ASSESSMENT OF BASIC TECHNOLOGICAL SUBSISTEM'S FORECASTED RELIABILITY IN CHP PLANT

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Abstract - Production of electricity and heat in cogeneration in high power efficiency conditions strictly depends on Combined Heat and Power (CHP) plant's basic equipment availability. Related to this, a study on forecast reliability of determinant subsystems, in producing combined heat and power, meaning - steam boilers, steam turbines and electric generators, was made. The study that concluded with the presented results has been made in CHP plant Oradea considering a few, presumable operating schemes, three for summer and two for winter period. For each of these five variants, Reliability Block Diagram (RBD) has been prepared, then there were determined the reliability and availability of each subsystem considering their maintainability and different time periods assigned for corrective maintenance.

Key words: CHP plant, Reliability, Availability.

1. INTRODUCTION

District heating systems (DHS) provides thermal energy for heating and hot water consumption for a large number of consumers (characterized by a high thermal density of use) Thermal energy is produced in a CHP plant and it's transported and distributed by pipeline networks known as thermal networks (RT).

For a DHS, being competitive as a whole system, it's necessary to assure a high level of continuity in supplying thermal energy in high efficiency conditions, means that each subsystem must meet particular requirements [1, 2, 3, 4, 5]. These requirements refer both to power efficiency and also the reliability and operational confidence of mentioned subsystems. The forecast reliability studies of CHP plant have a significant role in assuring high operational confidence.

For studying the system's forecast reliability, specific literature [6, 7, 8, 9, 10, 11, 12, 13] recommends techniques of representation and evaluation models that are quasi-general valid for technical systems.

CHP plant has a complex structure with a very large number of elements, so it's recommended to evaluate reliability and availability performances based on Reliability Block Diagrams (RBD) of analyzed structures. RBD are represented for each successful level of the system. Depending on the target reliability indicators, the complexity of schemes and the component characteristics, after representing the RBD, calculating reliability indicators may be done (depending on the structure) directly based on RBD, by binomial method or using constant parameter Markov processes.

Using the mean values of reliability indicators (λ_i, μ_i) for elements and subsystems of CHP plant, determined following the analysis of operational reliability or recommended by specific literature [10,12, 13], a quantitative assessment of reliability level of the power plant can be made for the analyzed operating scheme.

Reliability analysis of basic equipment of CHP plant is made considering that external operating conditions are provided as:

- Needed fuel at presumed quantity and quality;
- Needed water at presumed quality;
- Connection to the SEE (national power system) to evacuate produced electric energy;
- Connection to heat distribution network for evacuating produced heat;
- Evacuation of storage possibility for the resulted waste, according to environment regulations.

Reliability performances of CHP plant can be evaluated based on indicators with specific expressions as:

- Time, energy and power safety;
- Time, energy and power availability.

Availability is a consequence of equipment reliability and their maintenance.

Lack of thermal energy at the end user feed by CHP plant can be caused by: damaging of subsystems elements, preventive maintenance actions, power reductions (constrained or deliberate – as in case of interruptions in fuel provision).

The following sections present the results of a case study which outlines an approach and handling mode of forecasted reliability of functional structures in CHP plant Oradea, in different operating schemes.

2. METHOD OF CALCULATION

Knowing the structure of the system (Fig. 1), the fundamental indicators of reliability [12, 13] of basic units of subsystem (Table 1) and functions the system must satisfy, RBD are prepared related to the criteria "providing the necessary heat and the appropriate electric energy by combined production" for possible operation alternatives.

Based on RBD and mentioned information reliability indicators are calculated according to adopted criteria as:

- parallel or Equivalent reliability indicators for serial, combined schemes of boilers (R_C^k) and steam turbine - electric generator assemblies (R_{TG}^k);

- Reliability (RS^k) and non-reliability (FS^k) of structures;
- Total functioning time α(TA) and total refuse time β(TA), for the analyzed period;
- Availability (A_S^k) for analyzed structures.

