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| Abstract | Since their introduction, properties of Phase Type (PH) distributions have been analyzed and many interesting theoretical results found. Thanks to these results, PH distributions have been profitably used in many modeling contexts where non-exponentially distributed behavior is present. Matrix Exponential (ME) distributions are distributions whose matrix representation is structurally similar to that of PH distributions but represent a larger class. For this reason, ME distributions can be usefully employed in modeling contexts in place of PH distributions using the same computational techniques and similar algorithms, giving rise to new opportunities the fact, they are able to represent different dynamics, e.g., faster dynamics, or the same dynamics but at lower computational cost. In this work, we deal with the |

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Phase Type and Matrix Exponential Distributions in Stochastic Modeling

Andras Horvath, Marco Scarpa and Miklos Telek

Abstract Since their introduction, properties of Phase Type (PH) distributions have been analyzed and many interesting theoretical results found. Thanks to these results, PH distributions have been profitably used in many modeling contexts where non-exponentially distributed behavior is present. Matrix Exponential (ME) distributions are distributions whose matrix representation is structurally similar to that of PH distributions but represent a larger class. For this reason, ME distributions can be usefully employed in modeling contexts in place of PH distributions using the same computational techniques and similar algorithms, giving rise to new opportunities the fact, they are able to represent different dynamics, e.g., faster dynamics, or the same dynamics but at lower computational cost. In this work, we deal with the characteristics of PH and ME distributions, and their use in stochastic analysis of complex systems. Moreover, the techniques used in the analysis to take advantage of them are revised.

1 Introduction

Stochastic modeling has been used for performance analysis and optimization of computer systems for more than five decades [19]. The main analysis method behind this effort was the continuous time Markov chains (CTMC) description of the sys-

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18 tem behavior and the CTMC-based analysis of the performance measures of inter-
19 est. With the evolution of computing devices, model description languages (e.g.,
20 queueing systems, Petri nets, process algebras), and model analysis techniques (a
21 wide range of software tools with efficient analysis algorithm using adequate data
22 representation and memory management) the analysis of more and more complex
23 systems has become possible. One of main modeling limitations of the CTMC-based
24 approach is the limitation on the distribution of the random time durations, which
25 is restricted to be exponentially distributed. Unfortunately, in a wide range of prac-
26 tical applications, the empirical distribution of field data differs significantly from
27 the exponential distribution. The effort to relax this restriction of the CTMC-based
28 modeling on exponentially distributed durations resulted in the development of many
29 alternative stochastic modeling methodologies (semi-Markov and Markov regener-
30 ative processes [11], analysis with the use of continuous system parameters [8]), yet
31 all of the alternative modeling methodologies suffer from infeasible computational
32 complexity very quickly when the complexity of the systems considered increases
33 beyond basic examples.

34   It remains a significant research challenge to relax the modeling restriction of the
35 exponentially distributed duration time and still evaluate complex model behaviors.
36 To this end, one of the most promising approaches is the extension of CTMC-based
37 analysis to non-exponentially distributed durations. Initial steps in this direction date
38 back to the activity of A.K. Erlang in the first decades of the twentieth century as
39 reported in [10]. These initial trials were referred to as the method of phases, which
40 influenced later terminology. M.F. Neuts characterized a set of distributions which
41 can be incorporated into CTMC-based analysis by introducing the set of phase type
42 (PH) distributions [16].

43   The extension of CTMC-based analysis (where the durations are exponentially
44 distributed) with PH distributed durations requires the generation of a large CTMC,
45 referred to as extended Markov chain (EMC), which combines the system behavior
46 with the description of the PH distributions. In this chapter, we summarize the basics
47 of EMC-based stochastic analysis and provide some application examples. Finally,
48 we note that in this work we restrict our attention to continuous time stochastic
49 models, but that the same approach applies for discrete time stochastic models as
50 well.

1.1 Structure of the Chapter

52 The next two sections, Sects. 2 and 3, summarize the basic information on PH and
53 ME distributions, respectively. The following two sections, Sects. 4 and 5, discuss the
54 analysis procedure for complex stochastic systems with PH and ME distributed dura-
55 tions, respectively. The tools available to support EMC-based analysis of stochastic
56 systems is presented in Sect. 6. Numerical examples demonstrate the modeling and
57 analysis capabilities of the approach are discussed in Sect. 7 and the main findings
58 and conclusions are given in Sect. 8.

