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MODELING OF RAILWAY SYSTEM MAINTENANCE AND AVAILABILITY BY MEANS OF COLORED PETRI NETS

MODELOWANIE UTRZYMANIA RUCHU I GOTOWOŚCI SYSTEMU KOLEJOWEGO ZA POMOCĄ KOLOROWYCH SIECI PETRIEGO

Prognostics and health management (PHM) technologies permit actionable information to enable proper decision-making for improving systems' performance. With the increasing requirements placed on the rail systems' availability, better maintenance decisions should be evaluated before practical application. The aim of this work is to build maintenance models and estimate the performance of considered maintenance decisions regarding the rail system's reliability and availability by means of Colored Petri nets. As a high-level formalization method, Colored Petri nets provide different color sets, which are suitable to represent different maintenance attributions. The maintenance models are evaluated at both the structure and parameterization levels. At the structure level, the structure correctness of the maintenance models is evaluated by using the state space analysis. At the parameterization level, specific maintenance decisions are illustrated. With various maintenance parameters, comparisons of system reliability and availability are made with the results obtained with the Colored Petri nets model.

Keywords: *prognostics and health management, colored Petri nets, railway system, maintenance, availability.*

Technologie prognostyki i zarządzania zdrowiem (PHM) dostarczają praktycznych danych, które umożliwiają podejmowanie właściwych decyzji w zakresie poprawy wydajności systemów. Wraz z rosnącymi wymaganiami dotyczącymi gotowości systemów kolejowych, rośnie potrzeba oceny decyzji dotyczących utrzymania ruchu przed ich wprowadzeniem w życie. Celem przedstawionej pracy było zbudowanie modeli utrzymania ruchu oraz oszacowanie za pomocą kolorowych sieci Petriego możliwości realizacji rozważanych decyzji konserwacyjnych dotyczących niezawodności i gotowości systemu kolejowego. Kolorowe sieci Petriego to metoda o wysokim poziomie formalizacji, którą w przedstawionej pracy wykorzystano do reprezentacji za pomocą różnych zestawów kolorów, różnych atrybutów utrzymania ruchu. Modele utrzymania ruchu oceniano zarówno na poziomie struktury jak i parametryzacji. Na poziomie struktury, poprawność struktury modeli utrzymania ruchu oceniano za pomocą analizy przestrzeni stanów. Na poziomie parametryzacji, zilustrowano konkretne decyzje dotyczące konserwacji. Niezawodność i gotowość systemu przy różnych parametrach utrzymania ruchu porównano z wynikami uzyskanymi za pomocą modelu kolorowych sieci Petriego.

Słowa kluczowe: *prognostyka i zarządzanie zdrowiem, kolorowe sieci Petriego, system kolejowy, utrzymanie ruchu, gotowość.*

1. Introduction

Maintenance plays an essential role in a system's life cycle. At the system level, the maintenance influences the reliability and availability of the system [3]. Achieving a high maintainability in the railway system requires a proper maintenance strategy. More maintenance means more life-cycle cost, while it may not lead to a dramatical improvement in the reliability. Hence, the performance of the strategy should be evaluated before it is put into the practical application.

Given that the enormous number of system components and maintainable items, it is a complex task to carry the analysis of railway system maintenance and availability. Railway system includes different subsystems, and the system structure will influence the overall system availability and performance. When managers plan a maintenance strategy, they have to take the system architecture into account. As in a free market, the optimal maintenance strategy can not only guarantee the availability of railway system but also have the best economic benefits. For the system maintenance and availability analysis, there are mathematical formulating and model-based analysis approaches. Garmabaki et al. presented the Multi-Attribute Utility Theory (MAUT), which used multiple objective functions to evaluate the cost and reliability of the maintenance optimization [5]. A gamma deterioration process was proposed by Meier-Hirmer et al., and it was applied to analyze the track maintenance [10]. Furthermore, the Maintenance Engineering Department of French National Railway Company (SNCF) introduced a formal method to estimate the maintenance strategy [1]. In publication [13], an application of stochastic Petri nets was presented to analyze the signal maintenance in France. All in all, comparing with the mathematical formulating approach, the model-based analysis can provide a more structured overview of the system. Additionally, it is much easier to read than the pure mathematical calculation [14].

Based on the existing database, some maintenance parameters are available. In order to evaluate the efficiency of the maintenance strategy, simulation-based analysis can be used to implement this task. Formalization & modeling can efficiently and cost-efficiently represent a real-world system. The system security analysis based on modeling is widely used in different research areas [17].

Stochastic-process techniques can be used to optimize the maintenance policies [4]. Due to the different overall system structure and complicated mathematical calculation, in this case the simulation-based analysis is used as a modeling tool [14][8]. For instance, stochastic Petri nets are used to model the railway system maintenance and availability [4]. Reliability block diagrams and Monte Carlo simulation are applied to analyze different maintenance strategies on the product availability. As an alternative to reliability block diagram (RBD) and continuous-time Markov chain (CTMC) models, non-Markovian stochastic Petri nets have also been used to model maintenance processes of complex systems.