Table 1. Reliability indicators of analyzed subsystems

Indicator/ Subsystem	R [-]	F [-]	λ [h^{-1}]	μ [h^{-1}]
C1	0.96441	0.03559	0.00049	0.01381
C2	0.96441	0.03559	0.00049	0.01381
C4	0.96063	0.03937	0.00047	0.01199
C5	0.96063	0.03937	0.00047	0.01199
C6	0.96968	0.03032	0.00054	0.01781
TA1	0.95009	0.04991	0.00043	0.00870
TA2	0.95009	0.04991	0.00043	0.00870
TA3	0.97259	0.02741	0.00036	0.01341
TA5	0.98746	0.01255	0.00035	0.02811
GE1	0.93333	0.06667	0.00030	0.00450
GE2	0.93333	0.06667	0.00030	0.00450
GE3	0.97118	0.02882	0.00017	0.00590
GE5	0.97162	0.02838	0.00021	0.00740

where: R – reliability ; F- nonreliability; λ -failure intensity; μ- repair intensity

2.1. Preparing Reliability Block Diagrams

Figure 1 presents *Schematic technological diagram of CHP plant Oradea* which is the starting point for settlement of the seasonal operating schemes of the power plant.

Operating schemes of basic units: boilers (C), steam turbine (TA) – electric generator (GE) assembly are settled down according to thermal load for summer respective winter period and the available fuel.

