INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 05 MELBOURNE, AUGUST 15 – 18, 2005

OPTIMISATION OF THE DESIGN PROCESS BY MEANS OF AVAILABILITY MODELLING

Trost, Monika; Bertsche, Bernd

Abstract

Customer's buying decisions often depend on the costs which will accrue for the product during its whole life-cycle. In this paper a concept for reliability and availability based life-cycle-cost analysis is shown. Thereby main emphasis is placed on the modelling techniques for performing this analysis. The basic elements of the methods, namely Markov process, alternating renewal process, system transport theory and extended coloured stochastic Petri nets, are demonstrated and their benefits and drawbacks are shown. For the extended coloured stochastic Petri nets the modelling procedure is demonstrated on behalf of a generic example. This comprehensive methodology is able to model and analyse the logical, chronological and economical aspects as well as dependencies of the system reliability and maintenance. It enables to integrate all relevant aspects related to operation, aging and maintenance of a system, such as reliability structure, components with several operational states and general distributed failure times, failure dependencies, maintenance strategies and dependencies, queuing aspects and operational costs.

Keywords: availability modelling, life-cycle-cost, extended coloured stochastic Petri nets

1. Introduction

In many cases product lifetime does not end with the first occurring failure, since due to preventive and corrective maintenance activities the function of the product can be preserved for a longer time interval [1]. The quality of these so called repairable systems can be defined by their availability whereas the availability and the costs of a technical system are inseparably linked. The availability of a system can be increased by raising the maintenance activities and the reliability of its components, but the costs for these components arise likewise since a higher development effort as well as higher material quality is needed. The benefit of the higher availability can be nullified by the higher effort for achieving this objective. Therefore a unilateral approach might not lead to the desired result. The goal of a holistic analysis is to find the optimal design of a system for achieving the best possible rate for the availability at inserted costs.

In this context the concept of life-cycle-cost (LCC) is gaining more and more recognition. The costs which arise at the start and during the planned operational period of a technical system impose a notable influence on investment decisions. Information about system failure behaviour during the operational period as well as about the used maintenance activities are needed to forecast the LCC. This demand on an analysis of repairable system caused the development of multiple methods for examination of reliability, availability and costs. The methods in the area of availability modelling of technical systems are often subjected to limitations and simplifications [2].

In the following the concept of LCC as well as the benefit of certain models such as Markov process, alternating renewal process, system transportation theory and extended coloured stochastic Petri nets will be shown and compared.

2. Basics and Definitions

2.1 Reliability

The reliability $R(t)$ is the ability of a system or component to perform its required functions under stated conditions for a specified period of time t [3]. Therefore reliability describes the failure behaviour up to the first failure occurring. The mathematical description is based on the probability density function (pdf) $f(t)$, the cumulative failure distribution function (cdf) $F(t)$, with $f(t) = \mathrm{d}F(t)/\mathrm{d}t$, the reliability $R(t) = 1 - F(t)$ and the hazard function (failure rate) $\lambda(t) = f(t)/R(t)$.

2.2 Exponential and Weibull Distribution

An exponential life distribution is one wherein the failure rate is constant in time, possessing the pdf

$$f(t) = \lambda e^{-\lambda t}, t \geq 0, \lambda > 0, \text{ with } \lambda = \text{constant}. \tag{1}$$

The exponential life distribution is best applied to analyse failures in the steady-state phase of the bath tub curve, during which the failure rate is constant. However, in most mechanical systems the failure rates of components like bearings, gearwheels or shafts are not constant. The failure of such components is often described by a three parametric Weibull distribution [1]

$$f(t) = \frac{b}{(T - t_0)} \left(\frac{t - t_0}{T - T_0} \right)^{b-1} e^{-\left(\frac{t - t_0}{T - T_0} \right)^b}, t \geq t_0 \geq 0 \tag{2}$$

with b = shape parameter; T = characteristic lifetime (scale parameter) and t_0 = failure-free time. The failure rate of the Weibull distribution is a function of time and therefore an increasing risk at higher lifetimes can be considered. With $b = 1$ and $t_0 = 0$ the Weibull distribution is reduced to the exponential case with $\lambda = 1 / T$.

Another characteristic quantity for describing the lifetime of components and systems is the expected life $E(L)$, which is the expected value of a failure distribution, the so-called MTTF (mean time to failure). MTTF = $1/\lambda$ applies only to the exponential case.

In general it can be calculated via the following integral

$$MTTF = E(L) = \int_0^\infty t \cdot f(t) \mathrm{d}t = \int_0^\infty R(t) \mathrm{d}t \,. \tag{3}$$

2.3 Availability

If repair, maintenance and renewal processes are also taken into account the analysis of the system does not inevitably end with the first system breakdown. In most cases one has to deal with repairable systems where service interruptions occur and the systems is repaired after an arising failure.

Consider a stochastic point process with two possible states. One of the two states is numbered as 1 and called ‘operational’ and the other is numbered as 0 and called ‘failed’. With these definitions a so-called state indicator can be introduced:

$$Z(t) = \begin{cases} 1 & \text{if the system is 'operational' at time } t \\ 0 & \text{if the system is 'failed' } \quad \text{at time } t. \end{cases} \tag{4}$$

Figure 1 shows such a stochastic point process and the state indicator $Z(t)$. Thereby the pdf $f(t)$ describes the transition from 1 to 0 (failure) and the pdf $g(t)$ the transition from 0 to 1 (repair).