Formalization & modeling can efficiently and cost-efficiently represent a real-world system. The system security analysis based on modeling is widely used in different research areas [15]. The model-based safety analysis can be classified into two groups: (a) failure logic based. For instance, Fault Tree Analysis (FTA) emphasizes the model of failure propagation logic; (b) system states based. This approach addresses the analysis of the transition of system states, in order to identify the routes that a system transits from a safe state to a hazardous state [16].

However, these aforementioned methods are not really included in the availability analysis of an overall transportation system, which has to take different maintenance strategies into account. In particular, these methods cannot guarantee the correctness of analysis procedures, which will affect the conclusion. Hence, it is necessary to provide a methodology that can validate the model correctness when the maintenance decisions are evaluated, and permit to find out the best maintenance strategy.

Motivated by the problems mentioned above, the aim of this paper is to build maintenance models and estimate the performance of considered maintenance decisions regarding the rail system's reliability and availability by means of Colored Petri nets (CPN). This method takes full advantages of CPN to represent different maintenance attributions, validate the overall system's structure correctness, and evaluate the maintenance decisions.

In this paper, we build a CPN model which involves both the failure logic and system states to carry out the corrective and periodic maintenance strategies. This model can be reused for different subsystems. The subsystems are composing an overall system by using the system structure model, which can consider both parallel and series system structures. With the advantage of CPN, a color set that having different maintenance attributions is applied to represent the main parameters of the maintenance strategies [6]. What is more, CPN can also be used to verify the system functional safety, and more details can be found in our previous publication [14]. While this paper focuses on the analysis of system maintenance and availability by means of CPN, which validates the correctness of system structure and estimates the performance of considered maintenance decision in an overall system level.

The remaining of this paper is organized as follows: after the introduction, the modeling methodology is introduced in section 2. In this section, different maintenance strategies are taken into account during the modeling process. What is more, both the parallel and series system structures are involved, and the system architecture is verified based on state space analysis. Section 3 advances the methodology proposed in section 2 by illustrating a case study in a line of the Sweden railway. In this section, the CPN model and operation procedure are presented; the numerical simulation data with different maintenance strategies is available to evaluate the overall system availability. Finally, some conclusions are drawn in section 4.

2. Modeling methodology

The CPN model is used to represent the maintenance strategy and system structure. In a real system, each subsystem should provide a fault treatment process when it is out of service [11]. Different maintenance strategies, which can be verified according to the purpose to be achieved, are taken into account during the modeling process [3]. To simplify the expression of the CPN model, only nets and color sets structures are discussed, no arc expressions and binding elements are involved, and the guard functions are described by logical expressions.

2.1. Periodical maintenance of the system with different failure rates

Before the fault is treated, it may cause hazards. Maintenance methods can be categorized into the preventive treatment, corrective treatment, and condition-based treatment. In this paper, the condition-based treatment is not considered in the treatment components.

The following assumptions are considered when treatments are applied:

- as long as a system is failed, the corrective treatment will be activated;
- the downtime required for corrective maintenance time is set to follow an exponential distribution;
- the downtime required for the periodic maintenance is negligible;
- after the maintenance procedure, the component is as new as original;
- the failure behavior is stochastically independent.

Failure rates of components can be divided into three periods, as shown in Fig. 1. It includes early failures, random failures, and wear out failures. Each section is described with its Weibull distribution as $\lambda(t)=\frac{b}{T}\cdot\left(\frac{t}{T}\right)^{b-1}$, where b is the shape parameter of the failure slope, T is the characteristic lifetime, t is the service time. For electronic components, a burn-in process is required, it makes the components enter into the random failures period. At this period, the shape parameter is 1.0. Hence, the failure rates are constants for electronic components. However, $b>1$ indicates that the failure rate increases with time.

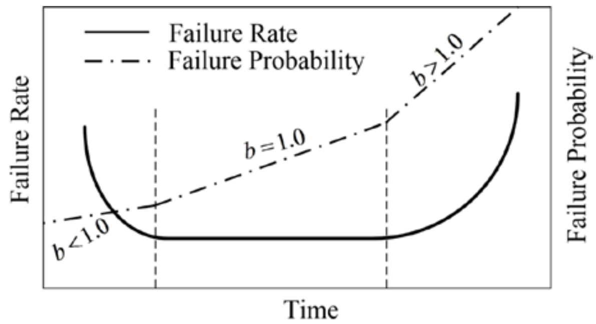

Fig. 1. Failure rates and Weibull parameter b

The probability density function of a Weibull random variable is given by:

$$f(t;T,b)=\frac{b}{T}\cdot\left(\frac{t}{T}\right)^{b-1}\cdot e^{-\left(\frac{t}{T}\right)^{b}} \tag{1}$$

where b is the shape parameter and T is the characteristic lifetime.