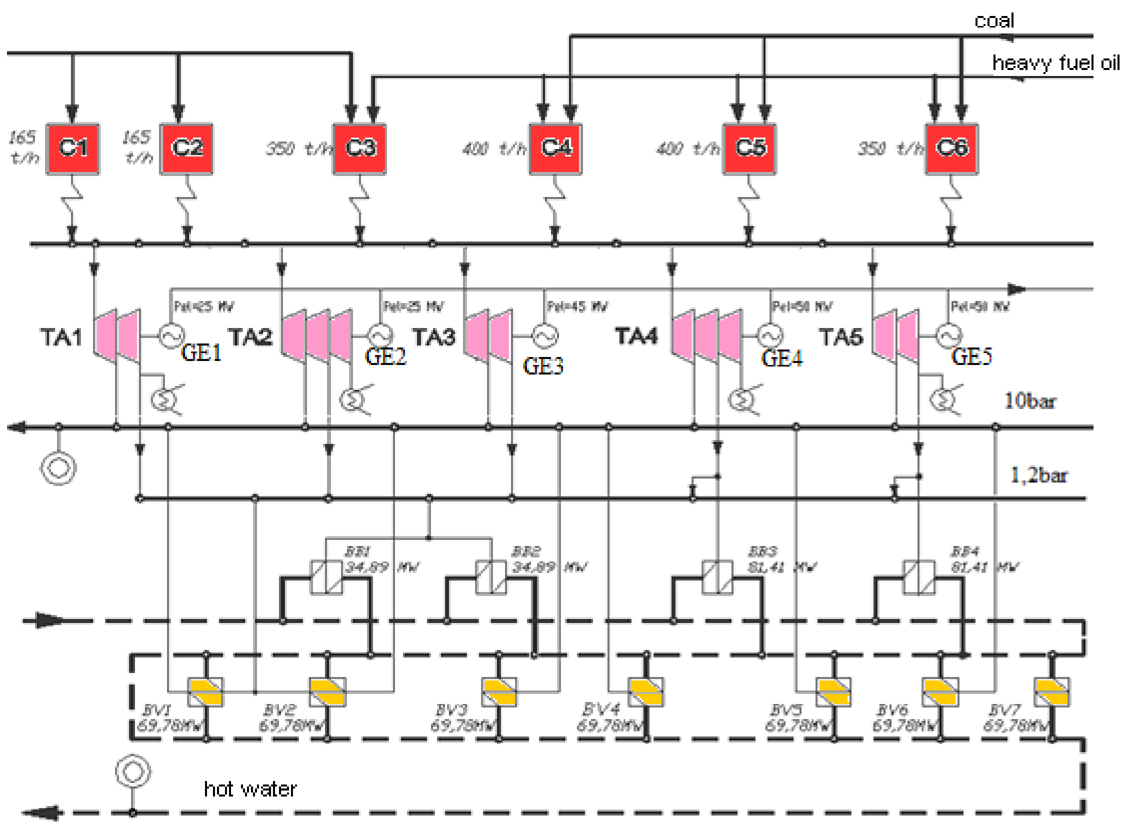

Fig. 1. Schematic technological diagram of CHP plant Oradea

Within this study, there were considered the coal fired boilers– C4, C5, C6 and the assemblies TA1-GE1(TG1), TA2-GE2(TG2), TA3-GE3(TG3), TA5-GE5(TG5). Boilers C1 and C2 fueled by natural gas, are currently used only in case of total unavailability of coal fired boilers, due to natural gases high price. For assessing reliability level, RDB of structures of CHP plant Oradea will be used for operation during summer time (three variants – V_1, V_2, V_3) respectively for winter time (two variants I_1, I_2). Values used to prepare RBD are presented in Table 2. Based on operating variants shown in table 2 RBD has been prepared to calculate forecasted reliability for power plant operation for the 5 variants, fig. 2÷6. Notations used in RDB presented below are: R_C–boilers subsystem reliability,

R_{TA}- steam turbine subsystem reliability, R_{GE}- electric generator subsystem reliability; R_s^k- system reliability for analyzed variant where $k \in \{V1; V2; V3, I1; I2\}$.

Table 2. Determinations values for RBD structures

Structure, operating units/Operating variants	**Summer**			**Winter**	
	V_1	**V_2**	**V_3**	**I_1**	**I_2**
Steam produced by two coal fired boilers [MWt]	128	128	76	379	387
Needed heat [MWt]	35	35	35	228	250
Produced electric energy [MWe]	29	29	9	64	73
Operating Steam boilers	C4or C5 or C6	C4 or C5 or C6	C1 or C2	C4andC5 or C4andC6 or C5andC6	C4andC5 or C4andC6 or C5andC6
Operating steam turbine	TA5	TA1 and TA2	TA1 or TA2	TA3andTA5	TA3andTA5and (TA1 or TA2)
Operating electric generator	GE5	GE1 or GE2	GE1 or GE2	GE3 and GE5	GE3andGE5and (GE1orGE2)

Variant V1

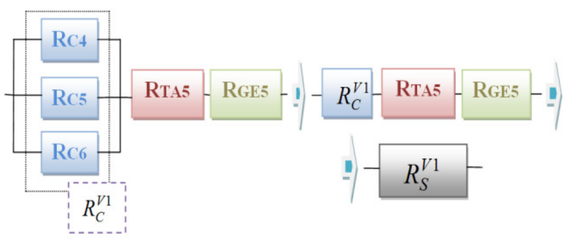

Fig. 2. RBD of CHP PLANT Oradea for variant V_1; R_C type: „1+2” [“1 of 3”]

Variant V_3

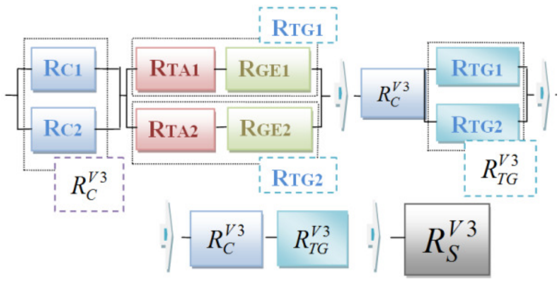

Fig. 4. RBD of CHP plant Oradea for variant V_3; R_C and R_{TG} type: „1+1” [“1 of 2”]

Variant V2

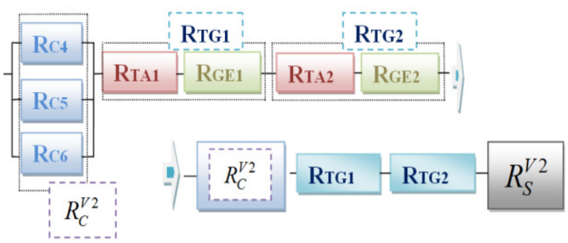

Fig. 3. RBD of CHP plant Oradea for variant V_2; R_C type: „2+1” [“2 of 3”]

Variant I_1

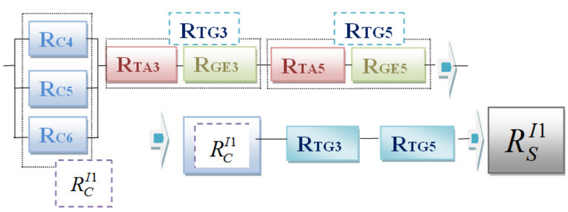

Fig. 5. RBD of CHP plant Oradea for variant I_1 R_C type: „2+1” [“2 din 3”]