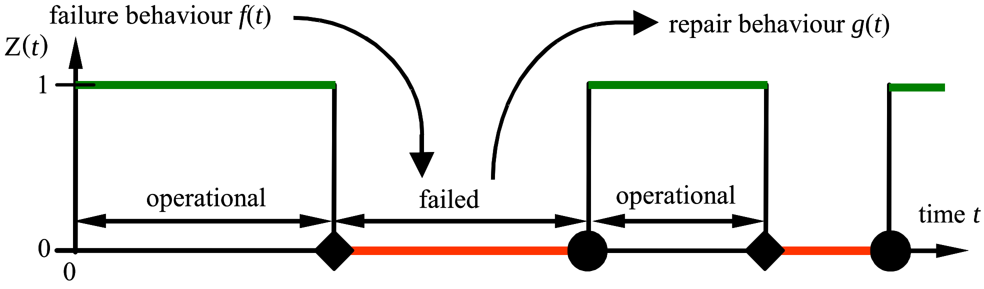

Figure 1. An alternating stochastic point process.

The availability (resp.: point-availability) $A(t)$ is defined as the degree to which a system or component is operational and accessible when required for use [3] and can be obtained as expected value of the state indicator being in the state ‘operational’ ($Z(t) = 1$)

$$A(t) = P(Z(t) = 1) = E(Z(t)) . \tag{5}$$

The steady state availability A_∞ is an asymptotic value which can be calculated according to

$$A_\infty = \lim_{t \to \infty} A(t) . \tag{6}$$

To describe repairable systems it is essential to consider stochastic repair behaviour besides stochastic failure behaviour. Therefore distribution functions are used for specifying the repair behaviour as well as the failure performance. The corresponding functions and descriptions of the failure and repair behaviour are listed in table 1.

Table 1. Description of the failure and repair behaviour.

failure behaviour		repair behaviour	
failure density	$f(t)$	repair density	$g(t)$
failure probability	$F(t)$	repair probability	$G(t)$
failure rate	$\lambda(t)$	repair rate	$\mu(t)$
reliability	$R(t)$	-----	
expected lifetime	*MTTF*	expected repair time	*MTTR*

3. Life-Cycle-Cost

The period of time between purchase order, planning, design, production, operation and disposal or salvage is defined as a system’s life-cycle. During this life-span expenses accumulate consistently which have to be borne by the costumer directly, e.g. in case of operational cost, or indirectly, e.g. in case of purchase cost. The sum of all these costs is defined as life-cycle-cost (LCC) [4].

The objective of a LCC analysis is to choose the most cost effective approach from a series of alternatives so that the lowest long-term cost of ownership is achieved. Thereby cost elements have to be considered which include planning, design, production, operation, maintenance, support, and final disposition of a system over its anticipated useful life span. LCC analysis helps evaluating systems based on total costs rather than the initial purchase price as the cost of operation, maintenance, and disposal cost exceed all other costs many times over [5].

Reliability, maintainability and availability exert high influence on the costs which accrue during the operation of a system. For an evaluation of the use and the profitability of reliability measures the consideration of cost aspects are crucial.

Decisions in early development phases cause little immediate costs, but they have a high effect on further life-cycle phases since they minimise the degree of freedom for later decisions [4]. Therefore a better part of later-on occurring costs is defined in early states, see figure 2a.

The unavailability of a product can exert a high influence on its LCC since it might cause further cost, e.g. for production losses caused by system downtimes. Therefore the availability has to be optimised with regard to the associated LCC. The relation between availability and LCC is shown in figure 2b. High reliability and expeditious maintainability lead to high purchase cost and maintenance cost increase as well with a better established maintenance organisation. Investments in these two types of costs result in an ascending system availability whereas the costs occurring for system downtimes decrease with higher availability [1]. The optimum for cost based availability considerations can be found at the minimum of the sum of purchase, maintenance and system downtime cost, see figure 2b.

