Reliability-based prognostics applications

Marco Papini

marco.papini@unifi.it

PhD in Computer Engineering – Cycle XXXIII

Tutor: Prof. Alessandro Fantechi

Department of Information Engineering, University of Florence

Outline

- Definition of Reliability and Failure rate
- Common Reliability evaluation techniques
- Proposed methodology (layered approach)
- Reliability-Based Monitoring
- Future works

Reliability

- Reliability $R(t)$ is defined as "the ability of a system or component to perform its required functions under stated conditions for a specified period of time"[1]
  - Probability that the system has successfully performed its required functions in time interval $[t_0, t)$ given that it was correctly operating at time t_0[2]
- Reliability is a key attribute used to guarantee the correct operation of systems
  - Used during Availability evaluation of $24/7$ systems
  - Used during Safety Analysis of Safety-critical systems
  - **It can be used to compute the probability of failure in a given time interval, thus realizing a Condition-Based Monitoring (Prognostics) application**

[1] IEEE, "ISO/IEC/IEEE International Standard - Systems and software engineering - Vocabulary", 2010

[2] CENELEC, "EN 50126-1: Railway Applications - The Specification and Demonstration of Reliability, Availability, Maintainability and Safety (RAMS) - Part 1: Generic RAMS Process", Technical report, 2017

Reliability

- Reliability R is a function of:
  - Time t
  - Failure rate $r(t)$
- Several failure rate models exist

Reliability

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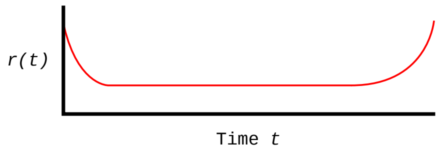

- Several failure rate models exist
- "Bath-tube failure rate model"
  - It is high and decreasing close to commissioning due to *infant mortality*
  - It is almost constant during the service
  - It is rapidly increasing close to end-of-life due to *ageing*

Reliability

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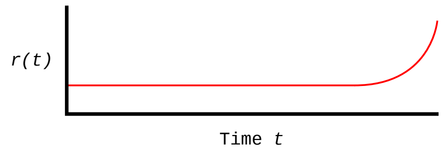
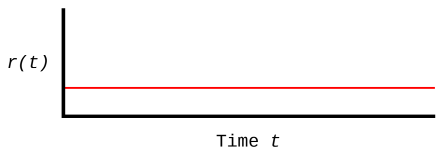


- Several failure rate models exist
- "Ageing failure rate model"
  - Several components suffer from ageing, e.g., Power-related components
  - Reliability modeled with Weibull distribution with $k > 1$

Reliability

- Reliability R is a function of:
  - Time t
  - Failure rate $r(t)$



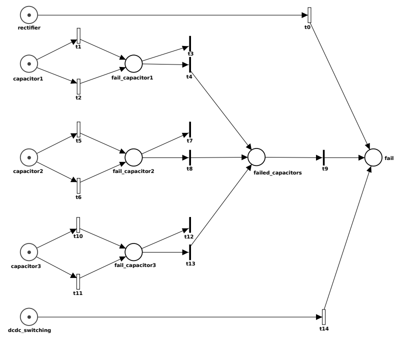
- Several failure rate models exist
- "Constant failure rate model"
  - $r(t) = \lambda = \frac{1}{MTTF}$
  - $R(t) = e^{-\lambda \cdot t}$
  - Widely used model due to the following facts:
    - Simple mathematics
    - Several standards (e.g., EN 61709) allow to estimate the MTTF through accelerated ageing

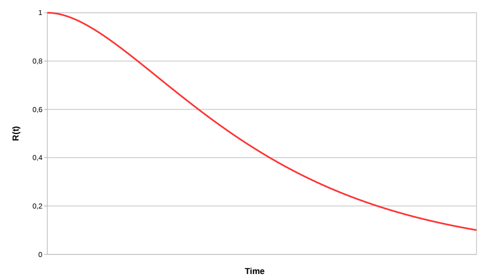
Reliability evaluation

- Several methods have been developed in order to evaluate the reliability
  - Failure Mode and Effects Analysis (FMEA)
  - Fault Tree Analysis (FTA)
  - Reliability Block Diagrams (RBD)
  - Stochastic Time Petri Nets (STPN)

