IAEA-CN-155/031

Application of dynamic system reliability methods for incorporation of age-dependent reliability parameters and data into the PSA model

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Second International Symposium on Nuclear Power Plant Life Management

Shanghai, China
October 15 – 18 2007

Resume

- System, Structure and Component (SSC) failures and repairs are implemented in time and consequently they are age-dependent.
- The paper presents the two alternative dynamic system reliability approaches - GO-FLOW and ATRD (Analysis of Topological Reliability of Digraphs) - to extend the FT (Fault Tree) methodology for NPP aging systems.
- Alternative methodologies are used to investigate the feasibility of increasing of failure, restore and repair rates of all component categories to take into account aging process in NPP availability.
- Both approaches are used for preparation of comparable aging process component and system models of a WWER-1000/V320.

Introduction

- Approaching the end-of-design-life and safety margins, the lifetime management becomes not only an immediate technical task but an essential political, economical and social requirement
- This problem nowadays is one of the greatest concerns of engineers and scientists of industry and also a topic of national and international discussions.
- These discussions give a new meaning to economical and political reality.
- The questions of free competitiveness, rights and obligations following social and environmental risk of NPP have been brought out.

Bulgarian PLiM Insights

- The first four units of Bulgarian Kozloduy NPP with reactors WWER-440/V230 have been already decommissioned because of external political reasons and economical factors.
- The 'old' units' safety and aging problems were of primary importance for modernization and reconstruction measures implementation. **These measures were not sufficient to convince the public opinion and some our partners to perceive the risk from these NPP units without prejudices!**
- Both the modernized NPP and the new one should be operated for extended period of time and efficient Plant Lifetime Management (PLiM) is a very important issue. It includes:
  - an investigation of the impact of aging effects on NPP safety,
  - justification, spreading and popularization of NPP risk-reduction measures.

Incorporation of age-dependence

- The aging process could take place as gradual degradation or improvement of characteristics of materials.
- Aging can affect systems and structures only through their components.The APSA (fault trees') models are modified on the level of component basic events only.
- The preferable way to take into account the SSC susceptible to aging is to embed *external physics-based reliability models* directly into the PSA software and to update the component reliability database of already calculated models - *hybrid deterministic-probabilistic models*.
- The *"plug-in" concept* allows easy integration of external calculation and extension by alternative dynamic SSC/processes models.

Age-dependent reliability description

Unrepairable components

$$\lambda(t) = \lambda_0 + a(t)(t-\tau) \qquad (1)$$

$$\lambda(t) = \lambda_0 + \alpha(\beta+1)(t-\tau)^{\beta} \qquad (2)$$

Repairable components

$$\lambda(t) = \lambda_0 + a(t)(t-t'-\tau) \qquad (3)$$

$$\lambda(t) = \lambda_0 + \alpha(\beta+1)(t-t'-\tau)^{\beta} \qquad (4)$$

$$\lambda_i = \lambda_0 / \gamma^{i-1}(t) \qquad (5)$$

t - the global time,

λ_0 - pre-aging constant failure rate,

τ - the threshold time at which aging starts and

a(t) - rate of degradation process

α - scale parameter

β - shape parameter

τ - location parameter

t' – the local time at which last repair/restore was completed

γ***(t)*** - degradation factor ***(0<γ<1)***

Reduction of risk and unavailabilities

- The plant availability and safety may decrease due to the aging of unrepairable and repairable components.
- The resulting increase could be reduced by different maintenance measures:
  - replacements and upgrading of renewable (repairable and restorable) components during repairs
  - changing of surveillance intervals of renewable components
  - setting the trend of the degradation factor to unit.

Categories of ageing components

- **Category 1. Unrepairable or irreplaceable components**
  - *unrepairable (non-restorable) irreplaceable components (Fig.6),*
  - *restorable irreplaceable components (Fig.5).*
- **Category 2. Repairable hard-to-replace components**
  - *non-restorable hard-to-replace components (Fig.4),*
  - *restorable hard-to-replace components (Fig.3).*
- **Category 3. Replaceable on a routine basis components**
  - *non-restorable replaceable components (Fig.2),*
  - *restorable replaceable components (Fig.1).*

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State transition diagram of gradually aging component with multiple failure modes