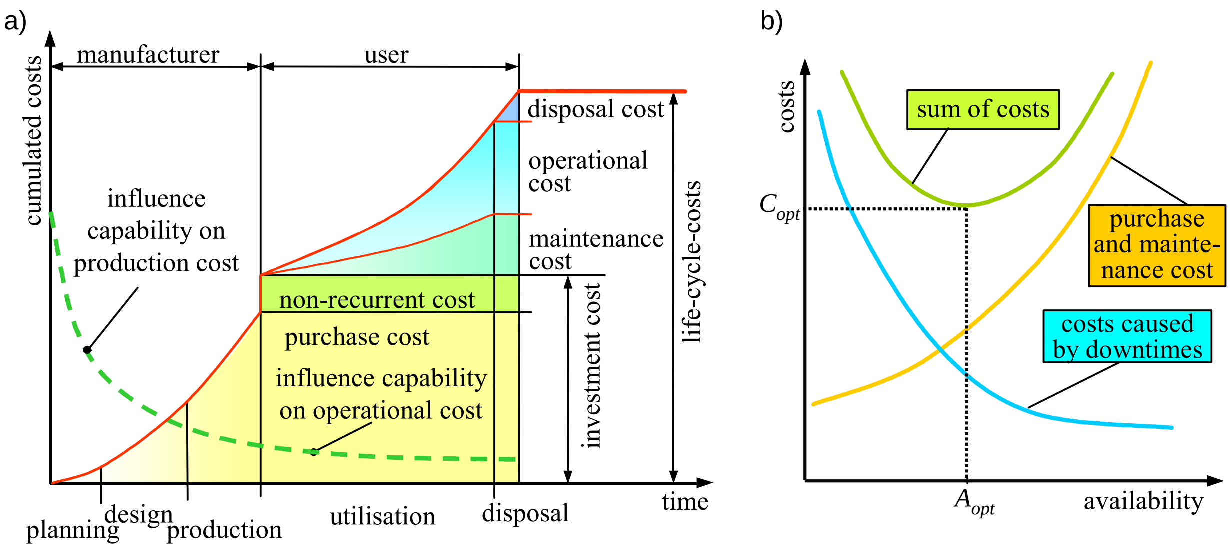

Figure 2. a) Life-cycle-costs during system life-cycle [6]
b) Simplified relation of availability and costs [1]

Furthermore there exists a contradiction between the specification, the appearance or interference of costs and the state of knowledge of the system, meaning that decisions on the cost structure of the system have to be made when limited knowledge on the system behaviour exists [4]. Therefore analytical methods or simulation are suitable instruments to minimise this gap in one's knowledge.

4. Methods for Repairable System Evaluation

The failure behaviour as well as the behaviour concerning the repair process is characterised by stochastic processes [7]. Therefore it is possible to apply methods in form of stochastic analysis of the reliability and availability of repairable systems. The available models vary in their complexity significantly. Many of them work with restrictions limiting the possibility to model complex maintenance actions.

In the following four different methods are discussed regarding their applicability to describe these aspects thoroughly.

4.1 Markov process

Repairable systems can be described in an analytic way by means of Markov modelling. The goal of this modelling technique is to determine the availability of the system as well as of the components themselves.

The Markov method is based on the Markov process, a stochastic process containing a finite amount of states Z_0, Z_1, …, Z_m. In this process the evolution for any point of time t depends only on the current state. The evolution up to this point of time is totally neglected [7],[8].

Therefore the following restrictions for repairable system modelling can be obtained:

- the Markov process is independent in time and memory-less
- after each maintenance measure the repaired component is as good as new

The elementary Markov equations express a simple balance between the flow out of state i and into state i. This leads to a system of state differential equations which can be used to calculate the availability of the system or components as a function of time.

The system's behaviour with constant transition rates is well-known and described by Markov equations [9]. In general one speaks of transition rates instead of failure and repair rates. The transition rate from state i into j is denoted by α_{ij}. The probability of being in state i at time t is defined by the state probability $P_i(t)$. A system with n possible system states yields to 2^n differential equations of the form:

$$\frac{dP_i(t)}{dt} = -\sum_{j=1}^{n} \alpha_{ij} P_i(t) + \sum_{j=1;\, j\neq i}^{n} \alpha_{ji} P_j(t) \qquad \forall\ i = 1(1)n \ \text{ and } \ \sum_{i=1}^{n} P_i(t) = 1 \tag{7}$$

where α_{ij} and α_{ji} are constant transition rates that are independent of time.

For example, the availability of a single component with exponential failure and repair distribution (two states 1: operational and 0: failed), see figure 3, arises from

$$A(t) = \frac{\mu}{\mu+\lambda} + \frac{\lambda}{\mu+\lambda} e^{-(\lambda+\mu)t}. \tag{8}$$

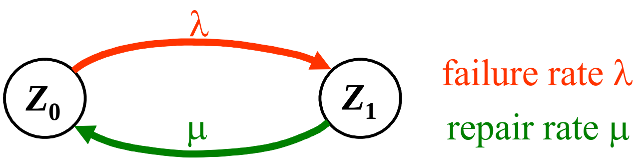

Figure 3. Example of component with two states

The steady state availability can be calculated using eq. (5) as

$$A_\infty = \lim_{t\to\infty} A(t) = \frac{\mu}{\lambda+\mu} = \frac{MTTF}{MTTF+MTTR}. \tag{9}$$

If transition rates are not constant, it is impossible to calculate the availability by means of the elementary Markov method. According to the Markov model the future only depends on the present but not on the past. This means, that in this case constant transition rates are inevitable. For time dependent transition rates the elementary Markov method can only be applied to calculate the steady state availability A_∞, but not the availability as a function of time.

4.2 Alternating Renewal Process

The alternating renewal process takes repair times and renewal times respectively into account. Therefore the situation shown in figure 4 can be modelled. The first component is placed into operation at time $t = 0$.