Failure probability:

$$F(t;T,b)=\int_{-\infty}^{t} f(t)dt=1-e^{-\left(\frac{t}{T}\right)^{b}} \tag{2}$$

Reliability:

$$R(t;T,b) = 1 - F(t) = e^{-\left(\frac{t}{T}\right)^b} \tag{3}$$

Failure rate:

$$\lambda(t) = \frac{Failures\_per\_Unit\_Time}{Quantity\_Exposed} = \frac{f(t;T,b)}{R(t;T,b)} = \frac{b}{T} \cdot \left(\frac{t}{T}\right)^{b-1} \tag{4}$$

For the numerical analysis, the system reliability is used to measure the probability that there is no failure happened before time t. The reliability of the system involved periodic treatment can be described as Eq. (5).

$$R_{PM}(t) = \left[1 - P\left(t \le k \cdot T_{PM}\right)\right] \cdot \left[1 - P\left(k \cdot T_{PM} < t \le (k+1) \cdot T_{PM}\right)\right]$$
$$= \left[1 - F\left(k \cdot T_{PM}\right)\right] \cdot \left[1 - F\left(t - k \cdot T_{PM}\right)\right] = R\left(k \cdot T_{PM}\right) \cdot R\left(t - k \cdot T_{PM}\right) \tag{5}$$

where T_{PM} is the periodic repairing interval; n means the n th periodic treatment; $R_{PM}(t)$ is the reliability of the system with the periodical treatment; $k \cdot T_{PM} \le t \le (k+1)T_{PM}$ is the time interval between the k th and $k+1$ treatment period; $k \in \mathrm{N}$. $P(T \le k \cdot T_{PM})$ indicates the probability that the system has failed in the period; $P\left(k \cdot T_{PM} < t \le (k+1) \cdot T_{PM}\right)$ is the failure probability after the k th renewal treatment. Hence, the reliability of the system with periodical maintenance is:

$$R_{PM}(t;T,b) = \exp\left[-\left(k \cdot \left(\frac{T_{PM}}{T}\right)^b + \left(\frac{t - k \cdot T_{PM}}{T}\right)^b\right)\right] \tag{6}$$

The reliability result is shown in Fig.2. When $b < 1$, after the first time maintenance, the system reliability decreases when compared with the original reliability. When $b = 1$, the periodical renewal does not influence the reliability performance of the system. When $b > 1$, the R_{PR} is greater than the original reliability, it means that the system will have a higher functional operation probability with the periodical maintenance involving. Hence, only if the failure rate $\lambda'(t) > 0$, the periodical maintenance comes with an advantage.

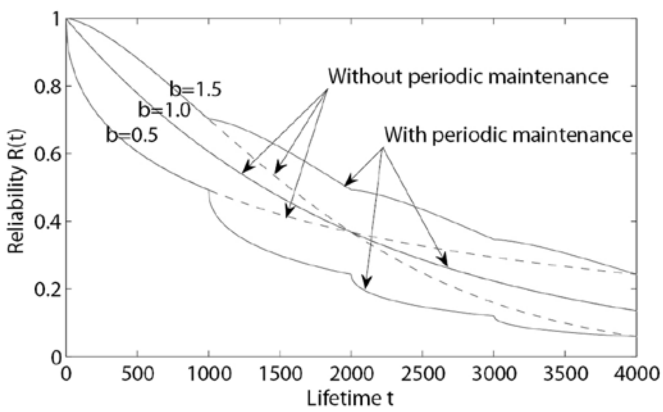

Fig. 2. System reliability with periodic maintenance

2.2. Maintenance and system architecture model

A maintained subsystem consists of these attributes: name, state, service time with relevant parameters, operation time, maintenance period, and characteristic lifetime. The subsystem has a name to identify it, and it can be in either fail or operating state. When the subsystem is failed, it will be repaired in a specific time. Section 2.1 illustrates a system's reliability with involving a periodic maintenance. Given that Weibull distribution is widely applied in the practical engineering, it can describe many behaviors of a failed system [1]. When we apply the Weibull distribution to predict the subsystem's service time, the characteristic lifetime T, service time τ, and shape parameter b should be involved. Additionally, by changing the shape parameter b, the Weibull distribution can be easily adapted to different system characteristics.

To represent the subsystem's aforementioned attributions, the declarations of the color structures are presented as in Fig. 3. Here, color sets *component* and *Data* represent subsystems and operation data, respectively. The subsystem with timestamps have the following attributions in *component*: subsystem name (*subsystem*), timestamps (*timestamp*), service time τ (*servicetime*), subsystem state (*state*), periodical maintenance period T_{PM} (*maintenance period*), characteristic lifetime T (*characteristic lifetime*), shape parameter b (*shape*), and mean time to repair (*MTTR*).

```
colset subsystem=string;
colset timestamp=int;
colset servicetime=int;
colset state=with operate|fail;
colset maintenance period=real;
colset characteristic lifetime=real;
colset shape parameter=real;
colset MTTR=real;
colset component=with
subsystem|timestamp|servicetime|state|maintenance
period|characteristic lifetime|shape parameter|MTTR timed;
colset Data=with subsystem|timestamp|state;
```

