A Markov Regenerative Model of Software Rejuvenation Beyond the Enabling Restriction

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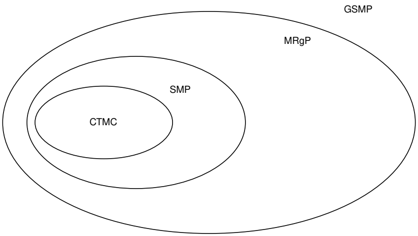
- this is about:
  - Stochastic models of software aging and rejuvenation
  - How class of the underlying stochastic process changes the expressivity
  - What are the consequences of expressivity change
  - Extension from MRgP under enabling restriction ...
  - ... by creating models in the class of MRgP under bounded regeneration

Sofware Aging & Rejuvenation Systems

- **Systems of interest** : long running hardware/software systems
- **Software Aging**: gradual shift from a robust state to degraded one
- **Rejuvenation**: restoration to the robust state through a **proactive maintenance**
  - **Advantage**: prevent failures
  - **Drawback**: implies a cost (downtime increment)
- **Rejuvenation Schedule**: plan when to perform the rejuvenation:
  - **Time-Triggered**: periodic rejuvenation
  - **Event-Based**: relying on diagnostic tests

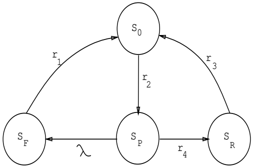
Software Aging & Rejuvenation Model

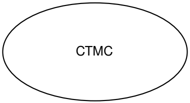
- Quantitative models analyse:
  - Effect of **aging** in the system
  - How **rejuvenation** impacts on the failure rate
  - Find the optimal rejuvenation **schedule** taking into account the **trade-off** between reliability and availability
- Differ in:
  - Available **model specification** approaches
  - Class of the underlying **stochastic process**



Continuous Time Markov Chain (CTMC)

- Expressivity:
  - **Markov condition**: always satisfied
  - **Sojourn Time**: only Exponential (memoryless) distributions
  - **Transition Selection**: time-independent random switch
  - Not good news for expressivity
- Specification:
  - Direct representation of the stochastic process
  - Higher level formalisms (SPN)

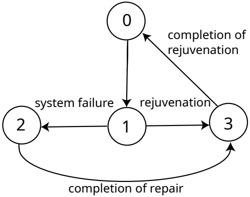


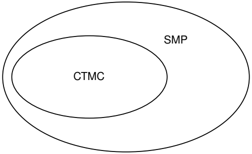


Model from: *Huang, Kintala, Kolettis, Fulton " Software rejuvenation: Analysis, module and applications", FTCS 1995*

Semi-Markov Processes (SMP)

- Expressivity:
  - **Markov Condition**: satisfied at the beginning of each sojourn time
  - **Sojourn Time**: GEN distributed durations
  - **Transition Selection**: based on a time-dependent random switch
  - Loses memory at each transition
- Specification:
  - Direct representation of the stochastic process

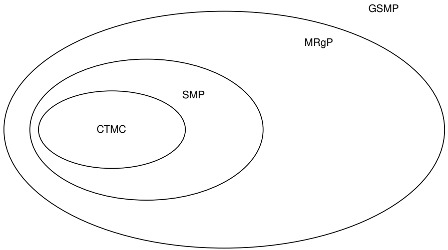




Model from: *Dohi, Goseva-Popstojanova, Trivedi "Statistical non-parametric algorithms to estimate the optimal software rejuvenation schedule", PRDC 2000*

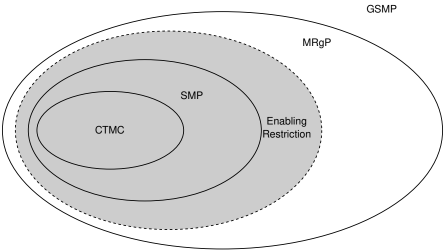
Markov Regenerative Processes (MRgP)

- Expressivity:
  - **Markov Condition**: eventually satisfied *w.p.1* at some point: the **regeneration**
  - **Sojourn Time**: GEN distributed durations
  - **Transition Selection**: based on the states and the time spent on them, since the last regeneration point
  - Represent activities overlapping their durations in epochs delimited by regenerations
- Specification:
  - Direct representation of the stochastic process
  - Usually expressed through higher level formalisms (SPN)