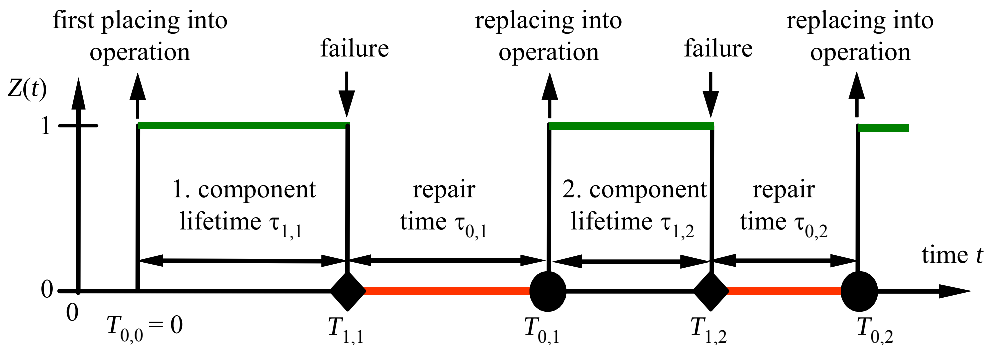

Figure 4. Alternating renewal process

The times $\tau_{1,n}$ and $\tau_{0,n}$ are following each other in an alternating way. The lifetimes and repair times are characterised by the parameters listed in table 1. The times which represent failure times are indicated as $T_{1,n}$ and the points in time when the system is placed again into operation are marked as $T_{0,n}$ with the index 0.

By applying Laplace transformation and geometric series expansion, the renewal density functions (rdf) $h_0(t)$ and $h_1(t)$ for the renewal points described by $T_{0,n}$ and $T_{1,n}$ are given by

$$\begin{aligned} h_0(t) &= f * g(t) + \int_0^t h_0(t-t')\big(f * g(t')\big)\mathrm{d}t' \quad \text{and} \\ h_1(t) &= f(t) + \int_0^t h_1(t-t')\big(f * g(t')\big)\mathrm{d}t'. \end{aligned} \tag{10}$$

For corresponding renewal functions $H_0(t)$ and $H_1(t)$

$$\begin{aligned} H_0(t) &= F * g(t) + \int_0^t H_0(t-t')\big(f * g(t')\big)\mathrm{d}t' \quad \text{and} \\ H_1(t) &= F(t) + \int_0^t H_1(t-t')\big(f * g(t')\big)\mathrm{d}t' \end{aligned} \tag{11}$$

can be found with

$$f * g(t') = \int_0^{t'} f(t'-t)\, g(t)\mathrm{d}t \tag{12}$$

where the operator * means convolution.

For the determination of the point availability three possibilities can be applied [9], [10]:

Method I: The point availability can be gained as a special case of the interval reliability using the forward recurrence time by

$$A(t) = R(t) + \int_0^{t} R(t-t')h_0(t')\,\mathrm{d}t'. \tag{13}$$

Method II: A second method for the calculation of the availability can be conducted without the use of the rdf in a recursive way

$$A(t) = R(t) + \int_0^{t} A(t-t')\big(f * g(t')\big)\mathrm{d}t'. \tag{14}$$

Method III: The difference between the renewal functions is equal to the unavailability, thus

$$A(t) = E\big(Z(t)\big) = 1 + H_0(t) - H_1(t). \tag{15}$$

By applying Laplace transformation it can be shown that all three methods provide the same point availability.

The spare part demand can be determined by using the renewal function for failures $H_1(t)$. Thereby it can be found that

$$\hat{H}_1(t) = \frac{t}{MTTF + MTTR} + \frac{Var(\tau_1) + Var(\tau_0) + MTTR^2 - MTTF^2}{2(MTTF + MTTR)^2} \tag{16}$$

is the asymptotic value of the renewal function $H_1(t)$ which can be used to estimate the spare part demand for long times.

4.3 System Transport Theory

To calculate the availability of non exponential distributed system behaviour a general state equation was suggested by Dubi [11]. Thereby a mathematic analogy between physical neutron transport in a medium and the failure and repair behaviour of a system in time has been found. The analogy is that a particle is moving in a three dimensional space colliding with other particles and thereby changing its state similar to a system changing its state in time. Considering the analogy between the physical neutron transport theory, described by the Boltzmann transport equation, and the behaviour of a reliability system in time, the so called event density $\psi_i(t)$ is defined. This quantity describes the number of entries into a state i at time t in interval dt. $\psi_i(t)$ fulfils the so called general state equation (transport equation)

$$\psi_i(t) = P_{i0}\delta(t) + \sum_{\substack{j=1\\ j\neq i}}^{n} \int_0^{t} \psi_j(t')R_j(t-t')\alpha_{ji}(t-t')\mathrm{d}t' \tag{17}$$

where P_{i0} is the probability that the system starts at time $t = 0$ in state i, $\delta(t)$ is the Dirac delta function and α_{ji} is the system transition rate.

The probability of being in the state i at time t is given by

$$P_i(t) = \int_0^t \psi_i(t') R_i(t-t') \mathrm{d}t' . \tag{18}$$

The theory on these equations is usually used for the Monte-Carlo simulation of the availability and spare part allocation of complex systems.