Fig. 3. Color set declaration

Fig. 4 shows the net's structure of the CPN model. The sub-nets of the system structure share the same model layout but with different logics. For a parallel system, the overall system is failed only if all the components are failed, as shown in Eq. (7). As long as one component is repaired, the overall system will operate again, as shown in Eq. (8). Similarly, the logical expressions for a series system's failure and recovery are described by Eq. (9) and (10), respectively.

$$\neg(\#state : A) \wedge \neg(\#state : B) \tag{7}$$

$$(\#state : A) \vee (\#state : B) \tag{8}$$

$$\neg(\#state : A) \vee \neg(\#state : B) \tag{9}$$

$$(\#state : A) \wedge (\#state : B) \tag{10}$$

where $\neg$ means "not"; $\#state : A$ indicates the state of component A; $\wedge$ is "and"; $\vee$ is "or"; the transition will be enabled when the logical expression result is *true*.

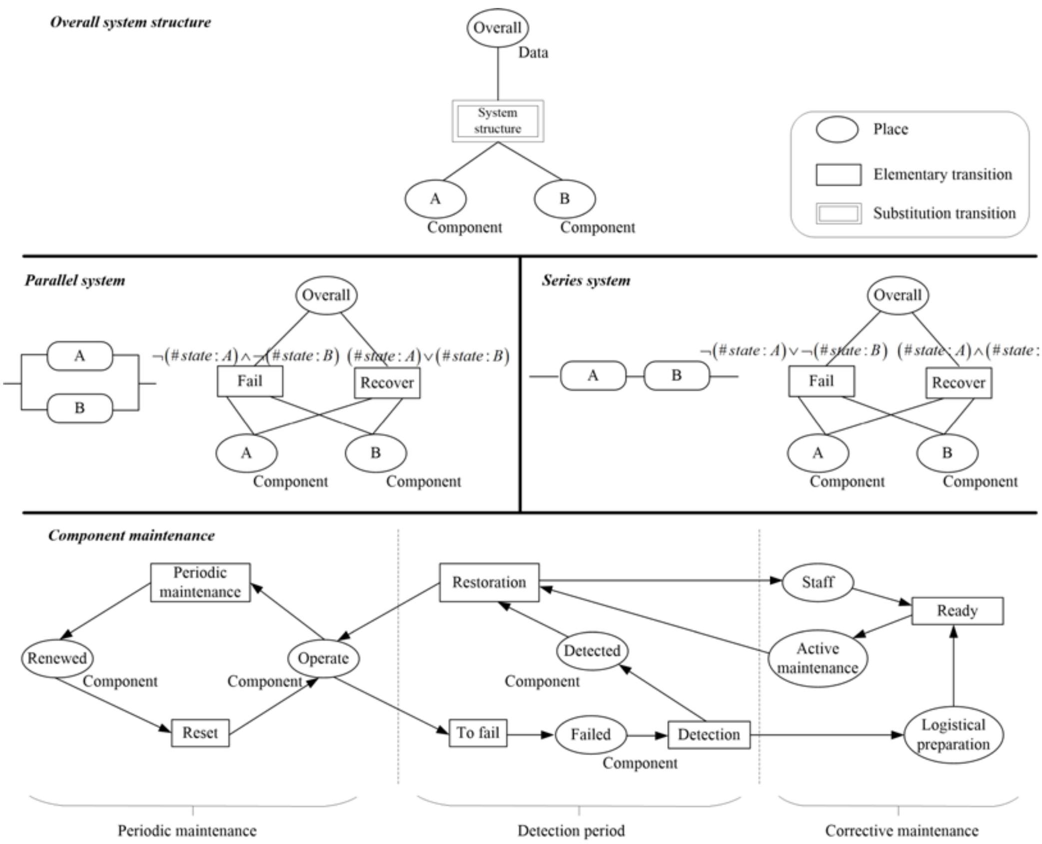

Fig. 4. CPN module of system

The component maintenance involves periodic maintenance, detection period, and corrective maintenance. The transition *Periodic maintenance* will be executed automatically based on the maintenance period T_{PM} . The transition *To fail* will be fired if component A is out of service before the next time periodical maintenance. After the failure is detected and the preparation and staff are ready, the transition *Restoration* will be enabled to carry the maintenance process, and reset the component state from *fail* to *operate*.

The architecture verification is carried out by using the model checking method [14]. To implement this verification, the state space analysis is required. The formal description of a system failure happening can be treated as that: in a marking M_i , when an enabled binding element (t,b) occurs, it will change the marking M_i to another marking M_{i+1}, defined by:

$$\forall p \in P: M_{i+1}(p) = M_i(p) - \sum_{(t,b)\in Y} E(p,t) < b > + \sum_{(t,b)\in Y} E(t,p) < b > \quad (11)$$

where $M_i(p)$ is the number of $M_i(p) - \sum_{(t,b)\in Y} E(p,t) < b >$ removes tokens from M_i while $\sum_{(t,b)\in Y} E(t,p) < b >$ added tokens to M_{i+1}. Moreover, M_{i+1} is directly reachable from M_i by the occurrence of the step Y , which denote as $M_i[Y > M_{i+1}$.