Modeling SAR Systems

- SAR systems literature deepens numerical approach with both **CTMC** and **SMP**
- Full-fledged MRgP models are **hard to analyse** numerically
- No general technique to built the process kernels
- **MRgP under enabling restriction**:
  - **Consolidated** numerical methods to analyse SAR
  - Basically, **at most one** GEN distribution fireable in any state

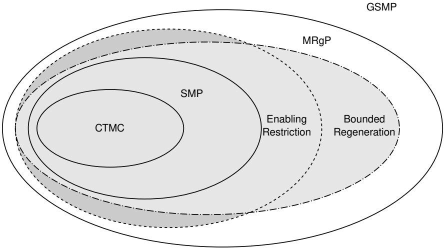


Consequences of the Enabling Restriction

- **Enabling Restriction:**
  - The single GEN distribution is usually (necessarily) spent for the **rejuvenation timer**
  - Distributions with finite coefficient of variation would result in **substantial approximation**
  - Remaining durations can be modeled **only as EXP**
- **Limits:**
  - **No concurrent GEN timers** can be represented
  - Durations can only fit the **first moment** from observational data

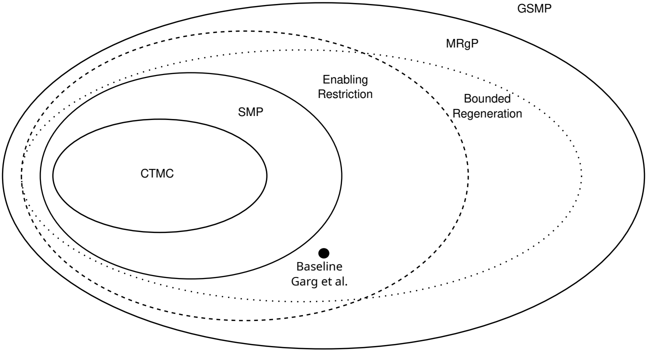
A Step Further, MRgPs Under Bounded Regeneration Restriction

- **Bounded Regeneration**:
  - Durations can be **DET** or **exponomial** distributions
  - **Bounded supports** distribution also allowed
  - **Constraint**: regeneration always reached within a **bounded** number of events
- **Stochastic State Classes**:
  - **Numerical solution** of model under bounded regeneration restriction
  - Implemented in the **Sirio Library** of the **Oris Tool**.[1]

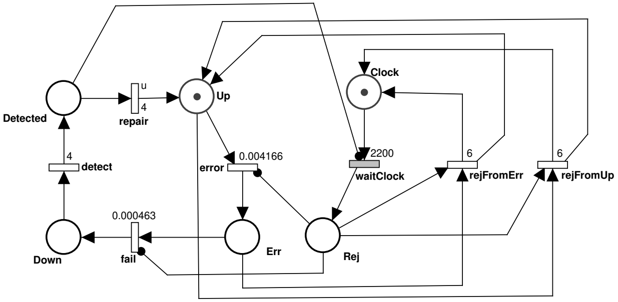


[1] *Paolieri, Biagi, Carnevali, Vicario, "The ORIS Tool: Quantitative Evaluation of Non-Markovian Systems" TSE 2021*

Starting Point



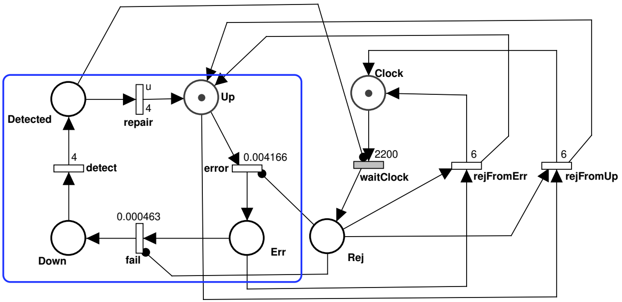
The SAR Model Baseline



- Based from the seminal model of *Garg et al.* [2]
- **Time-triggered** Rejuvenation with DET timer
- Tweaked to make it more complex
- All the duration except timer are EXP

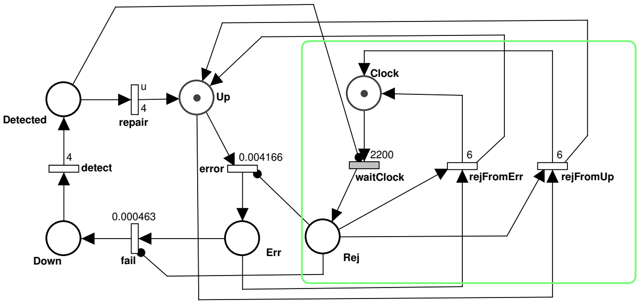
[2] *Garg, Puliafito, Telek, Trivedi "Analysis of software rejuvenation using Markov regenerative stochastic Petri net", ISSRE 1995*