For a two state stochastic process as illustrated in figure 4 the event densities can be written as

$$\psi_1(t) = \delta(t) + \int_0^t \psi_1(t')\big(g * f(t-t')\big) \mathrm{d}t' \text{ and } \psi_0(t) = f(t) + \int_0^t \psi_0(t')\big(g * f(t-t')\big) \mathrm{d}t' . \tag{19}$$

Thereby it can be found for the general state equation $\psi_0(t) = h_1(t)$, $\breve{\psi}_1(t) = h_0(t)$ and

$$\psi_1(t) = \delta(t) + \breve{\psi}_1(t) = \delta(t) + \psi_0(t) * g(t) \tag{20}$$

where $\breve{\psi}_1(t)$ is called truncated event density [11].

For a component with n different states and $i = 1$ denoting the operational state the availability can be calculated by setting eq. (20) into eq. (18)

$$\begin{aligned} A(t) = P_1(t) &= \int_0^t \big(\delta(t') + \breve{\psi}_1(t')\big) R(t-t') \mathrm{d}t' \\ &= R(t) + \int_0^t \breve{\psi}_1(t') R(t-t') \mathrm{d}t', \end{aligned} \tag{21}$$

which leads to the same results as eq. (13).

4.4 Extended Coloured Stochastic Petri Nets

Petri nets are a formalisms to describe and study systems that are characterised by concurrent activities, synchronised activities, causal dependence (e.g. sequence) and conflicts (shared resources, decision, choice), inherent in complex technical systems [12].

A Petri net is a graphical and mathematical modelling tool which consists of places, transitions, and arcs that connect them. They are a bipartite directed graph with input arcs connecting places with transitions and output arcs starting at a transition and ending at a place [13].

Places represent in this context the states of components and the system. Places are drawn by circles and they might contain tokens. The current state of the modelled system (the marking) is given by the number (and type if the tokens are distinguishable) of tokens in each place.

Transitions, drawn as squares, model activities which can occur (resp.: the transition fires) thus changing the state of the system, the condition or object, described by the marking of the Petri net. Transitions are only allowed to fire if they are enabled, meaning that all the preconditions for the activity must have been fulfilled (there are enough tokens of the right kind available in the input places). If a transition is enabled it may fire after waiting for a certain time delay in compliance with the attached distribution function. By firing, tokens according to the input functions are destroyed in each of the transition's input places and new tokens are created in each output place according to the output functions of the fired transition. Hence transitions represent the intrinsic dynamic of systems.

As a graphical tool, Petri nets can be used to model complex systems and visualise their properties similar to flow charts or block diagrams. A variety of Petri net classes has been developed up to now. They differ mainly in the type of distributions, which can be used to describe time aspects and in the type of tokens. The distributions are often limited to exponential distributions, like for the generalised stochastic Petri net (GSPN). GSPNs use anonymous tokens, whereas coloured Petri nets (CPN) [14] use coloured tokens, which can incorporate data. Essential restrictions concerning the development of the age of a component in different states and the limitations to complete renewals and minimal repairs led to the extension of the CPN and the development of the extended coloured stochastic Petri nets (ECSPN). The ECSPN incorporates timed transitions (generally distributed (Weibull, normal exponential, lognormal,…), immediate and deterministic firing delays), component age information, queuing and cost elements. Different aspects of the system and components can be described inside their own thematic level with the help of references places and reference transitions. A detailed description of the extensions of the ECSPN can be found in [15].

4.5 Comparison of the Different Models

In this chapter four different methods for availability modelling have been presented in form of Markov process, alternating renewal process, system transport theory and Petri nets. They possess different modelling power and they differ in the limitations and simplifications made in the description of the system properties and maintenance processes.

Recapitulating, the following statements can be made:

The ECSPN as well as the system transport theory are capacious methods. They are scarcely subjected to restrictions regarding the distribution functions for describing the state transitions, the number of modelled component-states, the number of components and their interactions. In most cases Monte-Carlo method has to be applied to receive a solution for both methods since finding analytic solutions is impractical [16]. The advantage of the Petri nets compared to the system transport theory is the demonstrative graphical modelling technique.

The alternating renewal process also considers generally distributed failure and repair times, but it is restricted to the two states "operating" and "failed" and only complete renewals (component is "as good as new") can be taken into account at every renewal point [2].

The Markov method is restricted to exponentially distributed failure and repair times. But the results of this method can be calculated analytically. Another drawback is that modelling of big systems with a big amount of components is extensive since the number of modelled states is increasing highly with a rising number of components [1].

5. Example

The applicability of ECSPN to technical system modelling will be presented in the following section by means of a simple example. The full list of declarations of the ECSPN is omitted in the example. Only the elementary pages of the entire net are presented. Thereby the variable i denotes the ID of the component (1 = component 1, 2 = component 2 or 3 = component 3), z denotes the state of the component (2 = passive, 1 = operational, 0 = failed, -1 = in repair), a is the age of the component and s presents the state of the system.

5.1 System level

The system is made up out of three different components. Component C_1 is in series to the redundant subsystem of component C_2 and C_3, see figure 5. The system is operating if component C_1 and either component C_2 or C_3 are functioning.

For the development of the ECSPN for the system states the methods for "minimal paths sets" and "minimal cuts sets" can be used. A valid "minimal cut" causes a transition from state "system operational" to the state "system failed" whereas a valid "minimal path" provokes a transition from state "system failed" to the state "system operational". If e.g. component C_1 is failed and unavailable transition tr_3 is activated and the system state is changed from operational to failed.

