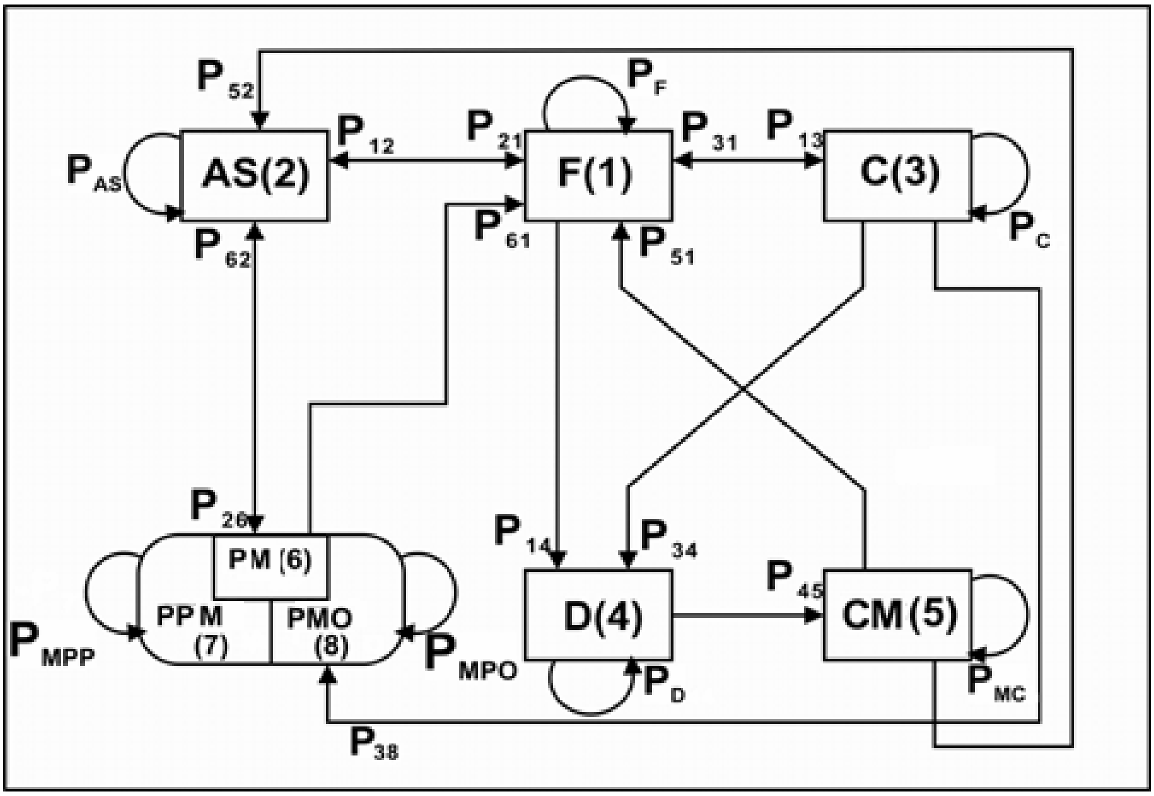

Fig. 5 – States of an UTSUEDT using state probability indicators (Pi) and transitions (Pij)

The two figures are valid for UTSUEDT subsystems (rails -R, electrically driven trams -EDT, recovery stations -RS), if these conditions are met simultaneously:
• There is EE supply from EES for all RS, with unrestricted power;
• Rail contacts and rails are 100% available;
• Sufficient EDT transport to service on schedule;
• RS and injection sections SI state allow to supply the power required for movement of all scheduled EDT and other receivers of EDT structure.
Therefore, the probability of state F (1) is determined as follows:

$$P_F = R_{EES}^{4of5} \cdot R_R \cdot R_{CW} \cdot R_{EDT}^{k.of.n} \cdot R_{RS}^{4of5} \cdot R_{SI}^{(n-1).of.n} \quad (3)$$

where:
R_{EES}^{4of5} - EE supply form EES for 4 out of 5 RS;
R_R – reliability of the whole rail system routs;
R_{CW}- reliability of the whole contact wire system routes;
$R_{EDT}^{k.ofn}$ -reliability of „**k** of **n**" system for EDT ≡ probability that from the totalof „**n**" EDT, at least a number of „**k**" – is necessary to be available;
R_{RS}^{4of5} - the probability the 4 out of 5 RS are available ≡ reliability of 4 out of 5 RS;
$R_{SI}^{(n-1)of.n}$ - probability that at least (n-1) of the „n" SI of each RS to function.