The SAR Model Baseline - The System



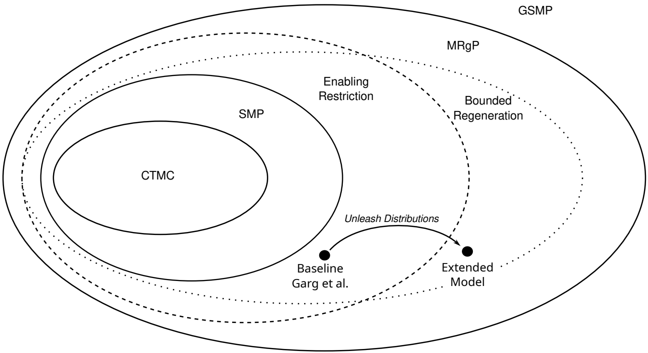
- System starts in **robust state** ("Up") and eventually goes in **error** ("Err" place)
- From erroneous state system may **fail** ("Down" place)
- Failure detection time is **not negligible** ("Down" and "Detected" places)

The SAR Model Baseline - The Rejuvenation Mechanism



- Rejuvenation mechanism **runs concurrently** with the actual system
- When triggered (“`Rej`” place), it **restores** the system in the `Up` place
- Possible in both “`Up`” and “`Err`” places

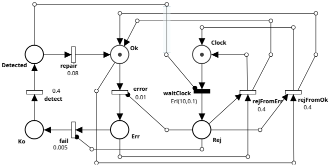
First of Two Steps Ahead, Unleashing Distributions

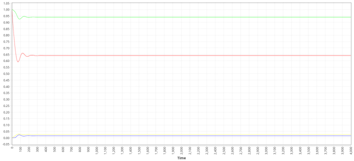


Effects of the Model Expressiveness on the Analysis Results

WaitClock
Erl(10,0.1)

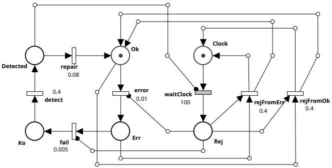
CTMC
(Erl as sequence of EXP)

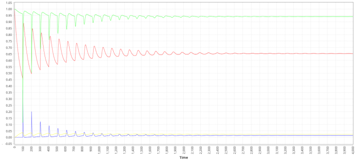




WaitClock
DET 100

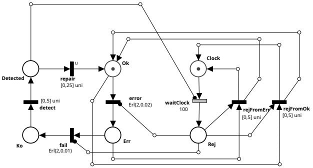
MRgP
Enabling
Restriction

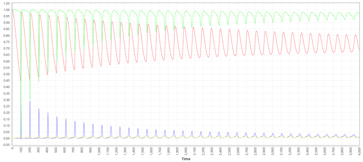




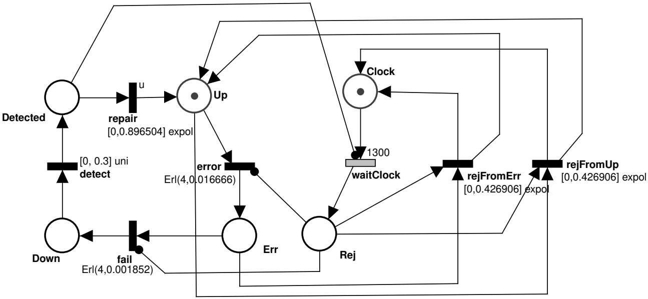
WaitClock
DET 100

MRgP
Bounded
Regeneration



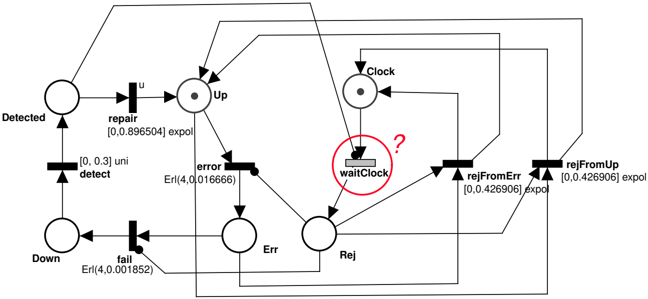


Extension Beyond Enabling Restriction



- The **same** structure of concurrence
- **GEN distributed** Durations
- Stochastic parameters maintain the **same expected values** of the baseline