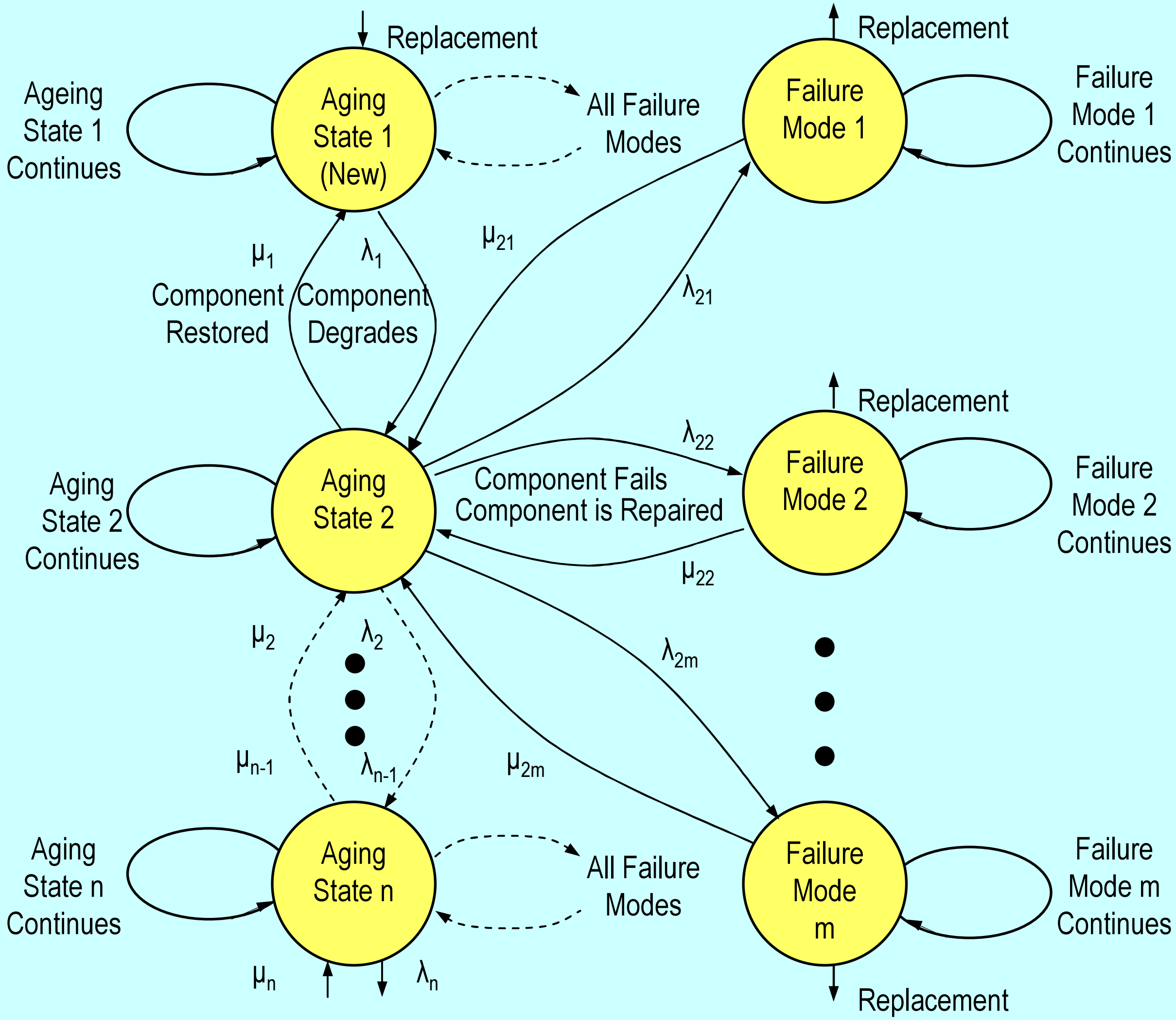

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Fig. 1. Restorable replaceable component