We find that „F" state doesn't mean an ideal energy efficiency functioning. Moving from an un programed state F in a waiting state happens at the appearance of one of the adverse events:
- EVN1 ≡ Loss of power of EES to all RS - during functioning hours, loss of power at the RS that fuels the depot;
- EVN2 ≡ failure of rail between depot and exit/entry of EDT, or contact wire on this section;
- EVN3 ≡ Loss of power of SEN or RS failure before EDT got out of the depot.

Programed change from F state while PM or CM into waiting state AS is possible while night waiting (not functioning time). Therefore the probability of AS state can be expressed as

$$P_{AS} = P_{AS1} + P_{AS2} - P_{AS1} \cdot P_{AS2} \quad (4)$$

P_{AS1} - probability of moving to a programed waiting state AS
P_{AS2} - probability of moving to AS state after the appearance of an unwanted event (EVN1, EVN2 or EVN3). The two components of P_{AS} are determined as:

$$\begin{cases} P_{AS1} = \dfrac{T_{AS}^{P}}{T_A} \\ P_{AS2} = P_{EVN1} + P_{EVN2} + P_{EVN3} \end{cases} \quad (5)$$

where:
T_{AS}^{P} - programed waiting time, waiting at night.

In the P_{AS2} relation one regarded (EVN1, EVN2 or EVN3) which are rare events so the probability of multiple events like this is negligible.

The "C" state (3) can occur during operation, because they exceeded allowable limits of UTSUEDT working by some determinant parameters for items or sizes. This state is short (transient), and is happening until the occurrence of one of the events:
• intervention controls, Protection and Control, resulting in return to state "F"
• The human operator decides on technical diagnosis based on-line or off-line switching elements in PMO degraded;
• irreversible damage occurs, leading to state "D".
The probability of state "C" can be expressed as:

$$P_C = \text{Prob}\,[\delta_M \cup P_{Fm} \cup I_M \cup Um \cup \theta_M] = \\ = \text{Prob}(\delta>\delta_M) + \text{Prob}(P_F<P_{Fm}) + \text{Prob}(I>I_M) + \\ \text{Prob}(U<Um) + \text{Prob}(\theta<\theta_M) \quad (6)$$

In (6) one has shown the probability of exceeding the limits m - minimum and maximum M-quantities that characterize the main elements or specific UTSUEDT processes as follows:
δ - interplay between elements in contact and moving;
P_F – pressure produced by the braking subsystem while braking;
(I,U) – effective value of current and voltage;
θ - temperature.

Obviously the values of (I, U) reflects the values of: insulation resistance (R_{iz}) and contact resistance (R_{CT}).

Relation (6) was written assuming the neglect of multiple events, which is admissible because the listed events are listed as "rare events" category. The first and second values of P_C probability are essential for risk assessment and security of UTSUEDT. Fault condition (D) is obviously undesirable since it involves the most risk, social and economic consequences. The defect state (D) is a state when UTSUEDT can not operate at capacity scheduled, in accordance with requests transmission service beneficiaries. Therefore, in addition to total fault condition, the UTSUEDT is completely blocked, and there are plenty of defect states (unavailable) in state (D_i), which are analyzed in correlation with structure and functional levels (availability) of UTSUEDT. He passes the fault condition (fully or partially) if the conditions of operation and the state of UTSUEDT is not the AS waiting state. Therefore, we can write with good approximation:

$$P_D = 1 - (P_F + P_{AS} + F_{EES}^{4of5}) \quad (7)$$

In (7) to be noted that the associated conditional non reliability of EES (F_{EES}^{4of5}) is the only cause of downtime and not failure cause of UTSUEDT. CM state is the consequence of the existence condition "D". MC state begins with identifying the affected continuously with the causes and remedies and be completed by repairing and testing of equipment / facilities in question. State probability of failure is considered equal to the CM ($P_{CM} = P_D$). After the work of CM, UTSUEDT or structural

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elements subject, are written in one of the states "F" or "AS", according to the needs of the transport service

PM state transition can be done in two ways:

- Following a schedule based on lifetime or travelled distance of EDT, being performed as PPM. PPM transition state is in standby (AS) by appointment, usual procedure for EDT to which the two ways of PPM is applied[9]
- After the deterioration condition of equipment or facilities, which is referred by human operators directly or through sub-technical diagnosis, cases registered in the state "C". In this case preventive maintenance to the object (PMO) is applied to the identified components. After performing the PM works UTSUEDT structural elements subject to these works are listed in "F" or "AS", according to the needs of the transport service. PM state probability can be determined by the relation:

$$P_{PM} = P_6 = 1 - \sum_{j=1}^{5} P_j = P_{PPM} + P_{PMO} \quad (8)$$

4. CASE OF STUDY FOR UTSUEDT OF OTL

UTSUEDT structure of the company "Oradea Transport Locate" (OTL) and its application diagram is given in [9]. UTSUEDT has several functional levels that can be analyzed according to the condition of structural subsystems and the time of a normal working day or a holiday, which determines the application range of the EDT. According to current analysis of the transport operator, one will perform in this context, analysis and representation of the reliability block diagram (RBD) of functional levels for maximum loading level: 40 of 73 EDT existing at OTL facilities, an analysis for the period when the application of EDT is lower. Obviously, based on ERD represented in Figure 1 can be written:

$$R_{ST} = R_{SSAD} \cdot R_{TFSS} \cdot R_{SSEDT} \quad (9)$$

We refer, further, the reliability of forecasting modeling for each SS, necessary step to identify the relationship between the level of reliability and functional level of UTSUEDT. In the OTL, SSAD is the type "4 of 5", meaning that if it at least 4 RS out of 5 are working, the SSAD function achieves its adaptation to any application level with EDT. RS - RBD is presented in Fig. 6.

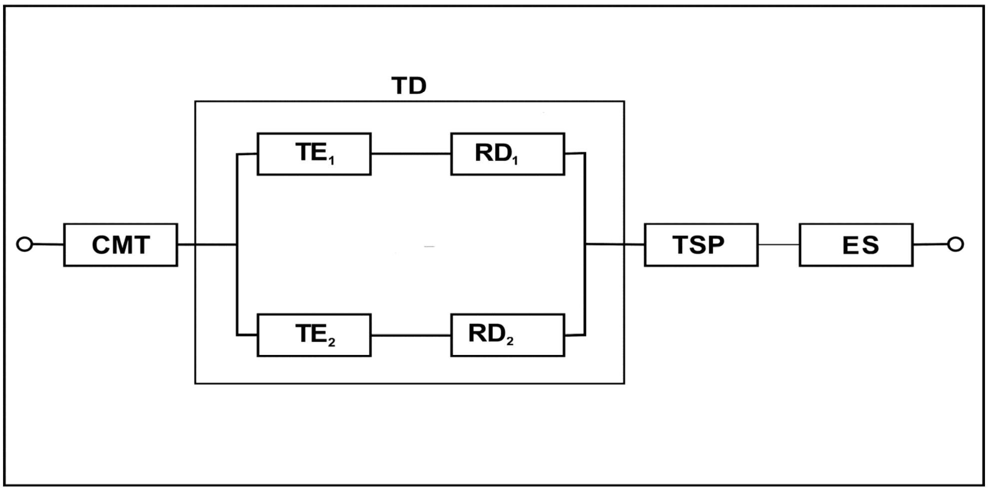

Fig. 6 – RBD of a RS

All the points of connection between the NPS and DC bars are considered included in the RS, clinging and auxiliaries transformer (TSP) and other specific elements (ES) required for the RS and maintenance workshops powered by own service transformer TSP. Significance others notations in Fig. 6 is:

CMT – medium voltage cell
TE1, TE2 – main transformers
RD1, RD2 - electrical rectifiers

One consider attached all the power equipment highlighted in the RBD, protections, control, measurement, automation necessary for proper functioning of RS. The reliability forecast evaluation of such structures is detailed in [10,11,12,13,14], so that in this framework we restrict the expression of the reliability function of the SSAD structure based on RS - RBD in fig.6 (" 4 of 5 ").

$$\begin{cases} R_{RS} = R_{CMT} \cdot R_{TD} \cdot R_{TSP} \cdot R_{ES} \\ R_{TD} = 1 - (1 - R_{TE1} \cdot R_{RD1})(1 - R_{TE2} \cdot R_{RD2}) \\ R_{SSAD} = \sum_{i=4}^{5} C_5^i \cdot R_{RS}^i \cdot (1 - R_{RS})^{5-i} = 5 \cdot R_{RS}^4 \cdot (1 - R_{RS}) + R_{RS}^5 \end{cases} \quad (10)$$

In the OTL, TFSS components (R, CS, SI) are subordinated but can be supplied and neighboring RS. Functional level of 100% of TFSS necessary to function fully, R,CS and to operate an adequate number of SI. Analysis [9] by comparing the number of SI. ascribed to each RS to load the supply network (SN) leads to the conclusion that the number of SI reserves is different for every RS. Based on these considerations, in Fig. 7 the RBD of TFSS at a 100% functional level is presented.