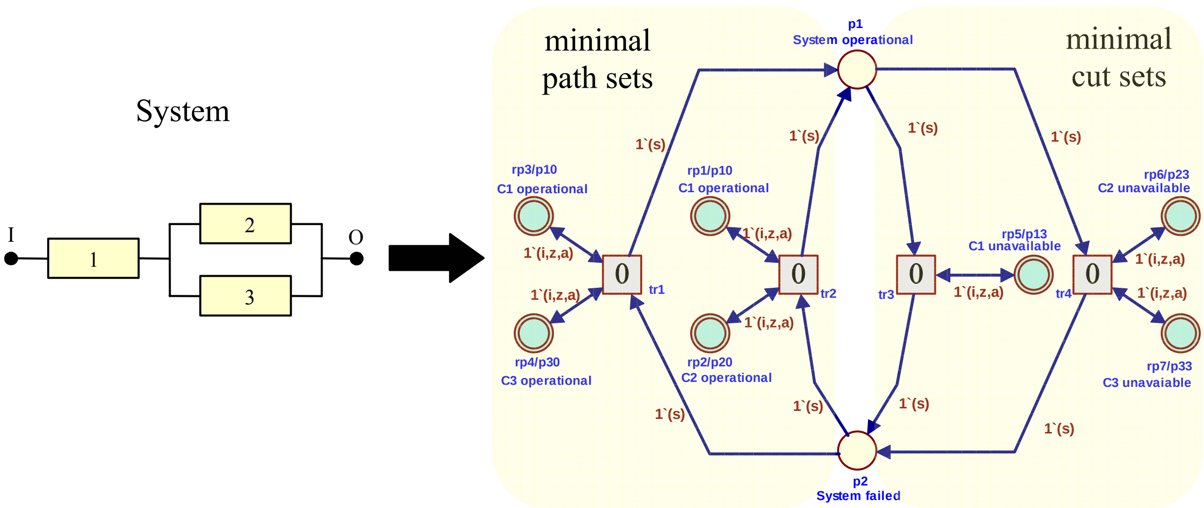

Figure 5. Reliability block diagram and ECSPN of the system

5.2 Component level

Figure 6 shows the states of the components C_1, C_2 and C_3. Place p_{10} represents the operational state and place p_{11} the passive state of C_1. A request for a change of the state of component C_1 is received from C_2 or C_3 by reference place rp_{12}/p_{23} or rp_{13}/p_{33} if they fail. Component C_1 may fail either via state transition tr_{10} or tr_{11} whereby Weibull distributed time delays are attached to both transitions. After firing, the age at the time of failure is assigned to the token by the function AgeFire, and the component state z is set to 0, see input arcs of p_{12}. Then the component is sent to corrective maintenance via reference place rp_{16}/p_{50}. If a failure of component C_1 occurs, the components C_2 and C_3 are requested to step into state "passive". After the maintenance measure is finished, the component is reconnected into state "operating". This is managed by the guard function of the transitions tr_{10} [i=1], tr_{20} [i=2] and tr_{30} [i=3]. Concurrently, the other two components are requested to return into state "operational" by a token in place p_{21} and p_{31}.