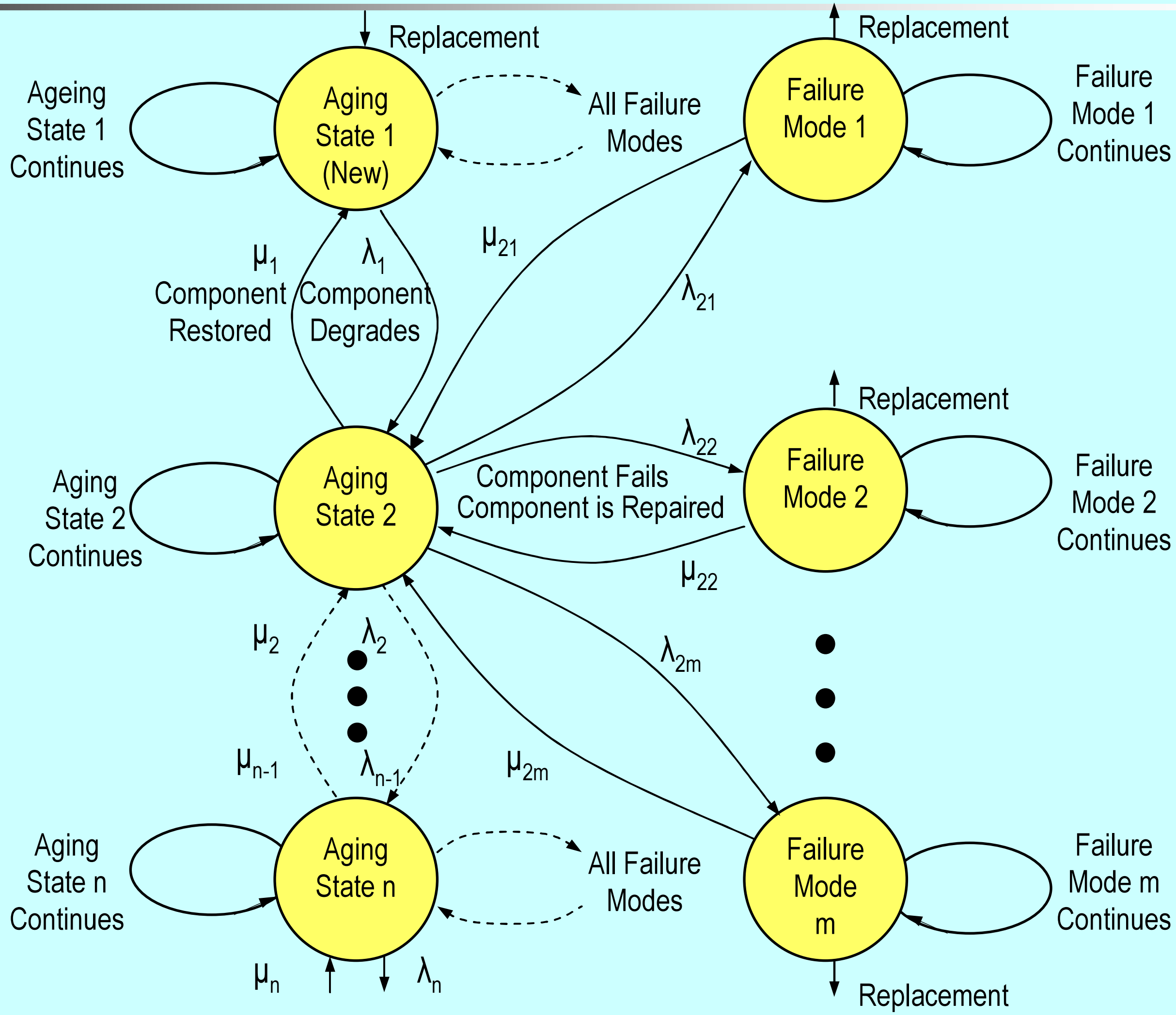


Fig. 2. Non-restorable replaceable component

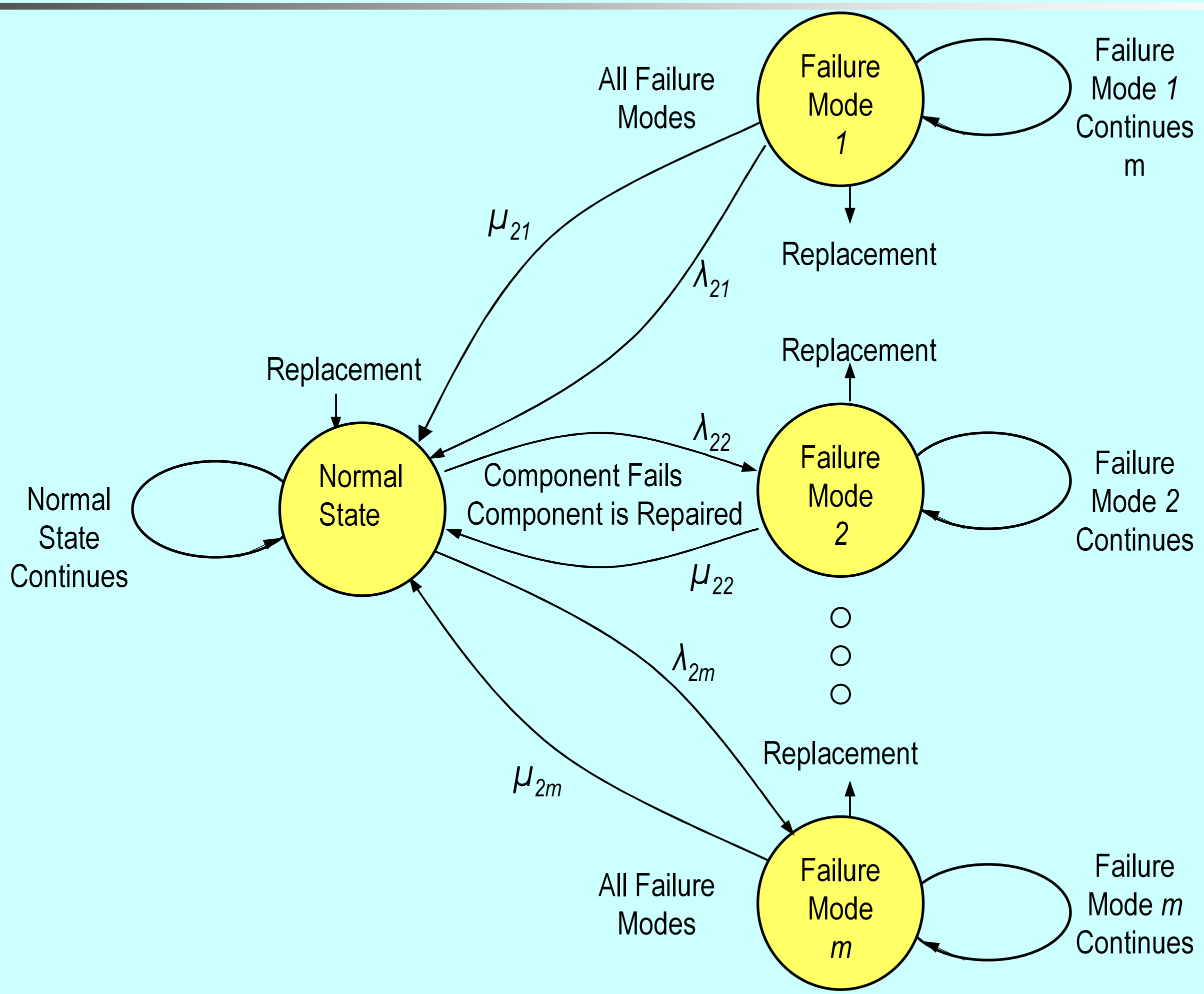


Fig. 3. Restorable hard-to-replace component

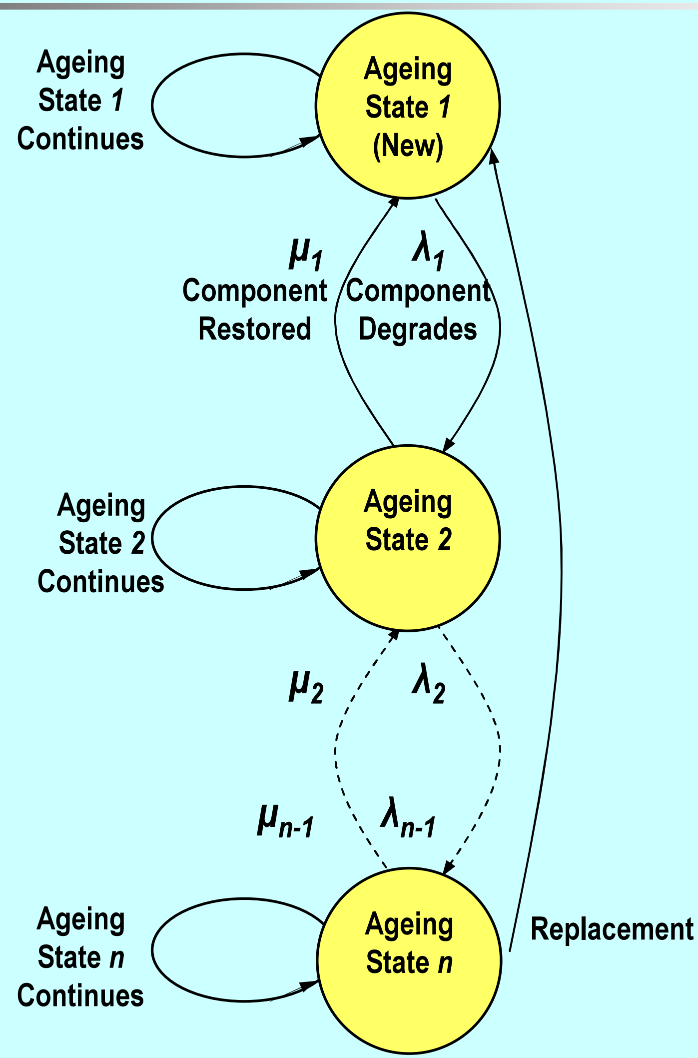


Fig. 4. Non-restorable hard-to-replace component

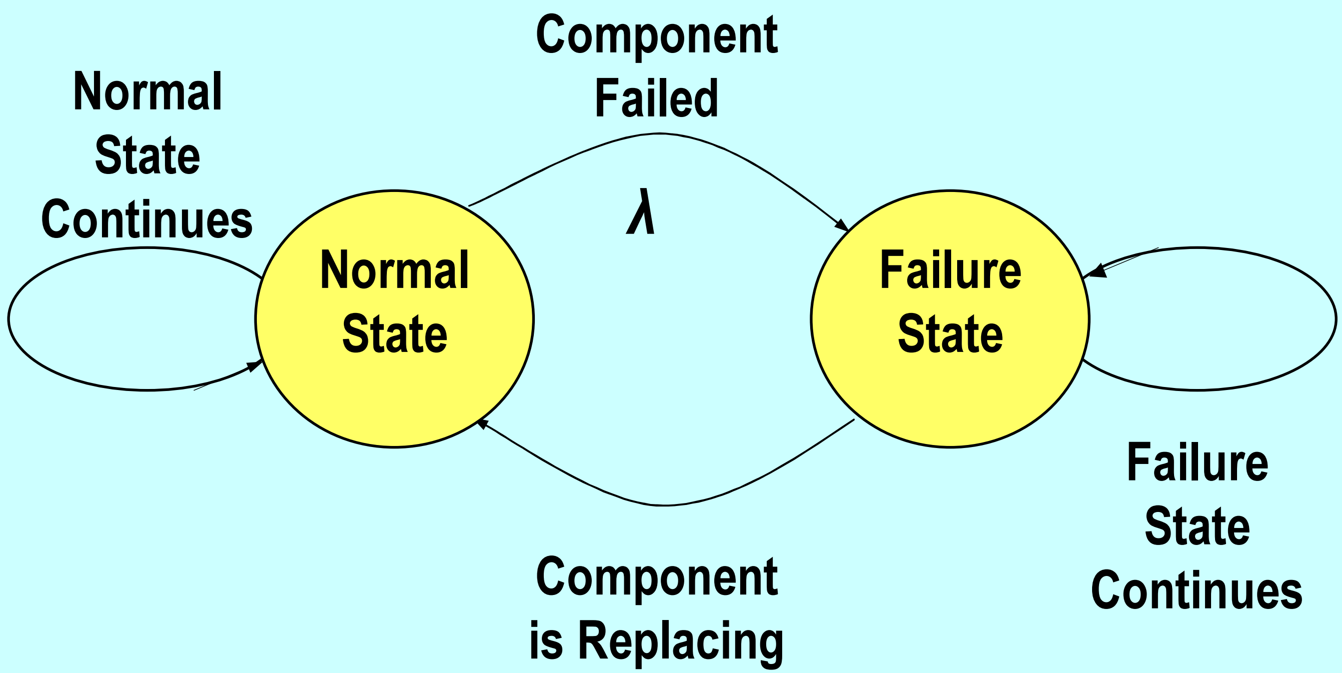


Fig. 5. Restorable irreplaceable component

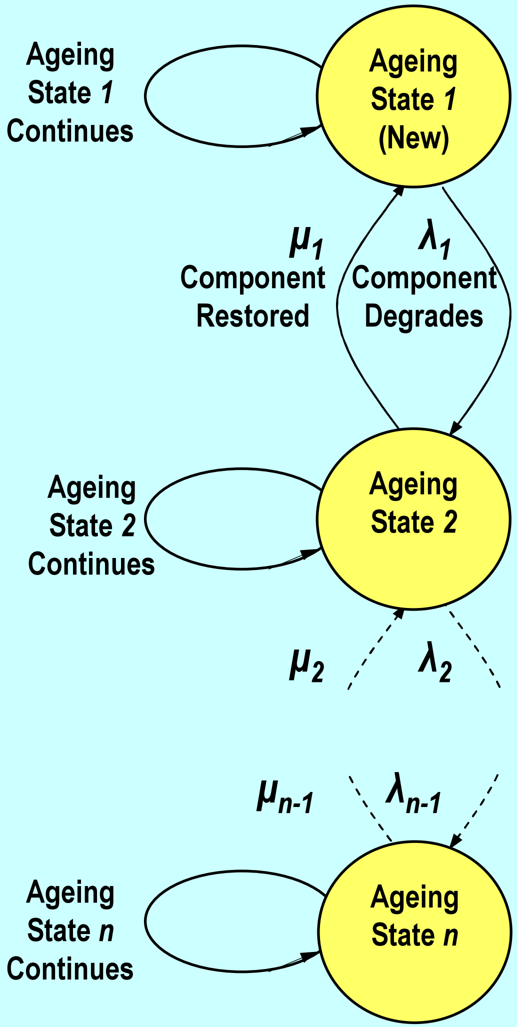
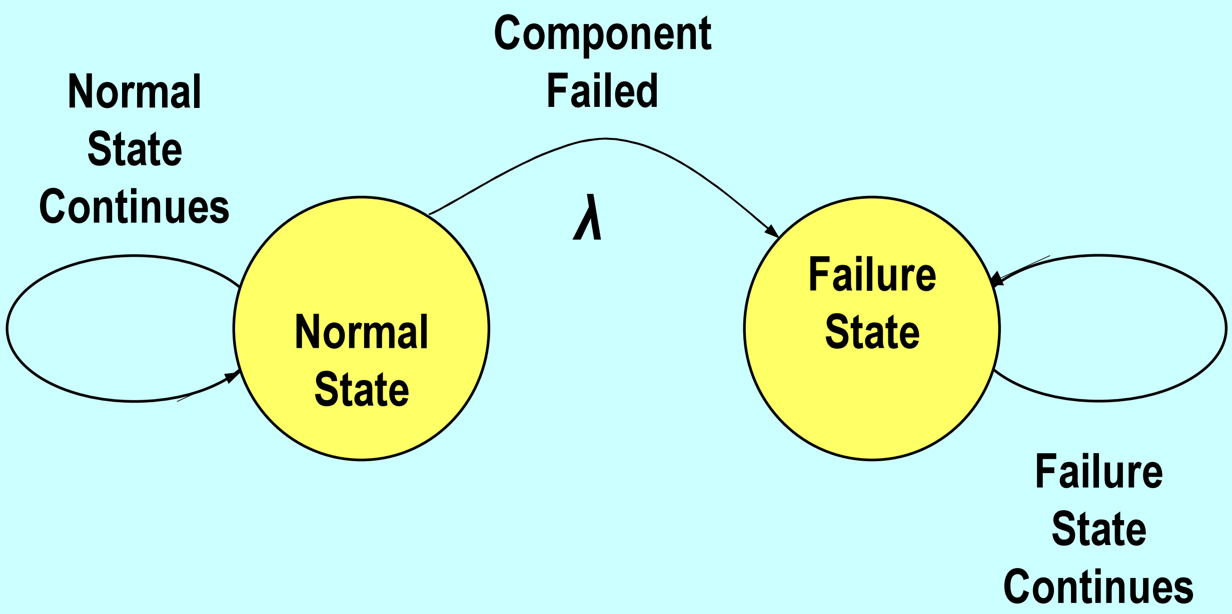


Fig. 6. Unrepairable irreplaceable component



Definition and quantification of states & modes' transition diagrams of aging components

$$\Lambda \equiv \begin{pmatrix} \lambda_{11}, \lambda_{12}, \dots \lambda_{1m} \\ \lambda_{21}, \lambda_{21}, \dots \lambda_{2m} \\ \dots \\ \lambda_{n1}, \lambda_{n2}, \dots \lambda_{nm} \end{pmatrix} \qquad M \equiv \begin{pmatrix} \mu_{11}, \mu_{12}, \dots \mu_{1m} \\ \mu_{21}, \mu_{21}, \dots \mu_{2m} \\ \dots \\ \mu_{n1}, \mu_{n2}, \dots \mu_{nm} \end{pmatrix}$$

$$\lambda \equiv \begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \dots \\ \lambda_n \end{pmatrix} \qquad \mu \equiv \begin{pmatrix} \mu_1 \\ \mu_2 \\ \dots \\ \mu_n \end{pmatrix}$$

where ***i=1…n*** - numbers of possible aging states;

and ***j=1…m*** - numbers of possible failure modes.