2 PH Distributions and Their Basic Properties

2.1 Assumed Knowledge

Transient behavior of a finite state Markov chain with generator $\mathbf{Q}$ and initial distribution π, specifically, the transient probability vector $p(t)$, satisfies the ordinary differential equation

$$\frac{\mathrm{d}}{\mathrm{d}t} p(t) = p(t)\mathbf{Q}, \text{ with initial condition } p(0) = \pi,$$

whose solution is a matrix exponential function

$$p(t) = \pi \mathrm{e}^{\mathbf{Q}t}, \tag{1}$$

where the matrix exponential term is defined as

$$\mathrm{e}^{\mathbf{Q}t} = \sum_{i=0}^{\infty} \frac{t^i}{i!} \mathbf{Q}^i.$$

The properties of generator $\mathbf{Q}$ and initial distribution π are as follows. The elements of π are probabilities, i.e., nonnegative numbers not greater than one. The off-diagonal elements of $\mathbf{Q}$ are transition intensities, i.e., nonnegative numbers. The diagonal elements of $\mathbf{Q}$ are such that each row sum is zero, i.e., the diagonal elements are non-positive. The elements of π sum to one, that is $\sum_i \pi_i = \pi \mathbf{1} = 1$. Each row of a generator matrix sums to zero, that is $\sum_j Q_{ij} = 0$, or equivalently, in vector form, we can write $\mathbf{Q1} = \mathbf{0}$, where $\mathbf{1}$ is a column vector of ones and $\mathbf{0}$ is a column vector of zeros. Hereafter, the sizes of vector $\mathbf{1}$ and $\mathbf{0}$ are defined by the context such that the dimensions in the vector expressions are compatible.

The stationary distribution of an irreducible finite state Markov chain with generator $\mathbf{Q}$, $p \triangleq \lim_{t \to \infty} p(t)$, can be computed as the unique solution of the linear system of equations

$$p\mathbf{Q} = \mathbf{0}, \quad p\mathbf{1} = 1. \tag{2}$$

In this chapter, we focus on the computation of the initial distribution and the generator matrix of the EMC and do not discuss the efficient solution methods for solving (1) and (2).

2.2 Phase Type Distributions

PH distributions are defined by the behavior of a Markov chain, which is often referred to as the background Markov chain behind a PH.

Let $X(t)$ be a Markov chain with n transient and one absorbing states, meaning that the absorbing state is reachable (by a series of state transitions) from all transient states, but when the Markov chain moves to the absorbing state it remains there forever. Let π be the initial distribution of the Markov chain, that is $\pi_i = P(X(0) = i)$. Without loss of generality, we number the states of the Markov chain such that state $1, \ldots, n$ are transient states and state $n + 1$ is the absorbing state. The generator matrix of such a Markov chain has the following structure

$$\mathbf{Q} = \begin{bmatrix} A & a \\ \mathbf{0} & 0 \end{bmatrix},$$

where A is a square matrix of size n and a is a column vector of size n. Since the rows of the generator matrix sum to zero, the elements of a can be computed from A, that is $a = -A\mathbf{1}$. Similarly, the first n elements of the initial vector π, denoted by α, completely defines the initial vector, since the $(n + 1)$st element of π is $1 - \alpha\mathbf{1}$. We note that α defines the initial probabilities of the transient states. With the help of this Markov chain, we are ready to define PH distributions.

Definition 1 The time to reach the absorbing state of a Markov chain with a finite number of transient and an absorbing state

$$T = \min\{t : X(t) = n + 1, t \geq 0\},$$

is phase type distributed.

Throughout this document, we assume that the Markov chain starts from one of the transient states and consequently $\alpha\mathbf{1} = 1$, i.e., there is no probability mass at zero and T has a continuous distribution on $\mathbb{R}^+$. Since the time to reach the absorbing state is a transient measure of the Markov chain, we can evaluate the distribution of random variable T, based on the transient analysis of the Markov chain with initial distribution π and and generator matrix $\mathbf{Q}$

$$F_T(t) = P(T < t) = P(X(t) = n + 1) = \pi e^{\mathbf{Q}t} e_{n+1},$$

where e_{n+1} is the $(n + 1)$st unit vector (the column vector with zero elements except in position $n + 1$ which is one).

This straight forward description of the distribution of T is not widely used due to the redundancy of matrix $\mathbf{Q}$ and vector π. Indeed, matrix A and the initial vector associated with the transient states, α, define all information about the distribution of T and the analytical description based on α and A is much simpler to use in more complex stochastic models. To obtain the distribution based on α and A, we carry on the block structure of matrix $\mathbf{Q}$ in the computation.