Variant I2

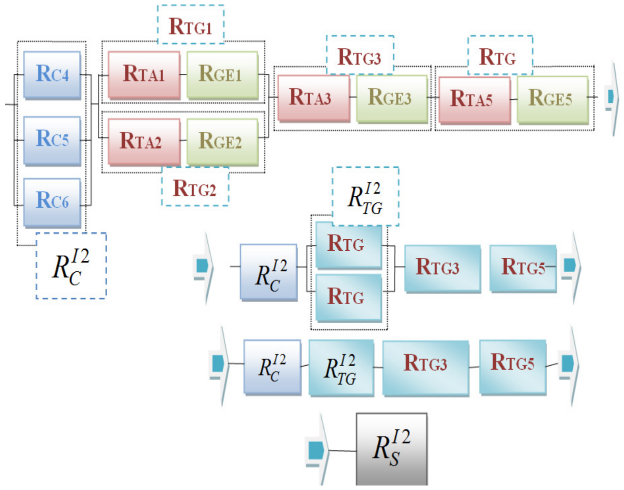

Fig. 6 RBD of CHP plant Oradea for variant I_2; R_C type: „2+1" ["2 of 3"] and R_{TG12} type „1+1" ["1 of 2"]

2.2 Calculation algorithm

The sequence of steps for determining indicators characterizing the reliability and availability of the analyzed systems for the k variants is as follows:

1) Calculation of the average values R^k_{mC} of reliability function for the boilers (C) subsystem and R^k_{mTG} steam turbine - power generator (TG) subsystem which are in parallel structure for the *k* option, equations (1), (2).

$$R^k_{mC} = \frac{\sum_{i=1}^{n} R_{Ci}}{n} \qquad (1)$$

where:

R_{Ci} – boiler i reliability, n – number of boilers in parallel connection;

$$R^k_{mTG} = \frac{\sum_{j=1}^{p} R_{TGj}}{p}; \qquad (2)$$

where:

$R_{TGj} = R_{TAj} \cdot R_{GEj}$,

R_{TAj}, R_{GEj} – reliability of TA_j and GE_j, p number of TG subsystems in parallel connection.

2) Based on RBD (fig. 2÷6) and applying binomial method we do calculate:

- Reliability of C subsystem, expression (3):

$$R^k_C = \sum_{i=1}^{n} C^i_n \cdot R^i_{mc} \cdot (1 - R_{mC})^{n-i} \qquad (3)$$

- Reliability of TG subsystem, expression (4):

$$R^k_{TG} = \sum_{j=1}^{p} C^j_p \cdot R^j_{pTG} \cdot (1 - R_{mTG})^{p-j} \qquad (4)$$

3) Considering RBD (fig. 2÷6) is calculated the forecasted reliability of operating structure of CHP plant Oradea for operating variants expression (5):

$$R^k_S = R^k_C \cdot R^k_{TG} \qquad (5)$$

4) For period considered for analysis (T_A) we obtain:

- Average operating time expression (6):

$$\alpha^k(T_A) = R^k_S \cdot T_A \qquad (6)$$

- Average failure time expression (7):

$$\beta^k(T_A) = T_A - \alpha^k(T_A) \qquad (7)$$

Time availability (A) of the analyzed structure is calculated considering reliability (R) and also maintainability (M) of structural equipment following the next steps:

5) Availability of boilers and turbine-generator assembly is determined with expressions (8), (9):

$$A^k_{Ci} = R^k_{Ci} + F^k_{Ci} \cdot M^k_{Ci} \qquad (8)$$

where: $F_{CS}{}^k$ – unreliability of boiler C_i,

$M^k_{Ci} = 1 - e^{-\mu_{Ci} \cdot t_{MC}}$ -boiler maintainability

C_i ; μ_{Ci} –Boiler *i* repair intensity;

t_{mc} – corrective maintenance time.

$$A^k_{TGj} = R^k_{TGj} + F^k_{TGj} \cdot M^k_{TGj} \qquad (9)$$

where: F^k_{TGj} =1- R^k_{TGj} - unreliability of *TGj* subsystem

$M^k_{TGj} = 1 - e^{-\mu_{TGj} \cdot t_{MC}}$ - maintainability of TGj subsystem μ_{TGj} - subsystem TG_j repair intensity; t_{mc} – corrective maintenance time.