Simplifications of the APSA models

For renewable component *Availability* is

$$A(t) = \frac{\mu}{\lambda+\mu} + \frac{\lambda}{\lambda+\mu} e^{-(\lambda+\mu)t} \quad (7)$$

and *Unavailability* is

$$Q(t) = 1 - A(t) = \frac{\lambda}{\lambda+\mu}\left[1 - e^{-(\lambda+\mu)t}\right] \quad (8)$$

for unrepairable component *Reliability* is

$$R(t) = A(t) = \exp(-\lambda t) \quad (9)$$

and *Unreliability* is

$$F(t) = Q(t) = 1 - \exp(-\lambda t) \quad (10)$$

Pseudo-constant rates assumptions

1. The component is in its prime of life;
2. the given component is large with many sub-components having different rates or ages;
3. the data are so limited that elaborate mathematical treatments are unjustified.

- The above matrices and vectors could be simplified for each sub-category of components by:
  - equations (1)÷(5),
  - age discretization,
  - flexible formulation of boundary conditions.

1) Why could be dynamic system reliability methods useful extensions to the APSA model?

- The conventional ET-FT methodology for reliability and risk assessment is designed to describe static relationships between logical variables and does not explicitly treat time, physical process variables, aging or human behavior.
- The overcoming of quasi-static tree models limitations needs essential extensions or alternative methodologies for due assessment of reliability and risk.
- Dynamic aspects of hardware-software-liveware systems and processes require more advanced tools to analyse them.
- The alternative methodologies should include extensions of the ET-FT approach, rather than revising the methodology itself.
- However, alternative methods could be intended also to supplant the ET-FT approach in certain situations.

2) Why could be dynamic system reliability methods useful extensions to the APSA model?

- It is possible to reduce the component multiple state model to the approximative two-state model that is quite applicable for the FT technique and no other modifications are necessary.
- If the approximation errors of these calculations are not negligible then the Markov transition diagrams must be constructed and solved (Figures above). However:
  - the conditional intensities are age-varying unknowns
  - it is quite complicated to solve analytically the model with many dependent and compatible aging states and failure modes.
- Such alternative methods may give more
  - flexibility
  - convenience
  - applicability for incorporation of age-dependent effects and dynamics of physical processes.

Dynamic systems and processes

- An important characteristic of natural and engineering systems and processes are that they behave dynamically.
- System and process dynamics evolves over time:
  - System components interaction with each other and with environment.
  - System components response to initial perturbations and changes of process variables.
  - System configuration changes depending on the required mission or occurrence of component failures.
  - Components' characteristics depend on their condition, standby or operating.

Alternative methods applicability

- The applicability of one or another alternative methodology for dynamic system reliability modeling depends on:
  - analysis level
  - quality of database
  - available knowledge of structural (physical and logical) and functional system relationships
  - possibility to compare, validate and verify the methodology results.