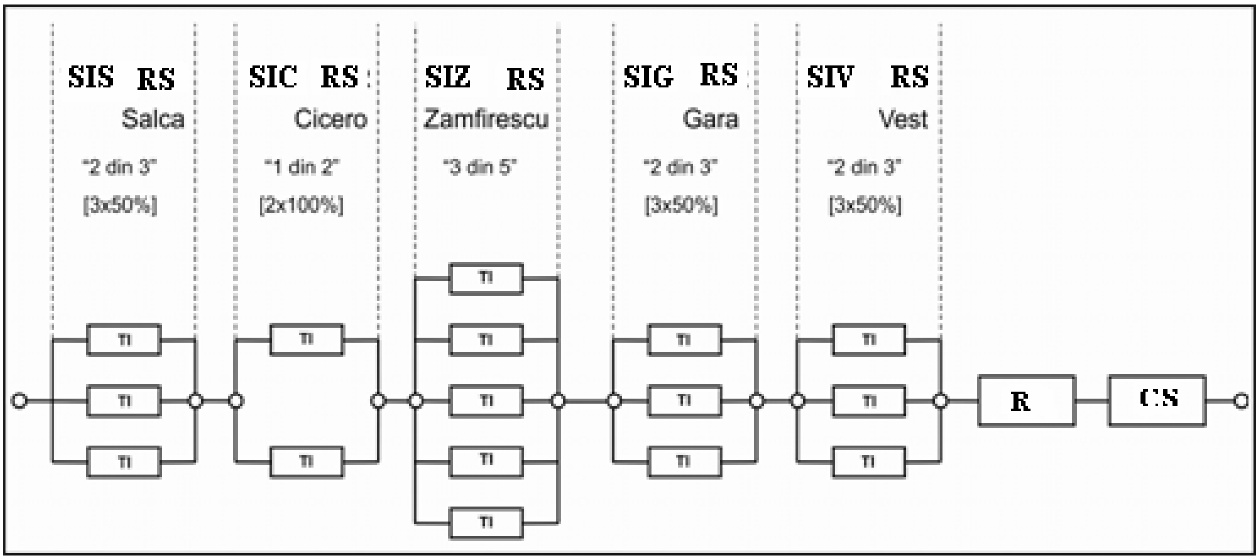

Fig. 7 – RBD of a TFSS [100% functional level]

Reliability function of TFSS can be expressed based on the RBD as:

$$R_{TFSS}=R_{SIS}\cdot R_{SIC}\cdot R_{SIZ}\cdot R_{SIG}\cdot R_{SIV}\cdot R_{R}\cdot R_{CS} \qquad (11)$$

Neglecting the length of IS that influence its reliability, one can write:

$$\begin{cases} R_{SIS}=R_{SIG}=R_{SIV}=\sum_{i=2}^{3}C_3^i\cdot R_{SI}^i\cdot(1-R_{SI})^{3-i}=3\cdot R_{SI}^2\cdot(1-R_{SI})+R_{SI}^3 \\ R_{SIG}=2\cdot R_{SI}-R_{SI}^2 \\ R_{SIZ}=\sum_{i=3}^{5}C_5^i\cdot R_{SI}^i\cdot(1-R_{SI})^{5-i}=20\cdot R_{SI}^3\cdot(1-R_{SI})^2+5\cdot R_{SI}^4\cdot(1-R_{SI})+R_{SI}^5 \end{cases} \qquad (12)$$

R_{SI} - probability of proper operation of an SI

Electrically driven tram subsystem (SSEDT) is the „k out of n" type, fig.8.

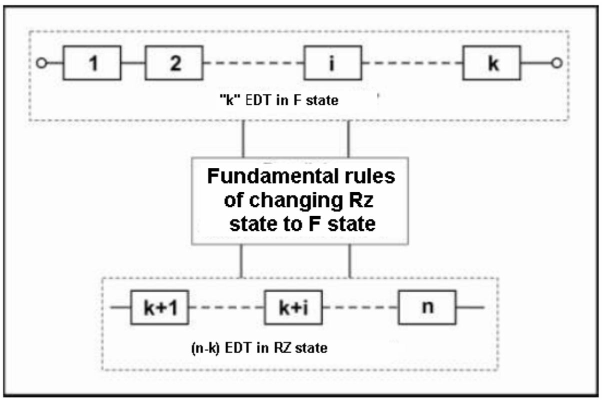

Fig. 8 – RBD of a SSEDT

From "T_F" in the analysis period T_A of the "n", EDT number "k" in use, and "n-k" is the reserve (RZ).This reserve is known as sliding or half active backup. In this case, the condition is more general RZ, whereas some of the "n-k" EDT may be in the state of PM, others in the CM, and others in waiting AS. Please note that the numbering of fig.8 is fictitious, unrelated to registration or inventory of EDT. For current UTSUEDT of OTL: n = 73 and k_{max} = 40. To express SSEDT reliability function, one uses the binomial method, which allows us to write:

$$R_{SSEDT}=\sum_{i=k}^{n}C_n^i\cdot R_{EDT}^i\cdot(1-R_{EDT})^{n-i} \qquad (13)$$

R_{EDT} - probability of good functioning (reliability)of EDT.