The Optimal Rejuvenation Period



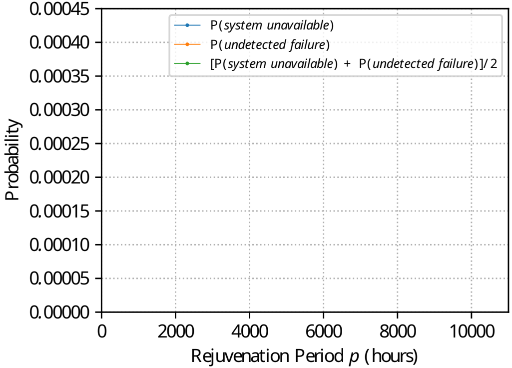
- **Aim**: Finding the best rejuvenation period
- A clock time aware of the reliability-availability **trade-off**
- The optimal value of the `Wait clock` transition

Finding the Optimal Rejuvenation Period

- **Steady-state** metrics are the core of the software aging analysis
- **Unavailability** $\bar{a}(p)$: quantifies the occurrence of states in which the system can not provide the service
- **Undetected failures** $\bar{r}(p)$: detect a reliability quality of the system
- **Optimal rejuvenation period** p^***:** selected minimizing:

$$p^* = \arg\min_p \left[\frac{\bar{a}(p) + \bar{r}(p)}{2} \right]$$

Optimal Rejuvenation with Bounded Regeneration



- $\bar{r}(p)$: increase with the rejuvenation period p
- $\bar{a}(p)$: initial decrease with subsequent increase
- p^*: 1300 hours with $\left[\frac{\bar{a}(p)+\bar{r}(p)}{2}\right] = 0.000091$

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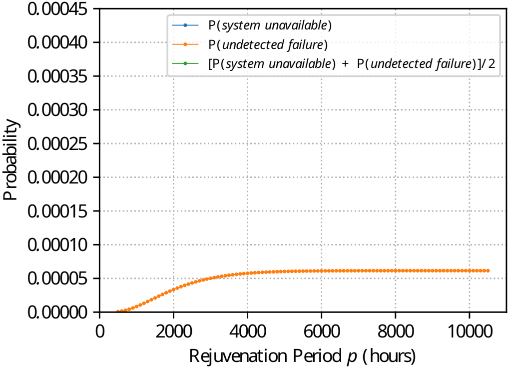

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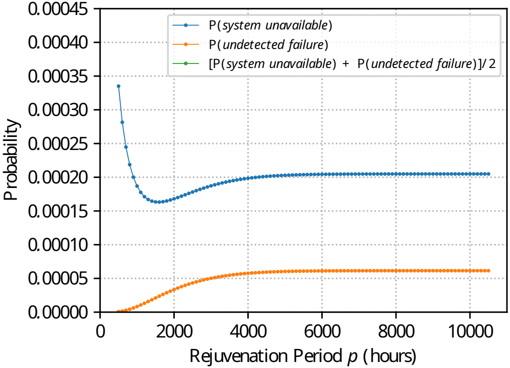

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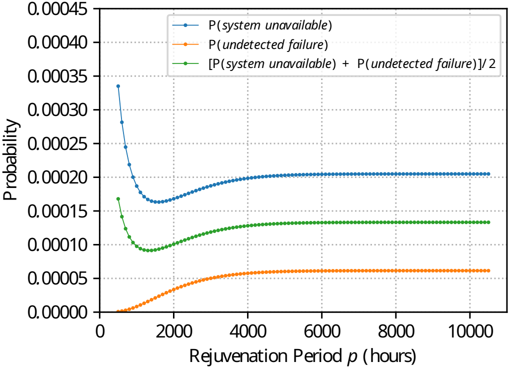

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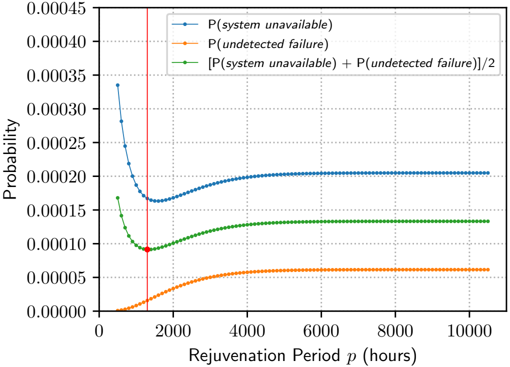