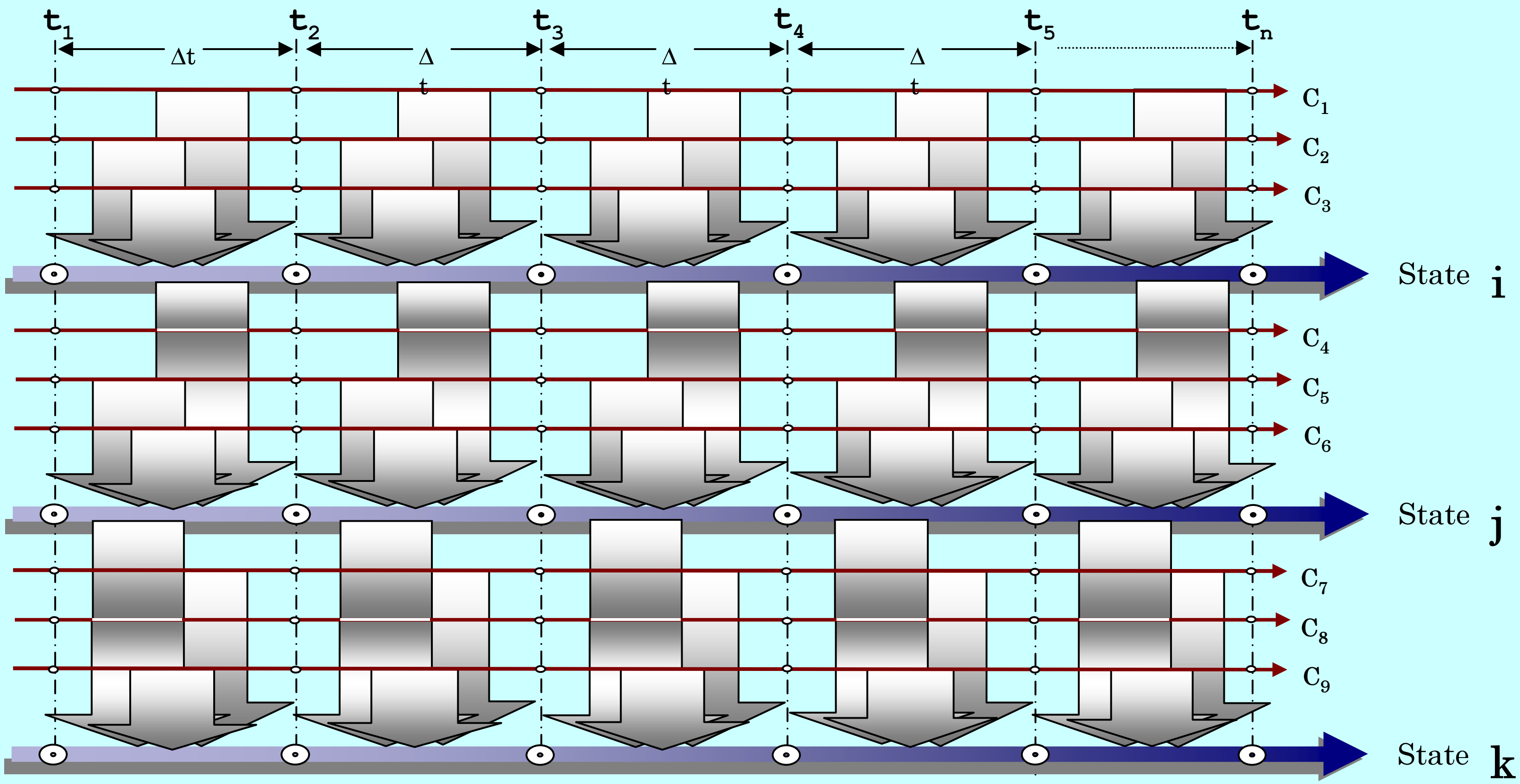
Spectrum of methodologies

- ET/FT extensions
  - Expanded ETs
  - GO-FLOW
  - Digraph-based FT construction
- Explicit state-transition methodologies
  - Event sequence diagrams (ESDs)
  - Explicit Markov chain models (controlled by global clock)
- Implicit state-transition methodologies
  - Continuous ETs (semi-Markov chains – local clocks are added to the global clock)
  - DYLAM
  - Dynamic ETs (DETAM)
  - Discrete event (Monte Carlo) simulation
- State-merging technique or “cell-to-cell” approach
  - Analysis of Topological Reliability Digraphs

GO-FLOW Methodology

- It is a success-oriented system reliability analysis methodology.
- GO-FLOW chart is constructed with standardized operators and signal lines.
- Analysis is performed by one GO-FLOW chart and one computer run.
- GO-FLOW analysis support system has been developed.
- Developed by Matsuoka & Kobayashi (National Maritime Research Institute, Japan, in 1988)

GO FLOW Procedure

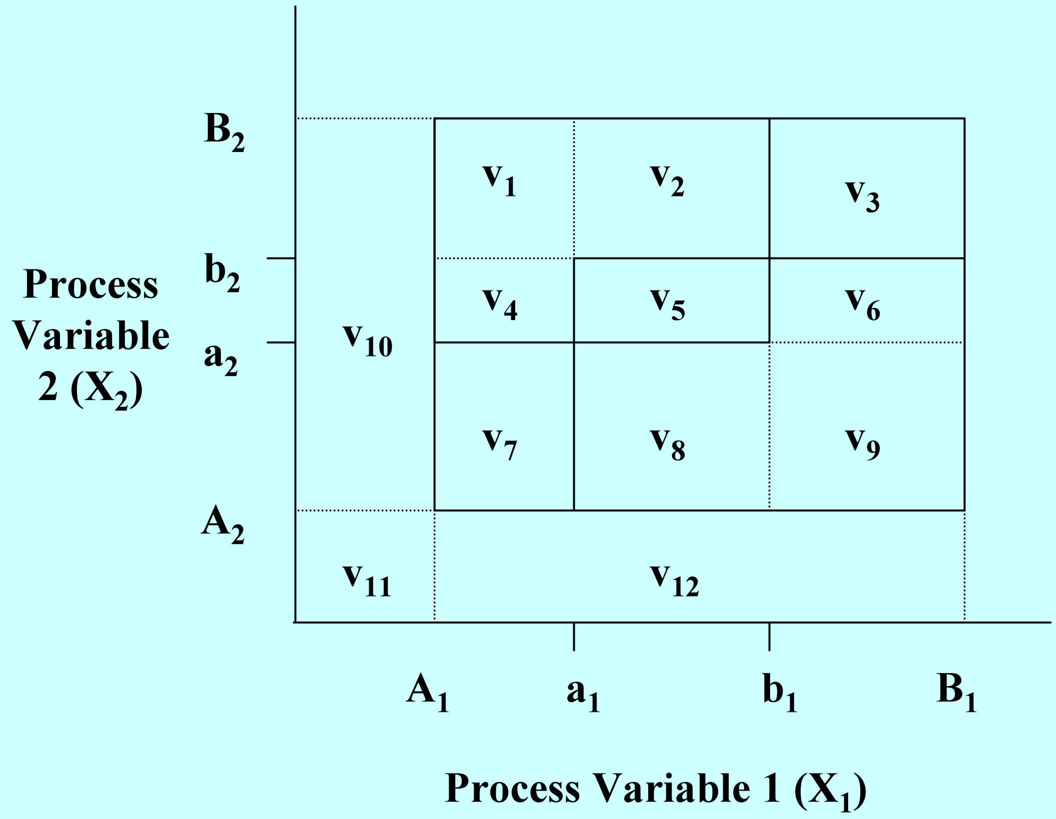


Conceptual image of GO-FLOW analysis procedure.

Explicit Markov Chain Models

- Probabilistic system behavior is simulated by the Markov chains - a set of first order differential equations with feedback describing the interaction between system variables
- Reliability space - failure and repair rates for components
- Discrete state space – time representation of system dynamics
- The action of operational control components are specified by the control laws and the system fails if any process variable is outside the control space
- Developed by Tunk Aldemir (Ohio State University, USA, in 1987)