Take a parallel system that has two components *A* and *B* as an example, both *A* and *B* are failed, the overall system is failed. Here, M_i represents that both *A* and *B* are failed; step Y represents the transition *Fail*; M_{i+1} means the *Overall* is failed. Markings M_i and M_{i+1} are found through the function *Check*(). In order to limit the size of state space, other parameters of the subsystem are set to 0 except for the name and state. This attribution can be checked by the following query.

```
---------Check query---------
fun  Check()=PredAllNode(fn  n=>Mark.Parallel.Overall
1 n=[("NULL",operate)]
andalso Mark.Parallel.A 1 n=[("A",0,0,fail,0,0.0,0.0)]
andalso Mark.Parallel.B 1 n=[("B",0,0,fail,0,0.0,0.0)]);
val Mi=Check();
OutArcs(p)
---------Results---------
val Mi=[p]:Node list
val it=[q]:Arc list
---------Check query---------
val Y =ArcToTI(p);
val Mi+1=DestNode(p);
Mark.Parallel'Overall 1 Mi+1;
Mark.Parallel'A 1 Mi+1;
Mark.Parallel'B 1 Mi+1;
---------Results---------
val Y =Parallel'Fail 1:TI.TransInst
val Mi+1 =r:Node
val it=[("AB",fail)]
val it=[("A",0,0,fail,0,0.0,0.0)]
val it=[("B",0,0,fail,0,0.0,0.0)]
```

As shown in the results, M_i is found in the node p , which represents that both components *A* and *B* are failed. In addition, arc q is the only out arc of M_i , and its destination marking is M_{i+1} in the node r . The binding transition of arc q is *Parallel'Fail*. The results mean the parallel system architecture meets the requirement.

3. Case study

3.1. System description

Railway involves different blocks, which are the minimum operation sections in the railway transportation. Fig. 5 is the RBD for a block section. A block is composed of the following subsystems [12].

- Track circuit: is used to detect the train location on the trail track.
- Interlocking: prevents conflicting movements by receiving information from other subsystems, outputs movement restrictions to make sure that the train can operate safely. It can be categorized as mechanical, electro-mechanical, relay, and electronic interlocking.
- Radio Block Center (RBC): is in charge of analyzing the train's position and transferring it to the interlocking system, and sending the movement authority and other commands to the train via radio.
- Signal: gives the driver pass information based on the state of the line ahead. It can be a mechanical or electrical device.

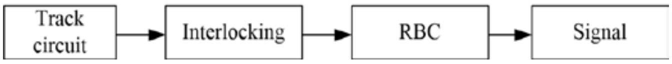

Fig.5. RBD of a block section in full functional operation

Table 1. Parameters for MTTF, MTTR, and maintenance strategy

Subsystem	MTTF (year)	MTTR (h)	Initial strategy	Shape b
Signal	2.1464	5.14	Corrective maintenance	1.0
Interlocking	2.8581	5.54	Corrective maintenance	1.5
Radio block center	2.8581	5.14	Corrective maintenance	1.0
Track circuit	2.004	3.36	Corrective maintenance	1.0

The maintenance data for this model is selected from a 203 km long railway in Sweden [12]. Note that the data is only used to do the illustration and show the efficiency of our approach. The results can be various based on different actual data. As shown in Table 1, the mean time to failure (MTTF), mean time to repair (MTTR), maintenance strategy, and distribution shape b are given. Certain assumptions are made that the signal, RBC, and track circuit subsystems are consisted of electrical items, and they are supposed to have constant failure rates. Hence, the distribution shape is $b=1$. However, the interlocking subsystem involves not only electrical but also mechanical elements, it is assumed that the mechanical wear should be taken into consideration. Hence, the distribution shape is $b=1.5$.

3.2. CPN model

Based on the aforementioned modeling methodology, the RBD in Fig. 5 can be transferred into the CPN model as shown in Fig. 6.