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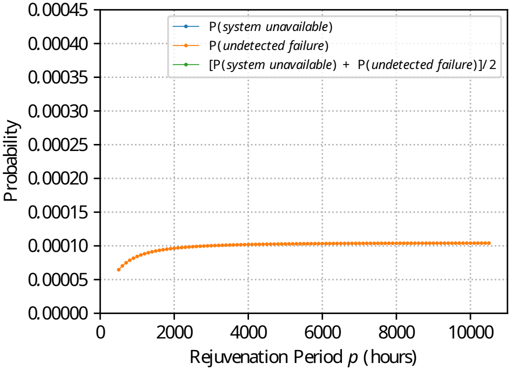
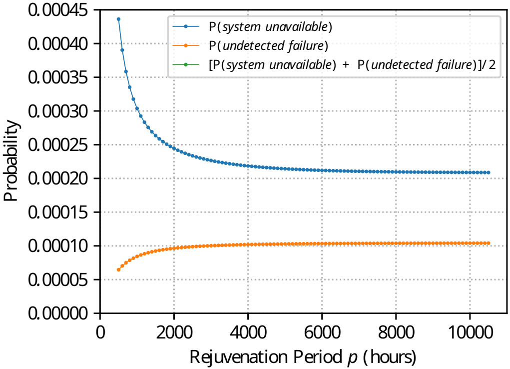
Optimal Rejuvenation with Enabling Restriction



- $\bar{r}(p)$: monotonic trend increasing
- $\bar{a}(p)$: monotonic trend decreasing
- p^*: cannot be assigned through the equation
- Selected p optimal as 2200 to anticipate the mean time of error detection (2300 hours)

Optimal Rejuvenation with Enabling Restriction



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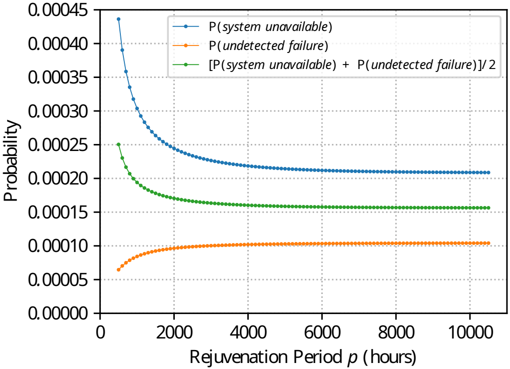

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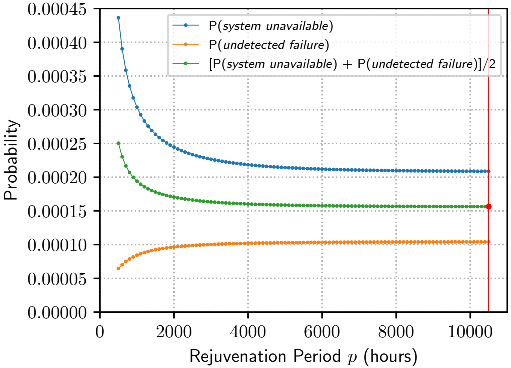

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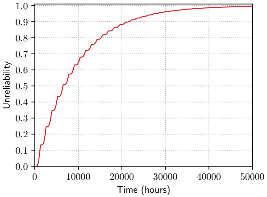
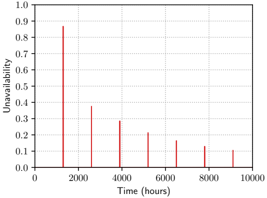
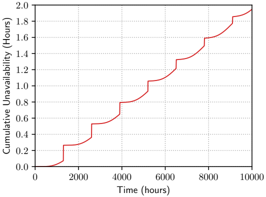
Transient Evaluation of the Bounded Regeneration Model