Explicit Markov Chain Procedure

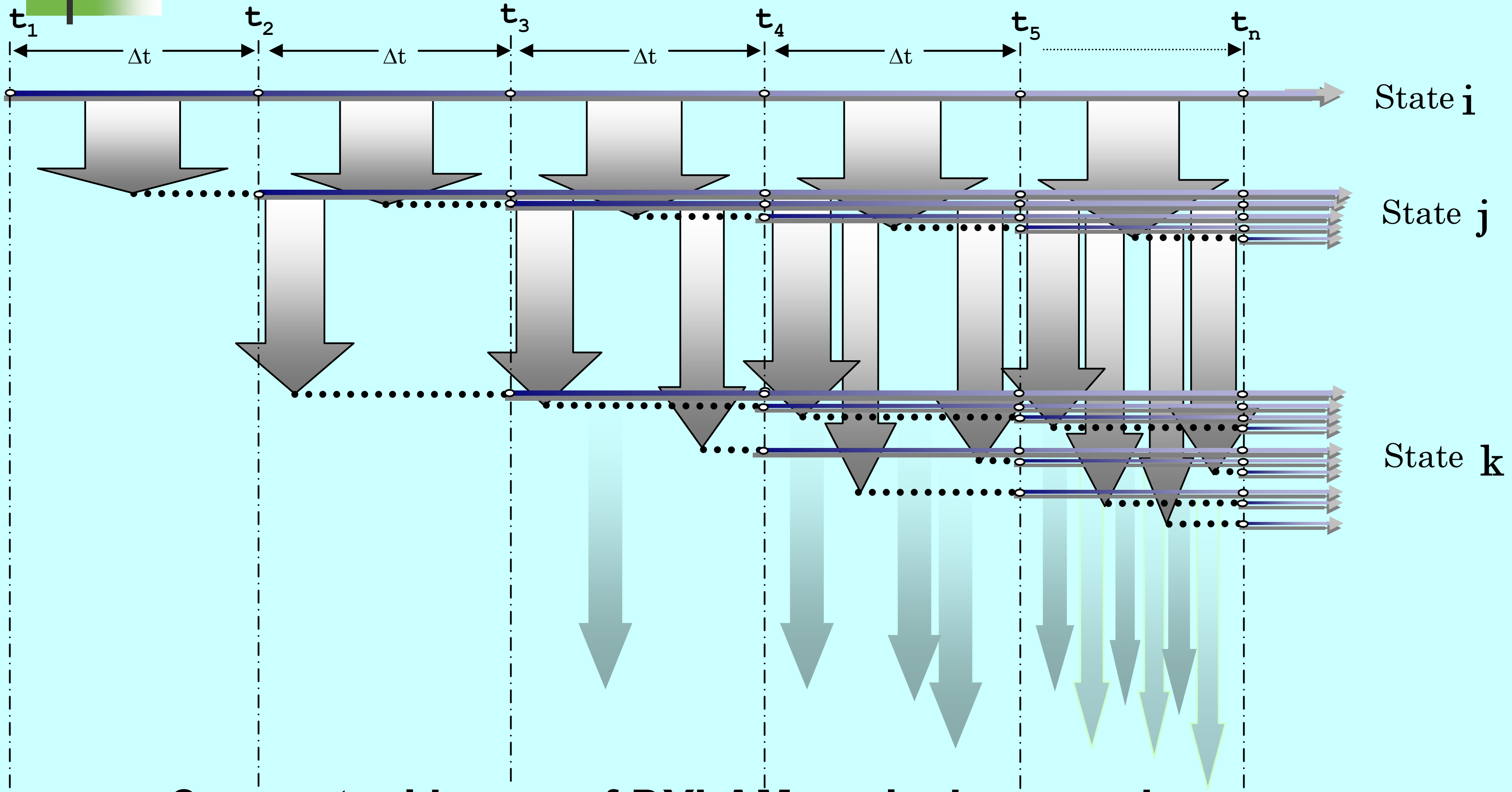


1. Identifying the control regions
2. **Choosing partitioning**
3. Determining operational and failed states
4. Mechanized construction of transition matrix

DYLAM Methodology

- Dynamic Logical Analysis Methodology
- Combination of process simulation and probabilistic model
- DYLAM is a computer program
- Developed by Cacciabue & Cojazzi (EU JRC Ispra, in 1983)

DYLAM Procedure



Conceptual image of DYLAM analysis procedure.

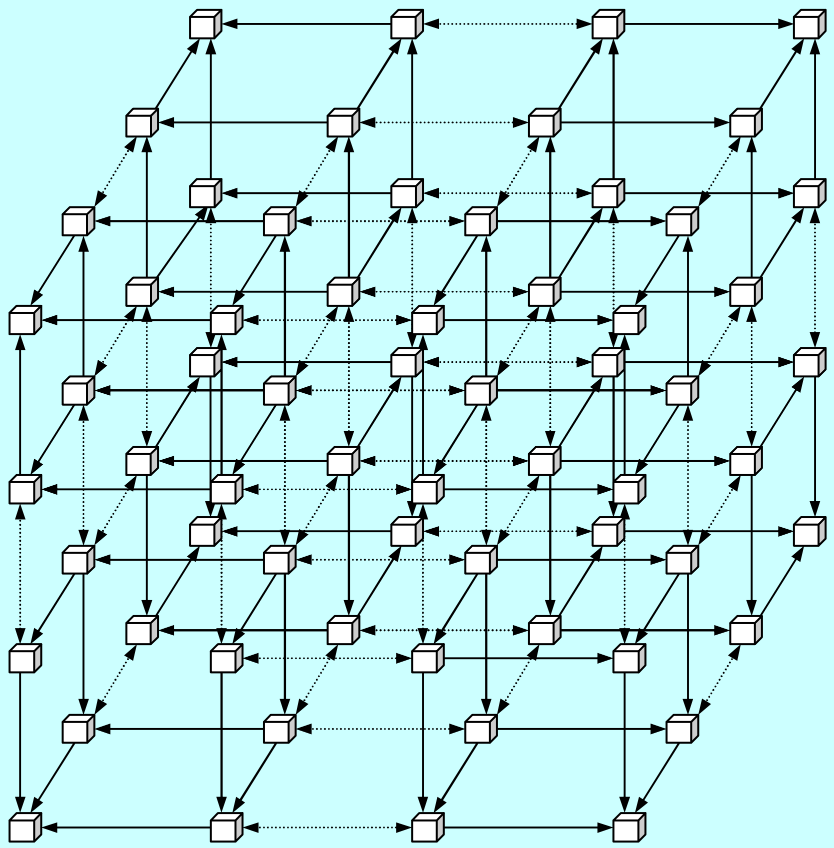
ATRD Methodology

- The ATRD method uses inductive logic where every physical and logical connection should be expressed in an explicit form.
- The ATRD system model is a digraph of system functioning. Reliability networks are presented as stochastically independent or dependent graphs.
- The multiple network with control links (Petri Nets elements) or places can discretely, hierarchically and dynamically change the state of the system components.

ATRD spectrum of applications

- Risk and Reliability Modeling of Process Control Systems and Measurements
- Dynamic Modeling of Physical Phenomena (Fire Analysis)
- Phased Mission Analysis
- Data Estimation and Collection
- Analyzing Human Actions in PRA and Accidents
- Dynamic Decision-making and Management Analysis
- Risk and Reliability Modeling of Human-Machine Systems
- Dynamic System Diagnostics and Modeling

ATRD ‘cell-to-cell’ procedure



- A ‘cell-to-cell’ ATRD procedure, called ‘matreshka’, is used to transform the complex dynamic system into a system of modules.
- Each module represents 3 - component dynamic system with 4 states (cube).
- The ATRD method traces each event sequence in cubes.
- Developed by G. Petkov (Moscow Power Engineering Institute, Russia, in 1992)

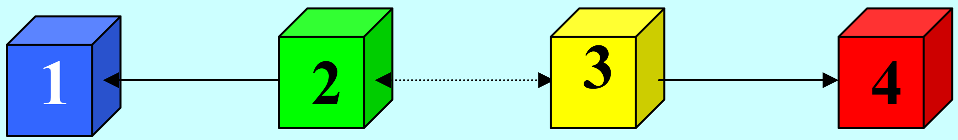
4-state dynamic system reliability model