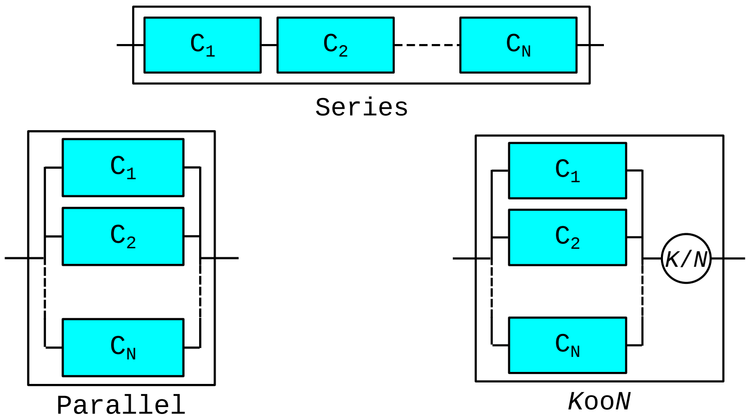
- STPNs are specialized oriented graphs
- Advantages:
  - Model a system of components
  - Model the Reliabilities of components
  - Model the dependency between the failure of a component and the failure rate of other components
- Drawback:
  - Complexity of analysis techniques increases with[3]
    - Number of enabled transitions
    - Number of enabled transitions with non-Markovian distribution
    - Length of paths without regenerations

[3] M. Malhotra, and K. S. Trivedi, "Power-Hierarchy of Dependability-Model Types", IEEE Transactions on Reliability, vol. 43(3), 1994





- RBDs are block diagrams
- Advantages:
  - Four basic blocks: Singleton, Series, Parallel and K-out-of-N (Koo$N$)
  - Simple mathematics and fast analysis
- Drawback:
  - Blocks are statistically independent



Mathematics for N equal components:

$$R_{series}(t) = R(t)^N$$

$$R_{parallel}(t) = 1 - (1 - R(t))^N$$

$$R_{KooN} = \sum_{i=K}^{N} \binom{N}{i} \cdot R(t)^i \cdot (1 - R(t))^{N-i}$$

Reliability Block Diagrams

Mathematics for N different components:

$$R_{series}(t) = \prod_{i=1}^{N} R_i(t)$$

$$R_{parallel}(t) = 1 - \prod_{i=1}^{N} (1 - R_i(t))$$

$$R_{KooN} = \sum_{i=K}^{N} \sum_{j=1}^{\binom{N}{i}} P_{path(N,i,j)}$$

$$P_{path(N,i,j)} = \prod_{l \in C(N,i,j)} R_l(t) \cdot \prod_{m \notin C(N,i,j)} (1 - R_m(t))$$

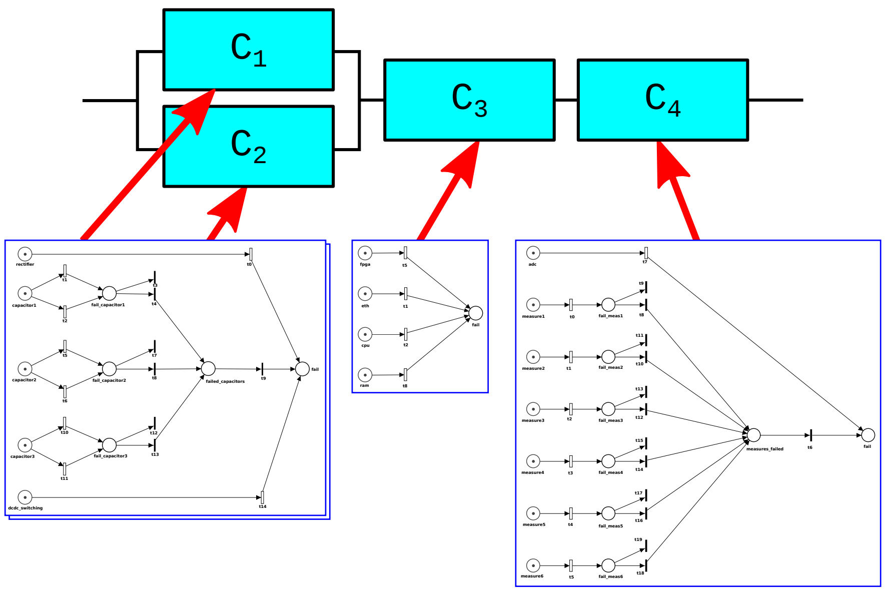
$$C(N,i,j) \stackrel{\text{def}}{=} j\text{-th combination of } i \text{ components out of } N$$