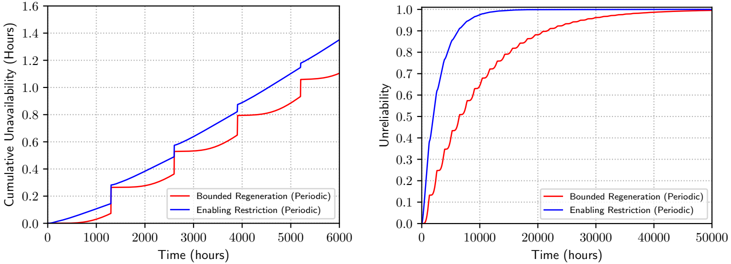






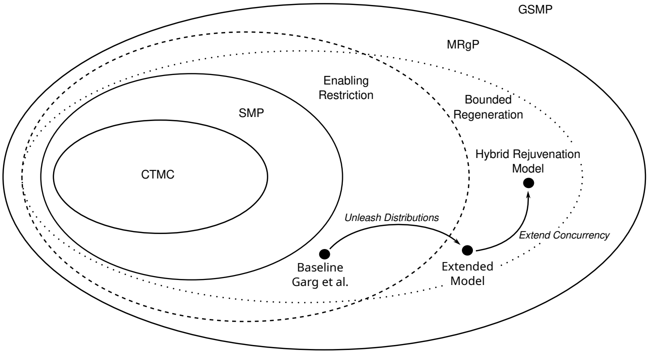
- **Unreliability** (left): converges to 1 after 50000 hours
- **Unavailability** (center): peaks around the multiples of p^* (1300 hours)
- **Cumulative unavailability** (right): sharp increase around the multiples of p^* (smoothed as time advances)

Transient Metrics Comparison



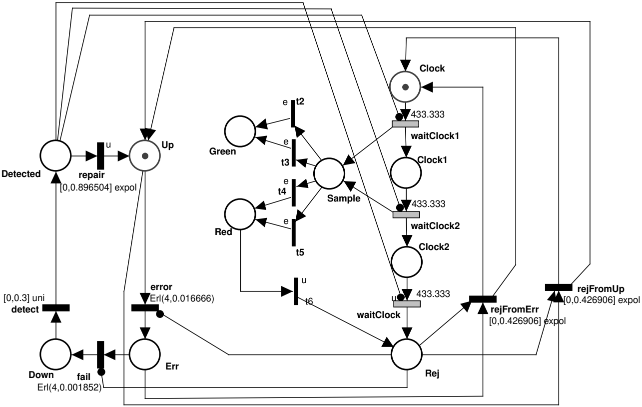
- **Unavailability**: bounded regeneration shows better performance
- **Unreliability**: enabling restriction make the model converge faster
- Type of distributions affect significantly the transient behavior

Bounded Regeneration: Beyond Parameters Fitting



- Using expressiveness gain **not only** to fit more precisely data
- Structure of concurrency modification to represent **hybrid rejuvenation policies**

Combining Event-Based and Time-Triggered Rejuvenation



- Structure of concurrency extended to include diagnostic process
- Same system behavior and rejuvenation effects
- Maximum rejuvenation period maintained to $p = 1300$
- Diagnostic tests executed during rejuvenation period

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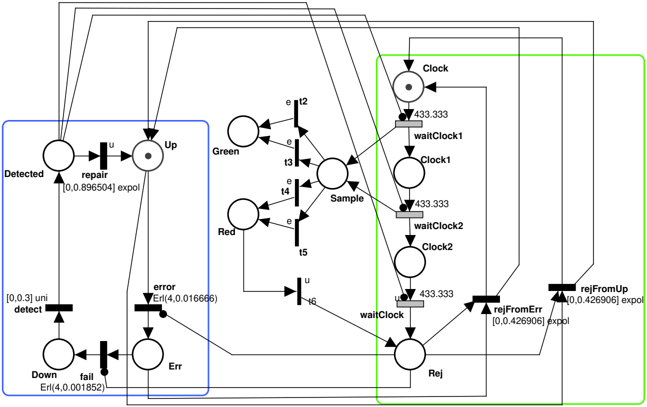