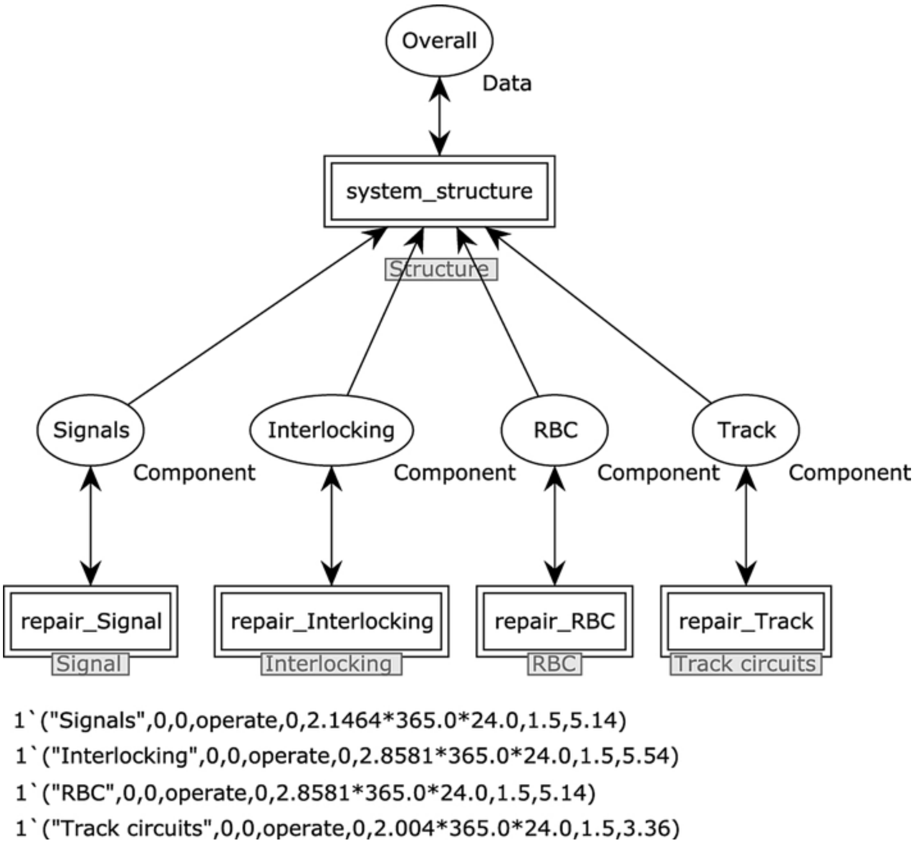

Fig. 6. CPN model of system structure

Each component is assigned with parameters based on the maintenance strategy in Table 1. The subnet *system_structure* represents the system architecture, which determines the rules to evaluate the overall system performance. In order to evaluate the full functional operation performance, which means all these components should operate correctly, these four subsystems are involved as the series system structure in this model.

The operation procedure of the CPN model can be shown in Fig. 7. Each subsystem, which has the attributions as shown in the color set *component*, has the periodic and corrective maintenance strategies. If the subsystem is failed before the periodic maintenance, the corrective maintenance is activated and the subsystem will be as new as original. The *Component* will be updated in real time, and once the binding element of transition *Fail* or *Recover* is enabled, the token in the color set *Data* will be updated. By monitoring the token on place *Overall*, the system performance can be recorded. Color set *Data* can record: which subsystem failed and caused the overall system out of service; the timestamps of when the system failed or recovered. For instance, when the subsystem signal is out of service at 3858 hours, there will one token (*1`("Signals",3858,fail)*) on the place *Overall*; when the subsystem is repaired in 2 hours later, the token will be updated to *1`("NULL",3860,operate)*.

3.3. Simulation data analysis

Note that, the train operation will be not totally out of service when one component failed. For instance, when the signal is out of service, the railway operation can still be possible if the driver obtains the permission from dispatchers and drives the train with a speed less than 40 km/h in the visual supervision mode. Hence, different sorts