1 ⇑ _ _ _

2 ↑ _ _ _

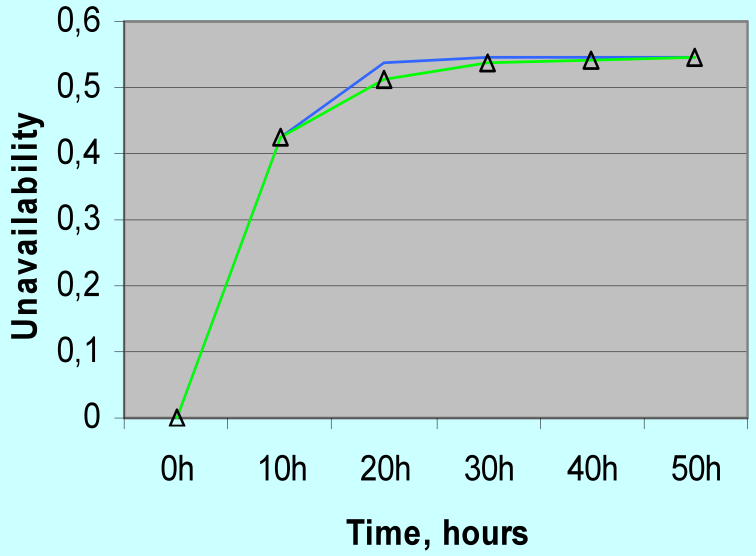
3 ↓ _ _ _

4 ⇓ _ _ _

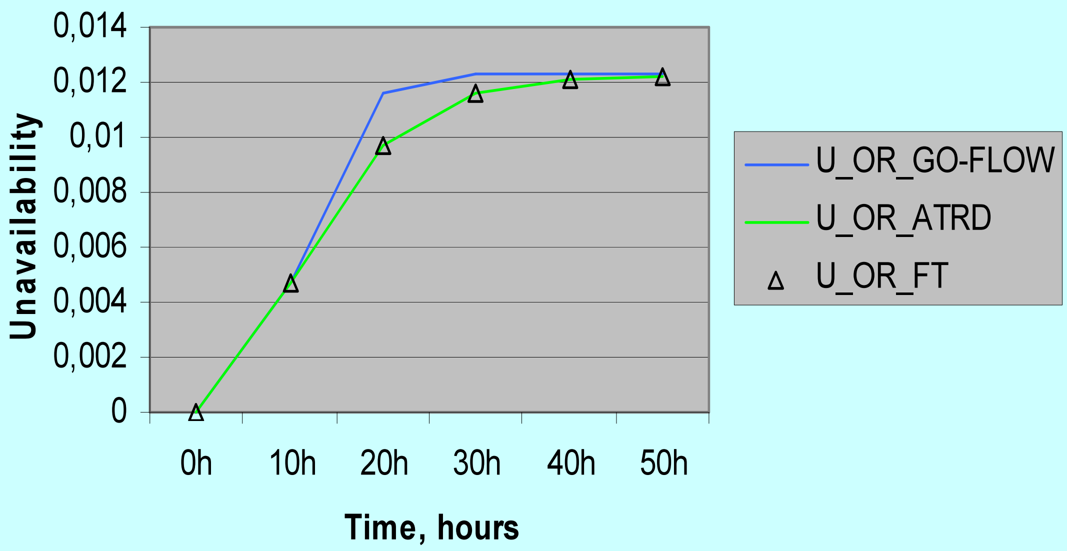


Precautionary insights

AND 3-component system and



OR 3-component system by 3 methods



Preliminary conclusions

- The addition of the time dimension leads unavoidably to a more complicated analysis.
- All methodologies are significantly more complex and have more extensive data requirements.
- The analyst needs to ensure that extra capabilities of the methodologies are indeed needed .
- The approaches allow an integrated treatment of aging process variables, hardware states and failure modes.

Intents of case study 'Age-dependent safety system reliability model'

- To investigate the feasibility of dynamic system reliability methods, GO-FLOW and ATRD, for:
  - increasing of failure, restore and repair rates of all component categories or
  - reducing the surveillance intervals of repairable components to take into account aging processes in plant availability.
- To prepare comparable FT, GO-FLOW, ATRD aging process component and system models (3-train RHRS of WWER-1000/V320);
- The case study comprises three categories of aging components:
  - *restorable replaceable* (FIG.1) – valves, pumps;
  - *non-restorable replaceable* (FIG. 2) – check valves and pipes;
  - *restorable hard-to-replace* (FIG.3) – tanks and heat exchangers.

Insights (1)

- The dynamic system reliability methods could be used to allocate the aging reliability data for basic events and aging failure mode and effect analysis.
- The aging processes description of safety systems differs from the processes of normal operation systems and must include aging in working and stand-by states at different intervals.
- The proposed decomposition of aging states seems appropriate.
- The failure mode database is concerned with component functions and rarely with physical component processes, including aging related processes.
- It means that only part of component failure modes should be suspected of aging.
- The quantification of age-related degradation effects must be sensitive to component's function.

Insights (2)

- The GO-FLOW and ATRD methods could be used for calculation and synchronization of the aging impact to the safety system component unavailabilities.
- They may extrapolate and predict the component unavailability curves up to stationary values, in different time intervals and to the end of plant lifetime.
- ATRD seems more appropriate for explicit obtaining of dynamic component unavailability functions and data preparation because the GO-FLOW results depend on calculation step and available operator type values.
- However, the GO-FLOW operators have been increasing.
- GO-FLOW could be especially useful for extrapolation of component/system unavailability curves in different time intervals.

Insights (3)

- All dynamic system reliability methods could be used to propose the optimal periodical test and preventive maintenance intervals for components based on determined options and criteria.
- A practicable approach seems to be the use of different individual aging process and component degradation and restoration factors.
- The shortening of surveillance intervals for renewable components, as an aging compensation measure, would be more explicitly modeled and treated in PSA if a restoration factor, similar to degradation factor, is introduced.

Continuation and extension of CS 'Age-dependent safety system reliability model'

- The case study will be continued and extended to:
  - assess system interactions based on degradation mechanisms an component aging behavior
  - identify the necessary FT modifications (additional gates, basic events, parameters and structure changes)
  - perform sensitivity study with the GO-FLOW and ATRD methods.
- Additionally, the impact of FT loop-free and Markov process' 'slow-fast' approximations is to be evaluated.
- A normal operation system aging case study should be conducted in parallel for better understanding how to incorporate aging effects into PSA applications.