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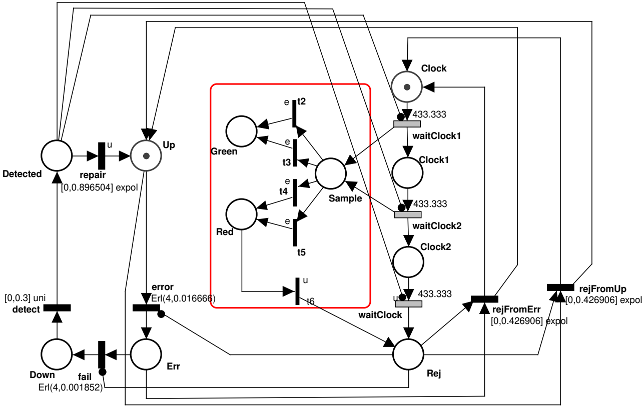
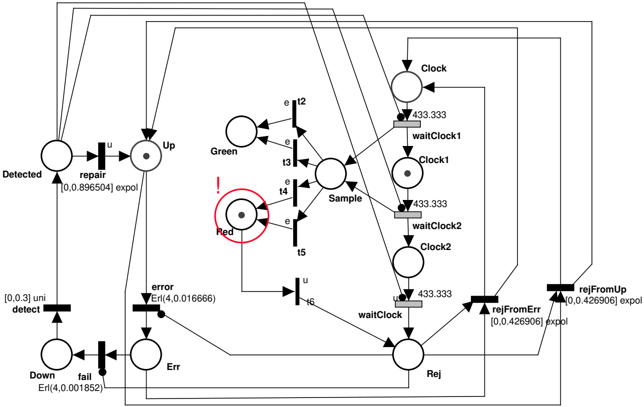


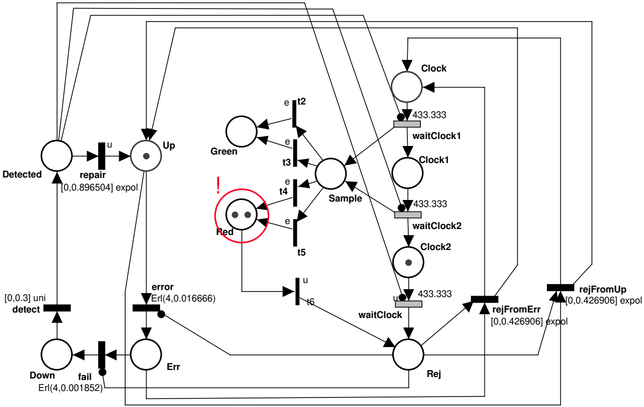
- **Diagnostics:** testing the system aging with a specific uncertainty level
- **Rejuvenation** can be **anticipated** if diagnosis indicates malfunctions
- Related to system **sensitivity** and **specificity**
- Sensitivity and specificity assumed equal to 0.9

Rejuvenation Policies Considered



- **1-Warning Rejuvenation**: rejuvenation triggered at the first warning
- **2-Warning Rejuvenation**: rejuvenation triggered after two warning in a row

Rejuvenation Policies Considered



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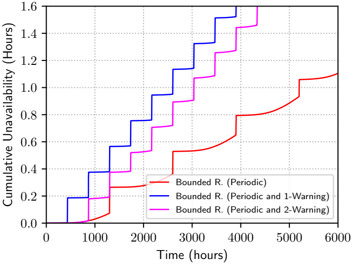
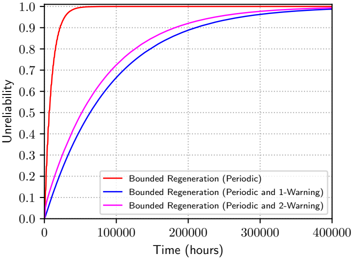
Steady State Metrics Comparison

	Rejuvenation Model (Bounded Regeneration)		
Metric	Periodic	1-Warning	2-Warning
P(*Undetected Failure*)	0.0000157	**0.0000017**	0.0000021
P(*System Unavailable*)	**0.0001670**	0.0003324	0.0003255

- **Unreliability**:
  - **1-warning**: reduced by an order of magnitude
  - **2-warning**: mitigated effects
- **Unavailability**:
  - **Hybrid rejuvenation**: less available
  - **Minor difference** between hybrid policies
- Trade-off Coherent

Transient Metrics Comparison





- **Cumulative Unavailability** (Left):
  - Better performance for periodic rejuvenation
  - Tangible differences even between 1-warning and 2-warning policies
- **Unreliability** (Right):
  - At $t = 5000$ periodic rejuvenation model is unreliable *wp1*
  - At $t = 5000$ hybrid rejuvenation models are unreliable with probability less than 0.5

Discussion and Future Directions

- **Aim of the Work:** Demonstrating that processes in the class of MRgP under bounded regeneration restriction provide an expressivity gain
- **Ongoing Direction:**
  - Automated efficient evaluation of optimal time parameters for the hybrid model with multiple waiting periods
- **Future Direction:**
  - Applications in the context of software defined networks.