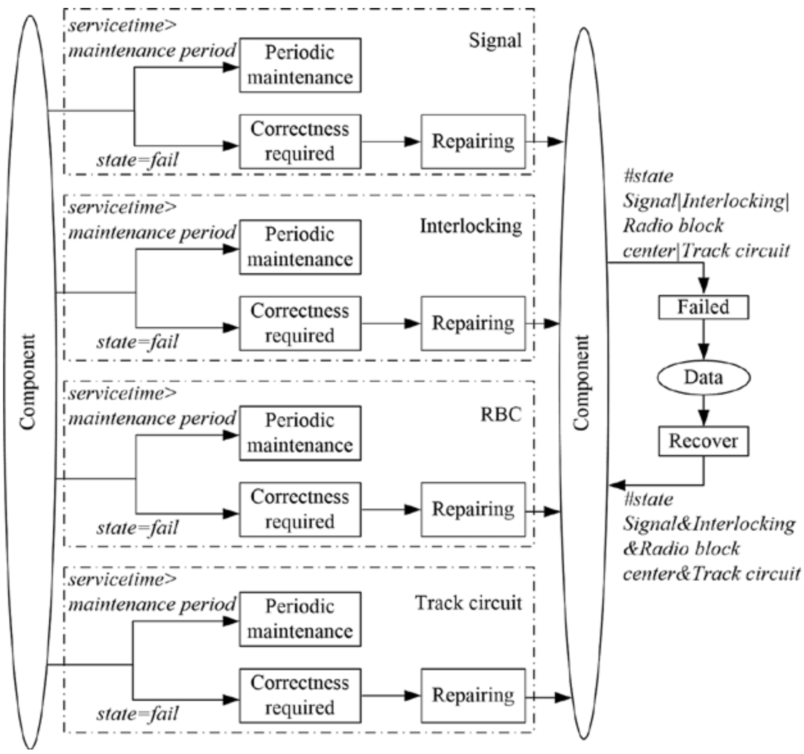

Fig. 7. CPN operation procedure

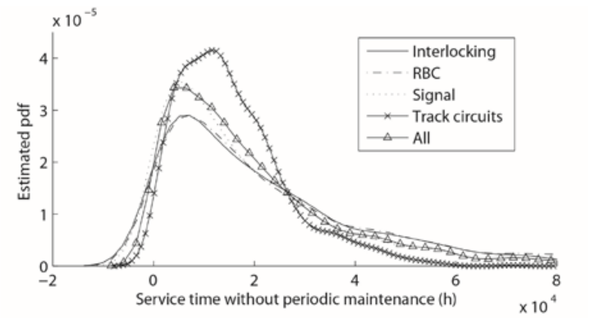

Fig. 8. Probability density function of the service time without periodic maintenance

of overall availabilities can be carried by determining respective rules.

Reliability ($R(t)$) is defined as the probability that a component performs during an operating time interval t . The achieved availability (A_A) can be obtained by calculating the mean time between maintenance ($MTBM$) actions and the average downtime $\bar{M}$ [7].

$$R(t) = P(T > t) \tag{12}$$

$$A_A = \frac{MTBM}{MTBM + \bar{M}} \tag{13}$$

Without having an onerous computation, the system reliability and availability calculation can be carried out by the statistical analysis of the CPN model simulation results.

As monitoring the *Overall* system, the performances of the subsystems can be monitored as well. Before the periodic maintenance is involved, the service time of each subsystem and the overall system is shown in Fig.8. It indicates that the track circuits' subsystem has the most considerable influence on the overall system service time.

By involving a periodic maintenance procedure to the initial maintenance strategy for each subsystem, the difference in the service time can be available to do the analysis. The periodic maintenance interval is 2000 hours. As shown in Fig.9, the distributions of the track circuits and overall system are changed dramatiscally when involving the periodic maintenance. However, the distributions of the interlocking, RBC, and signal subsystems are not changed. This result is also corresponding to the mathematical calculation conclusion in the section 2.1: with a different shape parameter b the periodical renewal has the respective influence on the system performance.

As shown in Fig.10, the reliability of the overall system is increased with the periodic maintenance involving. Fig. 11 indicates the relation between the availability and the periodic maintenance interval. Given that more periodic maintenance means more cost, the