6) Average values of availability A^k_{mC}, for subsystem C and A^k_{mTG} for TG subsystem, elements of the parallel structure are determined with expression (10) and (11) :

$$A^k_{mC} = \frac{\sum_{i=1}^{n} A_{Ci}}{n}; \qquad (10)$$

Where: A_{Ci} – is availability for boiler i, n – number of boilers within the parallel structure;

$$A^k_{mTGC} = \frac{\sum_{j=1}^{p} A_{TGj}}{p}; \qquad (11)$$

where: $A_{TGj} = A_{TAj} \cdot A_{GEj}$, A_{TAj}, A_{GEj} –availability of G_{Ej}, p-number of TG subsystems within parallel structure.

7) Based on RBD (fig. 2÷6) applying the binomial method, we calculate:

- Availability of C subsystem with expression (12):

$$A^k_C = \sum_{i=1}^{n} C^i_n \cdot A^i_{mc} \cdot (1 - A_{mC})^{n-i} \qquad (12)$$

- Availability of TG subsystem with expression (13):

$$A^k_{TG} = \sum_{j=1}^{p} C^j_p \cdot A^j_{pTG} \cdot (1 - A_{mTG})^{p-j} \qquad (13)$$

8) In the end forecasted availability of CHP plant Oradea operating structure is obtained for operating variants by expression (14)

$$A^k_S = A^k_C \cdot A^k_{TG}. \qquad (14)$$

3. RESULTS AND INTERPRETATIONS

As stated, the existing equipment of CHP plant Oradea allows operation in various structures (schemes). Selection of an operating structure is made, in a first stage, considering economical operation, to produce the necessary heat. In this context, it was intended to maximize the amount of electric energy produced in cogeneration based on the needed heat, as defined in [14, 15, 16].

For the selected operating structures, there were determined the main reliability indicators: R_S^k, $\alpha_k(T_A)$, $\beta_k(T_A)$, A_S^k. To calculate these values, corresponding to the structure which may provide the needed heat, in the 5 analyzed variants, there were used results, obtained within an operational reliability study on boilers and steam turbines, [12] and results from [13] for electric generators.

Value of indicators R_S^k, $\alpha_k(T_A)$, $\beta_k(T_A)$, obtained for the analyzed structures presented in table 3 are graphically presented in charts fig. 7 and fig 8. Results show the factors which influences the whole structure reliability. These factors are:

- Subsystem's reliability (C, TA, GE)
- Operating configuration (series, parallel)
- Structure redundancy

Thereby (As seen) the best indicator values have variant 3 with a structure 1+1(1 of 2) at boilers (C1 or C2) in serial connection with a structure 1+1 (1of 2) at TG (TG1 or TG2). The worst indicators have variant 2, which have to ensure minimal flow for one of the coal fired boilers (C4 or C5 or C6), the functioning of both TG1 and TG2 turbines in serial connection, which have the most lower reliability.

Table 3. Values of structure reliability and operating time for analyzed variants

Variant/ Indicator	Operating variant				
	V_1	V_2	V_3	I_1	I_2
R_S^k [-]	0.95939	0.78628	0.98592	0.90274	0.89116
F_S^k [-]	0.04061	0.21372	0.01408	0.09726	0.10884
$\alpha^k(T_A)$ [h]	8404.25	6887.81	8636.65	7908.1	7806.56
$\beta^k(T_A)$ [h]	355.75	1872.19	123.35	851.9	953.44

Considering the operating time $\alpha_k(T_A)$ we can see that for all analyzed variants, it exceeds an operating season period (summer or winter) which creates conditions for an uninterrupted operation for these periods.