Proposed methodology[4]

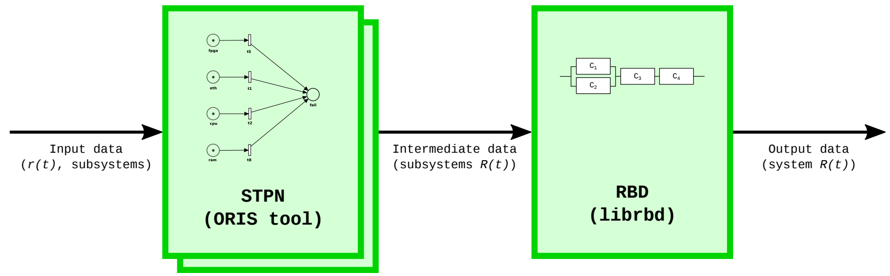
- Take advantage of both STPNs and RBDs
- Analyze the System and subdivide it into independent Subsystems
- Define System RBD using Subsystems as blocks
- For each Subsystem, perform the following operations:
  - Perform the Subsystem detailed analysis (i.e., assess the failure rate functions for each Component)
  - Model the Subsystem and perform its Reliability analysis using STPNs
- Apply RBD mathematics to Reliabilities of analyzed Subsystems and obtain System Reliability

[4] L. Carnevali, L. Ciani, A. Fantechi, M. Papini, "A novel layered approach to evaluate reliability of complex systems", In: RTSI2019

Proposed methodology

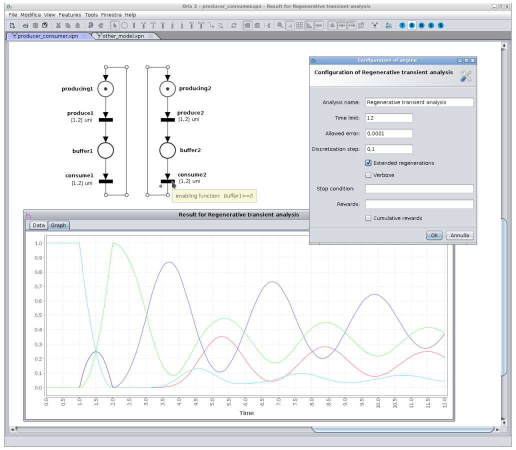


Proposed methodology



Remark: ORIS Tool (`http://oris-tool.org`)

- Graphical User Interface to model, simulate, and analyze Petri nets
- Non-deterministic analysis of Time Petri Nets (TPNs)
- Transient and steady-state analysis of Stochastic Time Petri Nets (STPNs)
- Interactive simulation (token game) of TPNs and STPNs
- Full Java implementation (cross-platform)



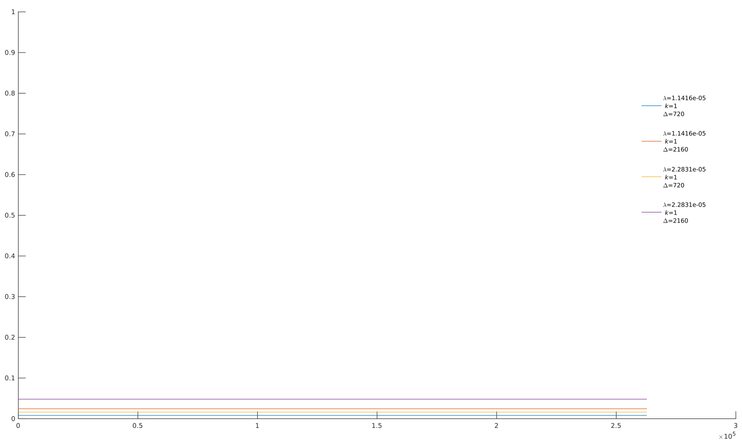
Remark: librbd

- Several RBD tools exist, with (at least one of) following limitations:
  - Commercial tools
  - Support for constant failure rate only
  - Support for equal components inside block only
- `librbd` is an RBD computation library (under development)
  - C/C++ library with multi-threading support
  - Numerical computation of Reliability of RBD basic blocks
  - Support for generic failure rate functions
  - Support for both equal and different components inside a block
  - Cross-platform (compatible with Windows, Linux and OS X)