121 $$F_T(t) = P(T < t) = P(X(t) = n + 1) = 1 - \sum_{i=1}^{n} P(X(t) = n + 1)$$

122 $$= 1 - [\boldsymbol{\alpha}, 0] e^{\mathbf{Q}t} \begin{bmatrix} \mathbf{1} \\ 0 \end{bmatrix} = 1 - [\boldsymbol{\alpha}, 0] \sum_{i=0}^{\infty} \frac{t^i}{i!} \begin{bmatrix} \boldsymbol{A} & \boldsymbol{a} \\ \mathbf{0} & 0 \end{bmatrix}^i \begin{bmatrix} \mathbf{1} \\ 0 \end{bmatrix}$$

123 $$= 1 - [\boldsymbol{\alpha}, 0] \sum_{i=0}^{\infty} \frac{t^i}{i!} \begin{bmatrix} \boldsymbol{A}^i & \bullet \\ \mathbf{0} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{1} \\ 0 \end{bmatrix} = 1 - \boldsymbol{\alpha} \sum_{i=0}^{\infty} \frac{t^i}{i!} \boldsymbol{A}^i \mathbf{1} = 1 - \boldsymbol{\alpha} e^{\boldsymbol{A}t} \mathbf{1},$$

124

125 where $\bullet$ indicates irrelevant matrix block whose elements are multiplied by zero.
126 The PDF of T can be obtained from the derivative of its CDF.

127 $$f_T(t) = \frac{\mathrm{d}}{\mathrm{d}t} F_T(t) = \frac{\mathrm{d}}{\mathrm{d}t} \left(1 - \boldsymbol{\alpha} \sum_{i=0}^{\infty} \frac{t^i}{i!} \boldsymbol{A}^i \mathbf{1} \right) = -\boldsymbol{\alpha} \sum_{i=0}^{\infty} \frac{\mathrm{d}}{\mathrm{d}t} \frac{t^i}{i!} \boldsymbol{A}^i \mathbf{1}$$

128 $$= -\boldsymbol{\alpha} \sum_{i=1}^{\infty} \frac{t^{i-1}}{(i-1)!} \boldsymbol{A}^{i-1} \boldsymbol{A} \mathbf{1} = -\boldsymbol{\alpha} e^{\boldsymbol{A}t} \boldsymbol{A} \mathbf{1} = \boldsymbol{\alpha} e^{\boldsymbol{A}t} \boldsymbol{a},$$

129

130 where we used $\boldsymbol{a} = -\boldsymbol{A}\mathbf{1}$ in the last step.
131 Before computing the remaining properties of PH distributions we need to classify
132 the eigenvalues of $\boldsymbol{A}$. The i, j element of matrix $e^{\boldsymbol{A}t}$ contains the probability that
133 starting from transient state i the Markov chain is in transient state j at time t. If
134 states $1, \ldots, n$ are transient states then as t tends to infinity $e^{\boldsymbol{A}t}$ tends to zero, which
135 means that the eigenvalues of $\boldsymbol{A}$ have negative real part and, as a consequence, $\boldsymbol{A}$ is
136 non-singular.
137 The Laplace transform of T, $E(e^{-sT})$, can be computed as

138 $$f_T^*(s) = E(e^{-sT}) = \int_{t=0}^{\infty} e^{-st} f_T(t) \, \mathrm{d}t = \int_{t=0}^{\infty} e^{-st} \boldsymbol{\alpha} e^{\boldsymbol{A}t} \boldsymbol{a} \, \mathrm{d}t$$

139 $$= \boldsymbol{\alpha} \int_{t=0}^{\infty} e^{(-s\mathbf{I}+\boldsymbol{A})t} \, \mathrm{d}t \boldsymbol{a} = \boldsymbol{\alpha}(s\mathbf{I} - \boldsymbol{A})^{-1} \boldsymbol{a},$$

140

141 where we note that the integral surely converges for $\mathcal{R}(s) \geq 0$ because in this case
142 the eigenvalues of $-s\mathbf{I} + \boldsymbol{A}$ also possess a negative real part.
143 To compute the kth moment of T, $E(T^k)$, we need the following integral relation

144 $$\left[t^k e^{\boldsymbol{A}t} \right]_0^{\infty} = \int_{t=0}^{\infty} k t^{k-1} e^{\boldsymbol{A}t} \, \mathrm{d}t + \int_{t=0}^{\infty} t^k e^{\boldsymbol{A}t} \boldsymbol{A} \, \mathrm{d}t,$$