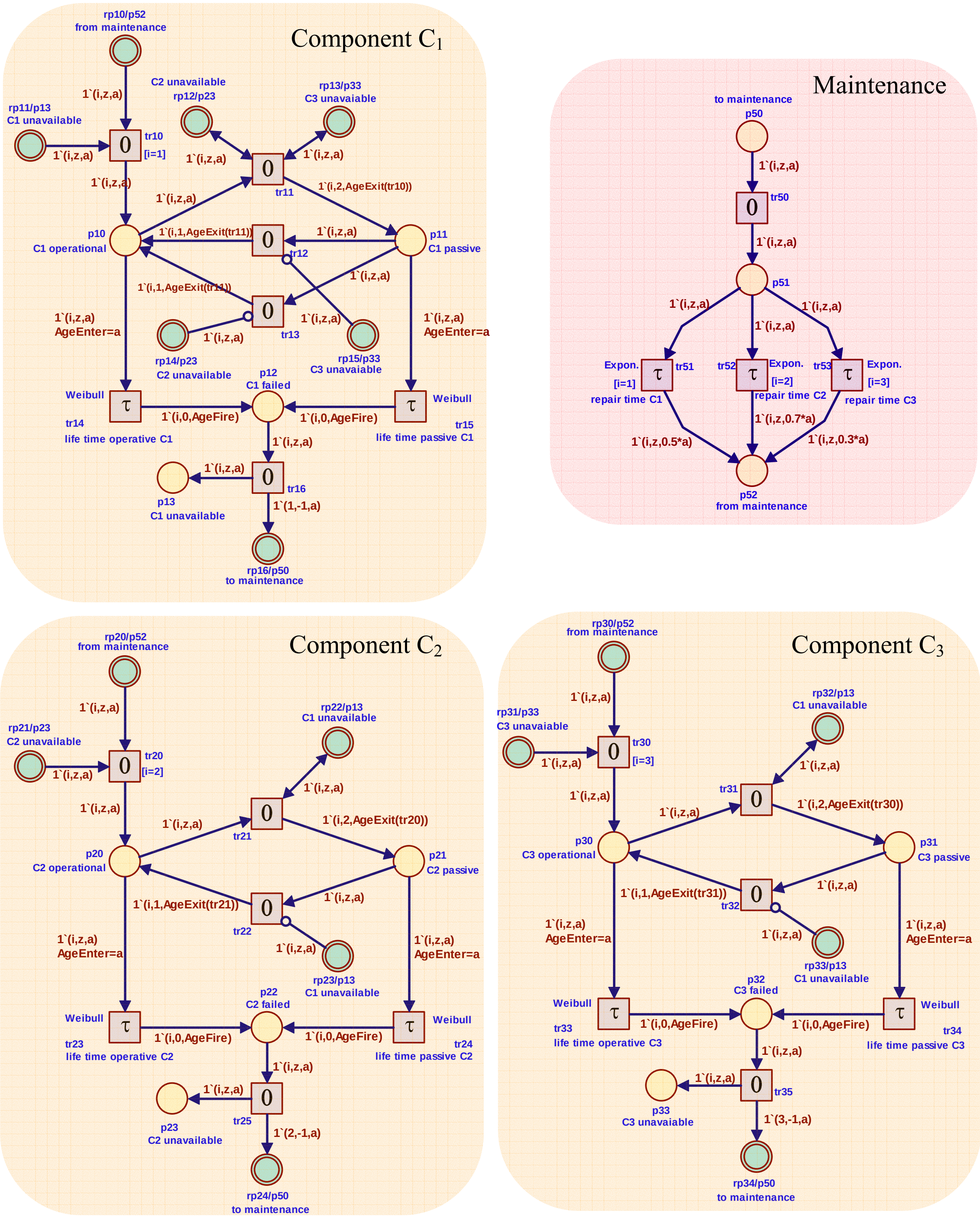

Figure 6. ECSPN of component C1, C2, C3 and attached maintenance process

5.3 Maintenance level

Figure 6 shows the maintenance process for component C_1, C_2 and C_3. Every maintenance order is set into place p_{51}. According to the value of the component ID, the component is allocated to one of three different corrective maintenance measures. The repair times for all three components are exponentially distributed as denoted for transitions tr_{51}, tr_{52} and tr_{53}, but they possess different distribution parameters and varying degrees of renewal ($\varepsilon_1 = 0,5$; $\varepsilon_2 = 0,7$; $\varepsilon_3 = 0,3$). The degree of renewal defines the quality of the maintenance actions whereas the age of the component after the repair or maintenance is given by

$$Age(t_{enter}) = Age(t_{exit}) \cdot (1 - \varepsilon) \tag{22}$$

with $0 \leq \varepsilon \leq 1$, where t_{exit} = time of failure and t_{enter} = time of reconnection. The maintenance activities can be classified by using a degree of renewal ε into minimal repair (ε = 0), repair with partial renewal (0 < ε < 1), and complete renewal (ε = 1) [15].

5.4 Cost Level

The operational costs can be accumulated in a separate level using the corresponding reference places and reference transitions. They are connected with the cost places and cost transitions in order to accumulate the costs in the desired cost centres multiplied with the cost factors, which are used to determine the amount of the types of cost. Thereby costs can accrue per time or per action. In this example the values of the cost factors refer to the operation of the system and its components and the maintenance actions.

Thereby it is possible to calculate operational cost in dependency of components reliability, system structure and maintainability to compare them with the development and purchase cost for the modelled system setups to find the cost optimum of reliability and maintenance cost and costs due to system downtimes.

6. Conclusions

In this paper four models to evaluate repairable system as basis for LCC analysis were presented in respect to their theoretical principles and required modelling elements. These four models, namely Markov process, alternating renewal process, system transport theory and ECSPN, were valuated regarding their modelling power. For the last presented method, the ECSPN, an example of the modelling procedure for a system with mixed system structure was given. The example system demonstrated the power of this modelling procedure for its application in the field of lifetime management. The major advantage of this approach is the possibility to easily model complex systems without any restriction to the used failure behaviour of the system elements and the maintenance processes like different maintenance strategies or restricted maintenance personnel.

However, a greater part of the information required for these calculations is not available until late in the development process. Therefore in early phases of the production process historic information that is normally available in company databases or through rough estimates can be used for these considerations [17], whereas reliability, maintainability and maintenance supportability data shall be systematically collected throughout the whole system life-cycle for future use in reliability and regularity prediction [18].

Collected regularity and reliability data should be analysed for trends and problems that may require corrective action, see figure 7. A programme of post-design improvements should be considered whenever poor reliability results in unacceptable production shortfalls, maintenance costs or risk to personnel arise [17].