OTL - UTSUEDT has three types of EDT with differentiated levels of reliability. Therefore, to assess R_{SSEDT} is necessary to determine, first, an equivalent amount of indicator R_{EDT}. Note: (a, b, c) - the number of the 3 types of EDT [a-ULF, b-T4D, c-KT4D] (λ_{EDTi}, μ_{EDTi}) - intensities of failure and maintenance of the 3 types of EDT, values calculated in the study of operational reliability [15]. The values of equivalent indicators (λ_{EDT}, μ_{EDT}) are calculated using the relations:

$$\begin{cases} \lambda_{EDT}=\dfrac{a\cdot\lambda_{EDT1}+b\cdot\lambda_{EDT2}+c\cdot\lambda_{EDT3}}{n}. \\ \mu_{EDT}=\dfrac{a\cdot\mu_{EDT1}+b\cdot\mu_{EDT2}+c\cdot\mu_{EDT3}}{n} \end{cases} \qquad (14)$$

$$n=a+b+c$$

Having the values of fundamental indicators, one can calculate the equivalent reliability function for EDT, with the relationship [10,11]:

$$R_{EDT}=\frac{\mu_{EDT}}{\lambda_{EDT}+\mu_{EDT}} \qquad (15)$$

For OTL - UTSUEDT, for a maximum load level of (k_{max}=40), we have:

$$R_{SSEDT} = \sum_{i=40}^{73} C_{73}^{i} \cdot R_{EDT}^{i} \cdot (1 - R_{EDT})^{n-i} =$$
$$C_{73}^{40} \cdot R_{EDT}^{40} \cdot (1 - R_{EDT})^{33} + C_{73}^{41} \cdot R_{EDT}^{41} \cdot (1 - R_{EDT})^{32} +$$
$$+ C_{73}^{72} \cdot R_{EDT}^{72} \cdot (1 - R_{EDT}) + R_{EDT}^{73} \quad (16)$$

The calculation of core (λ_{EDTi}, μ_{EDTi}) and therefore the calculation of equivalent indicators (λ_{EDT}, μ_{EDT}, R_{EDT}) is considering the two components of the intensity of maintenance (μ_{CM}, μ_{PM}), whereas for EDT, preventive maintenance is mandatory within the PM, EDT is not available. Given values for fundamental indicators [15], and when using the constant values (a = 10, b = 43 and c = 20), the EDT in the OTL at a maximum application, we obtain: λ_{EDT} = 0,031 [h^{-1}] μ_{EDT} = 0,065 [h^{-1}] R_{EDT} = 0,694. Bearing in mind the expression (16) only get 10 terms, we obtain: R_{SSEDT} = 0.9968. From this brief analysis shows that, SSEDT reliability is high, even for the maximum demand (k_{max} = 40), which means that for lower levels ($k<k_{max}$), demands are even better. This is confirmed in UTSUEDT practice operation and is reflected in the statistics presented in [9].

5. CONCLUSIONS

For analysis and evaluation of UTSUEDT reliability and subsystems of its structure is recommended to apply one or more of the models: direct assessment, based on equivalent diagrams reliability assessment based on events and fault trees, Markov chains method based with continuous parameter binomial method.

A lot of UTSUEDT components are characterized by failure modes of the derived parameters , implying their parametric reliability assessment.

The modeling of UTSUEDT reliability forecasting is by carrying over the overall system performance, characterized by the vector quantity components: for safety, availability, maintainability, efficiency, reliability and security.

UTSUEDT and its components can evolve over a sufficient period of analysis, the following states: running, critical, waiting, defects, corrective maintenance and preventive maintenance.

The first step in the systematic analysis of the reliability of forecasting UTSUEDT - RBD is its representation that reflects the utility of systematic analysis of three subsystems with specific functions: adaptation SS, transfer SS and electrically driven trams SS.

Execution subsystem SSEDT is "k of n" type, often with a consistent number of spare parts, whose level of reliability is convenient, sufficient and precisely estimates by applying the binomial method.

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