Towards Reliability-Based Monitoring

- Particular case of Condition-Based Monitoring
- Compute probability of having a failure at time t_f in interval $[t, t+\Delta]$

$$P\{t_f \in [t, t+\Delta]\} = RBM(t,\Delta) = \frac{R(t) - R(t+\Delta)}{R(t)}$$



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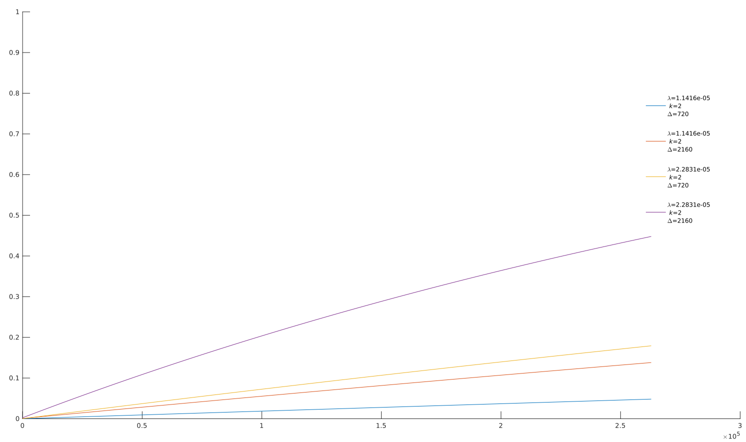

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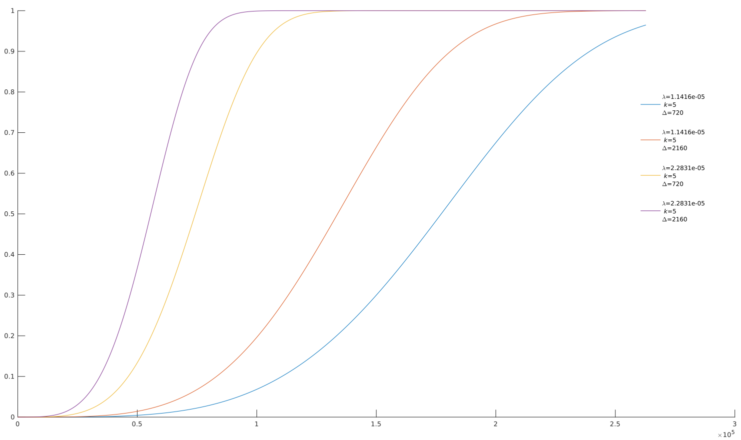

Towards Reliability-Based Monitoring (cont.)

- Establish a set of available diagnostics measures (currents, voltages, etc.)
- For each component, define a model for Reliability evaluation which takes into account available diagnostics data
- Periodically, perform the following operations
  - Acquire diagnostics measures from Industrial System
  - Feed diagnostics data into the models of each component and obtain refined Reliability parameters
  - Update the rates of all STPNs using the refined ones and repeat Sub-System Reliability evaluation using STPNs
  - Repeat System Reliability evaluation using RBDs in order to have refined System's Reliability
  - Evaluate $RBM(t', \Delta)$, where t' is the current time
  - If $RBM(t', \Delta)$ is above a given threshold, then a maintenance alarm is raised

Final remarks

- We propose a layered approach to evaluate Reliability
  - More precise Reliability analysis
  - Usage of ORIS tool for modeling/analysis of STPNs
  - Usage of `librbd` library for numerical evaluation of RBDs
- We propose the implementation of Reliability-Based Monitoring
  - Usage of layered approach for Reliability evaluation
  - Usage of function $RBM(t, \Delta)$ to estimate probability of failure
  - Usage of diagnostics data to fit failure rates
- **Future research**
  - Finalize development of `librbd`
  - Apply proposed methodology to a case study
  - Finalize methodology for Reliability-Based Monitoring

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UNIVERSITÀ DEGLI STUDI FIRENZE

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