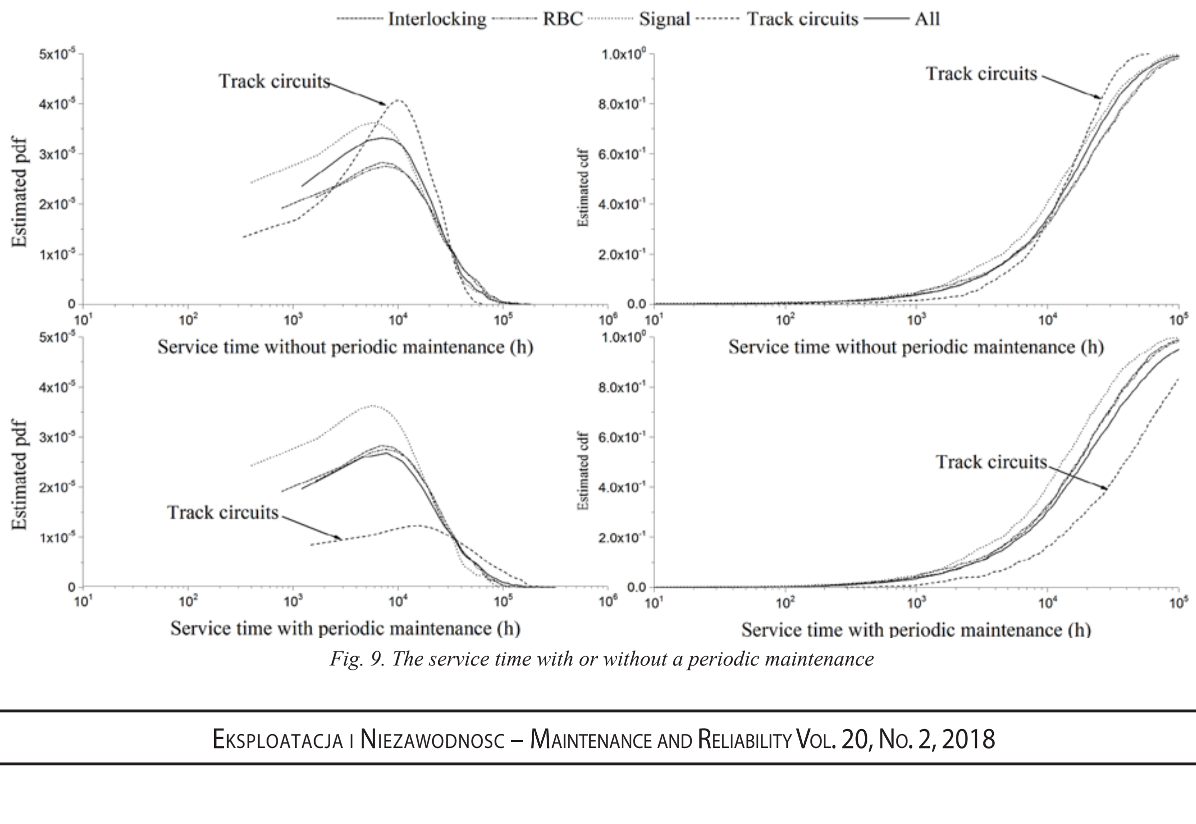

Fig. 9. The service time with or without a periodic maintenance

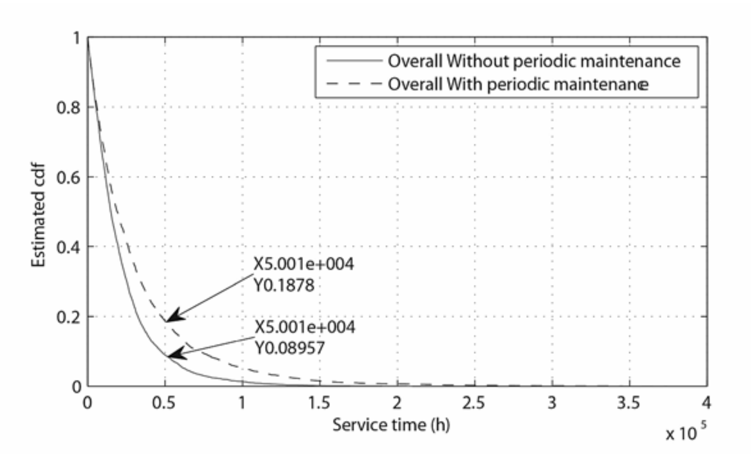

Fig.10. Overall system reliability

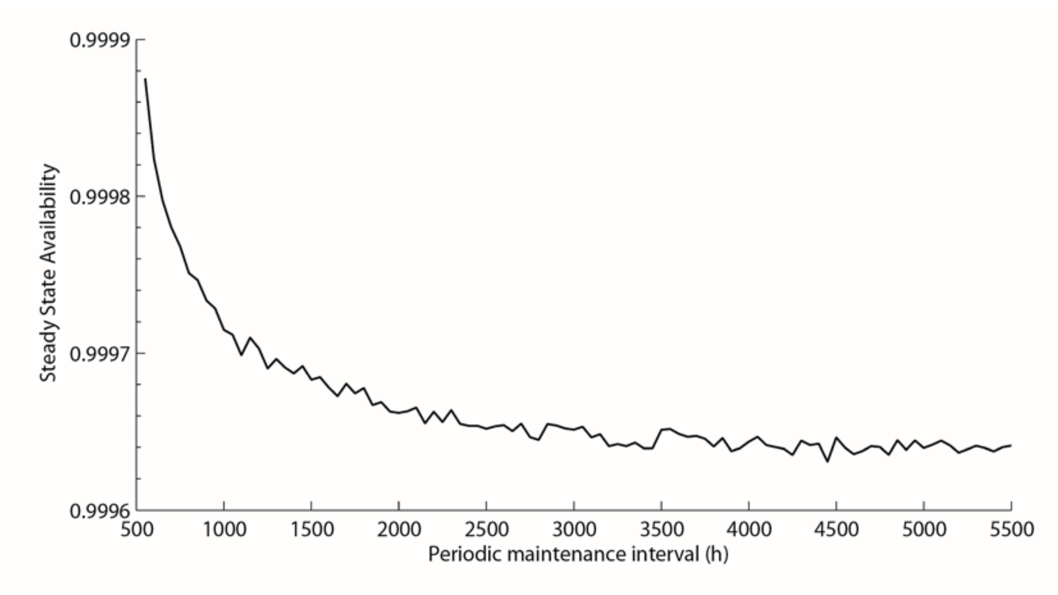

Fig. 11. Relation between the availability and the periodic maintenance interval

maintenance strategies can be modified based on the reliability and availability target.

4. Conclusion

In this paper, a maintenance CPN model, which can implement both corrective and periodical maintenances, was proposed to represent the maintenance procedure. Different subsystems were connected to compose an overall system by the system structure model, which can deal with both parallel and series systems. With the high expressive color sets in the CPN, different maintenance attributions were involved. The maintenance parameters can be modified easily to meet the practical requirements.

The results indicated that using the CPN model to simulate and analyze the overall system reliability and availability will be more efficient than the mathematical calculation. The structure of the overall system was represented by the subnet *system structure*, which was controlled by the logical expression in the CPN model. All in all, with the assistant of CPN model, the maintenance strategy can be evaluated before putting into practice, and the model permitted to find out the best maintenance strategy.

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