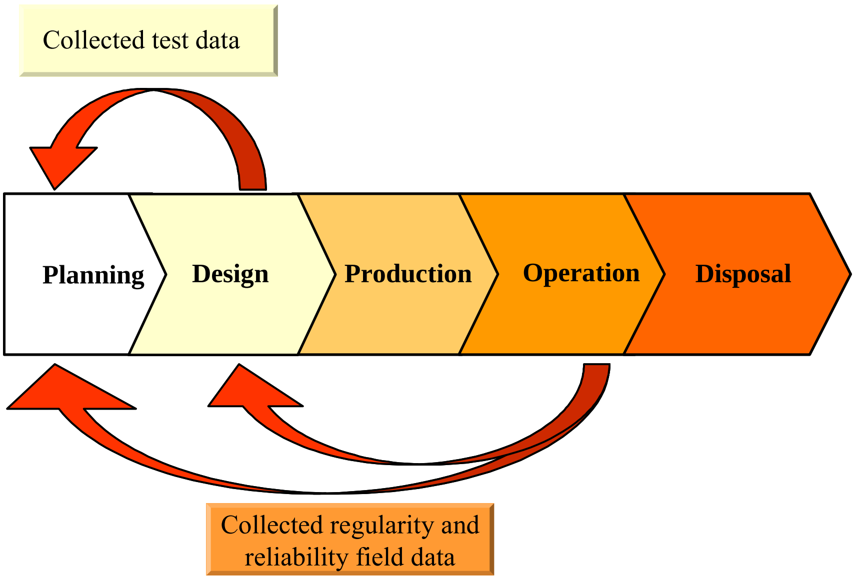

Figure 7. Availability based design process

The experience and information from the operational phase of the product should also be transferred to divisions involved in the design phase in order to stimulate improvements in design of new products. This includes a review and verification of assumptions made to the predictions in the planning and design phase in comparison to actual field conditions experienced during operation, see figure 7.

References

[1] Bertsche, B.; Lechner, G.: *Zuverlässigkeit im Fahrzeug- und Maschinenbau*. Berlin Heidelberg: Springer, 2004.

[2] Malhotra, M.; Trivedi, K.S.: Power-Hierarchy of Dependability Model Types. In: *IEEE Transactions on Reliability*, Vol. 43, No. 3 (1994) pp. 493-502.

[3] Institute of Electrical and Electronics Engineers: *IEEE Standard Computer Dictionary: A Compilation of IEEE Standard Computer Glossaries*. New York: 1990.

[4] Wübbenhorst, K.: *Konzept der Lebenszykluskosten: Grundlagen, Problemstellungen und technologische Zusammenhänge*. Darmstadt: Verlag für Fachliteratur,1984.

[5] Fabrycky,W.J.; Blanchard, B.S.: *Life-cycle cost and economy analysis*. Englewood Cliffs, NJ: Prentice Hall, 1991.

[6] Ehrlenspiel, K.; Kiewert, A; Lindemann, U.: Kostengünstig Entwickeln und Konstruieren. Berlin Heidelberg: Springer, 1998.

[7] Birolini, A.: *On the Use of Stochastic Processes in Modeling Reliability Problems*. Berlin Heidelberg New York: Springer, 1985.

[8] International Electrotechnical Commission (IEC): *IEC 61165 Ed. 2.0: Applications of Markov Techniques*. 2005.

[9] Birolini, A: *Reliability Engineering: Theory and Practice*. 4. Ed. Berlin Heidelberg New York: Springer, 2004.

[10] Aven, T.; Jensen, U.: *Stochastic Models in Reliability*. Berlin Heidelberg New York: Springer, 1999.

[11] Dubi, A.; Gurvitz, N.: A note on the analysis of systems with timedependent transition rates. In: *Ann. Nucl. Energy* 22(3/4) (1995) pp. 215-248.

[12] Volovoi, V.: Modeling of System Reliability with Stochastic Petri Nets. In: *Tutorial Notes Ann. Reliability and Maintainability Symp.* (RAMS 2004), Los Angeles, USA.

[13] Bause, F.; Kritzinger, P.: *Stochastic Petri nets – an introduction to the theory*. Braunschweig, Wiesbaden: Vieweg, 2002.

[14] Jensen, K.: *Coloured Petri nets: Basic Concepts, Analysis Methods and Practical Use, Volume 1*. Berlin Heidelberg New York: Springer, 1997.

[15] Pozsgai, P.; Bertsche, B.: Integrating the Age Development and Operational Costs into a Comprehensive System Analysis Modelling Procedure. In *Proc. 26th ESReDA Seminar*, Tampere, Finnland, 2004.

[16] Dubi, A.: *Monte-Carlo Applications in System Engineering.* New York: John Wiley & Sons Ltd., 1999.

[17] Norwegian Technology Standards Institution (NTS): *NORSOK Standard: Regularity Management & Reliability Technology Z-016 Rev. 1*. 1998.

[18] ISO 14224: *Collection and exchange of reliability and maintenance data for equipment.* 1999.

Trost, M.: Dep. Reliability Engineering, Institute of Machine Components, University of Stuttgart
Pfaffenwaldring 9, 70569 Stuttgart, Germany.
Phone: +49 711 685 6177; Fax: +49 711 685 6319;
e-mail: trost@ima.uni-stuttgart.de; URL: www.ima.uni-stuttgart.de

Bertsche, B.: Head of Institute of Machine Components, University of Stuttgart
Pfaffenwaldring 9, 70569 Stuttgart, Germany.
Phone: +49 711 685 6170; Fax: +49 711 685 6319;
e-mail: bertsche@ima.uni-stuttgart.de; URL: www.ima.uni-stuttgart.de