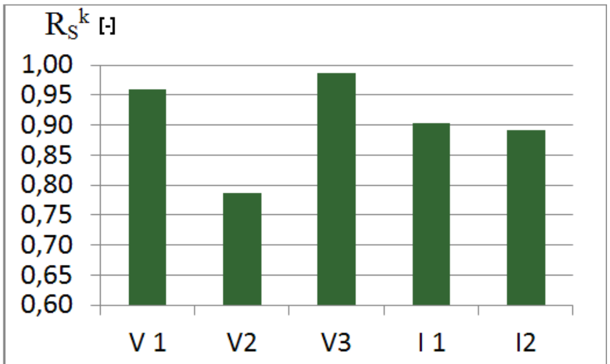

Fig.7. Analyzed structure reliability

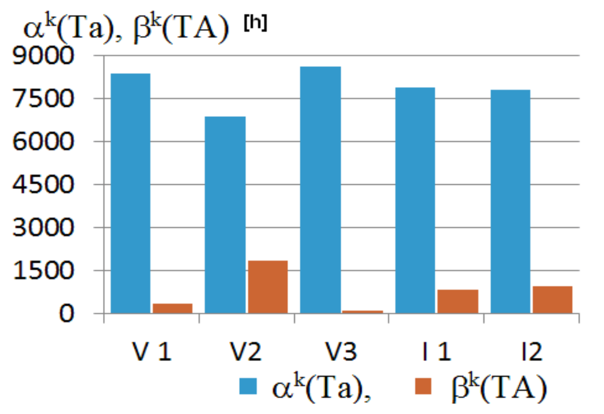

Fig. 8. Operating time and downtime for analyzed period

Values obtained for structures availability, considering time assigned for corrective maintenance are presented in table 4 and graphical representation in Fig. 9. It appears that allocating more time to maintenance has a convenient effect on structures availability. This is because making a larger volume of higher quality works during maintenance, makes the performances of concerned subsystems to strive for the initial values reducing number of accidental failures and the unavailability period. Allocation of time, human and financial resources for maintenance activities shall be the result of optimization calculations, in this respect models can be found in the specific literature [4, 9].

As in case of reliability, greatest availability value is for variant V3 and smallest for variantV2.

Table 4. System availability values for analyzed operating variants considering allocated correcting maintenance time

t_{MC} [hours]	AVAILABILITY [-]				
	A_S^{V1}	A_S^{V2}	A_S^{V3}	A_S^{I1}	A_S^{I2}
20	0.96783	0.80941	0.98870	0.92186	0.91259
40	0.97368	0.86304	0.99374	0.93618	0.92878
60	0.97791	0.88423	0.99525	0.94718	0.94127
80	0.98113	0.89958	0.99617	0.95582	0.95111
100	0.98368	0.91129	0.99679	0.96274	0.95898

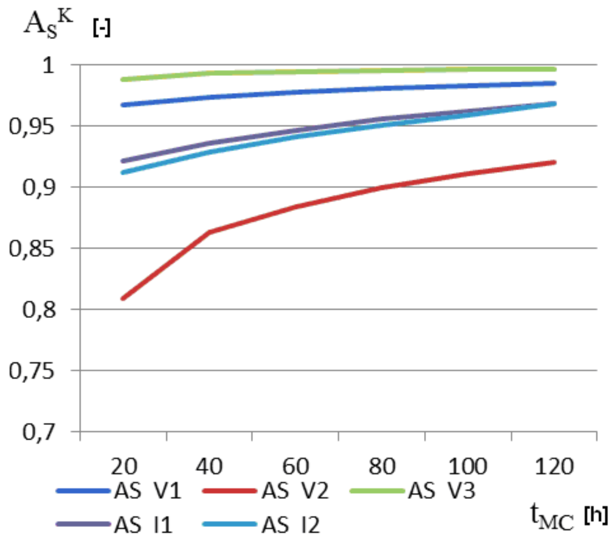

Fig. 9. Graphical representation of A_S^k related to t_{MC}

4. CONCLUSION

Forecast reliability analysis of CHP plant Oradea operating structures is based on existing operational reliability features (resulting from previous research) for basic equipment (steam boilers, steam turbines and electric generators). From possible operating schemes, for reliability analysis, were selected three schemes for summer and two for winter. Choosing these schemes has been made considering heat consumption in terms of maximizing electric energy produced in cogeneration. Reliability assessment methods recommended for subsystems considered in the paper is based on RBD, prepared for different operating schemes. Further, applying the binomial method numerical results were obtained, allowing the following conclusions:

- Highest reliability value is provided by the structure from variant 3, in this case we have a standby unit at both subsystems- boilers and also the steam turbine-electric generator assembly;
- Lowest reliability value, for variant 2, is caused by using low reliability subsystems serial connected;
- For all variants, operating time ensure operation for all heating season long, for the selected variant.

Structures availability can be improved by increasing corrective maintenance time, which ensure, through higher quality maintenance, decrease of number and duration of accidental downtime.

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