145

146 whose left-hand side is zero because the eigenvalues of $\boldsymbol{A}$ possess a negative real
147 part. Multiplying both side with $(-\boldsymbol{A})^{-1}$ we get

$$\int\limits_{t=0}^{\infty} t^k \mathrm{e}^{At} \mathrm{d}t = k \int\limits_{t=0}^{\infty} t^{k-1} \mathrm{e}^{At} \mathrm{d}t (-A)^{-1}.$$

Using this relation, the kth moment of T is

$$E\left(T^k\right) = \int\limits_{t=0}^{\infty} t^k f_T(t) \mathrm{d}t = \alpha \int\limits_{t=0}^{\infty} t^k \mathrm{e}^{At} \mathrm{d}t (-A) \mathbf{1} = k\alpha \int\limits_{t=0}^{\infty} t^{k-1} \mathrm{e}^{At} \mathrm{d}t \mathbf{1}$$

$$= k(k-1)\alpha \int\limits_{t=0}^{\infty} t^{k-2} \mathrm{e}^{At} \mathrm{d}t (-A)^{-1} \mathbf{1} = \cdots = k!\alpha(-A)^{-k}\mathbf{1}.$$

These four properties of PH distributions (CDF, PDF, Laplace transform, and moments) have several interesting consequences and some of which we summarize below.

- Matrix $(-A)^{-1}$ has an important stochastic meaning. Let T_{ij} be the time spent in transient state j before moving to the absorbing state when the Markov chain starts from state i. For $E\left(T_{ij}\right)$, we have

$$E\left(T_{ij}\right) = \frac{\delta_{ij}}{-A_{ii}} + \sum_{k, k \neq i} \frac{A_{ik}}{-A_{ii}} E\left(T_{kj}\right),$$

where δ_{ij} is the Kronecker delta symbol. The first term of the left-hand side is the time spent in state j while the Markov chain is in the initial state, and the second term is the time spent in state j during later visits to j. Multiplying both sides by $-A_{ii}$ and adding $E\left(T_{ij}\right) A_{ii}$ gives

$$0 = \delta_{ij} + \sum_{k} A_{ik} E\left(T_{kj}\right),$$

whose matrix form is

$$\mathbf{0} = \mathbf{I} + A\overline{\mathbf{T}} \quad \longrightarrow \quad \overline{\mathbf{T}} = (-A)^{-1},$$

where $\overline{\mathbf{T}}$ is the matrix composed of the elements $E\left(T_{ij}\right)$. Consequently, the (ij) element of $(-A)^{-1}$ is $E\left(T_{ij}\right)$, which is a nonnegative number.
- $f_T^*(s)$ is a rational function of s whose numerator is at most order $n-1$ and denominator is at most order n. This is because

$$f_T^*(s) = \alpha(s\mathbf{I} - A)^{-1}\boldsymbol{a} = \sum_{i} \sum_{j} \alpha_i (s\mathbf{I} - A)_{ij}^{-1}\boldsymbol{a}_j$$

$$= \sum_{i} \sum_{j} \alpha_i \left[\frac{\det_{ji}(s\mathbf{I} - A)}{\det(s\mathbf{I} - A)}\right]\boldsymbol{a}_j = \frac{\sum_{i} \sum_{j} \alpha_i \boldsymbol{a}_j \det_{ji}(s\mathbf{I} - A)}{\det(s\mathbf{I} - A)}.$$

175 $\det_{ji}(\mathbf{M})$ denotes the determinant of the matrix obtained by removing row j and
176 column i of matrix $\mathbf{M}$. The denominator of the last expression is an order n
177 polynomial of s, while the numerator is the sum of order $n-1$ polynomials,
178 which is at most an order $n-1$ polynomial of s.

179 • This rational Laplace transform representation indicates that a PH distribution
180 with n transient state can be represented by $2n-1$ independent parameters. A
181 polynomial of order n is defined by $n+1$ coefficients, and a rational function of
182 order $n-1$ numerator, and order n denominator is defined by $2n+1$ parameters.
183 Normalizing the denominator such that the coefficient of s^n is 1 and considering
184 that $\int_t f_T(t)\mathrm{d}t = \lim_{s\to 0} f_T^*(s) = 1$ adds two constraints for the coefficients, from
185 which the number of independent parameters is $2n-1$.

186 • The PDF of a PH distribution is the sum of exponential functions. Let $A = \mathbf{B}^{-1}\Lambda\mathbf{B}$
187 be the Jordan decomposition[1] of A and let $u = \alpha\mathbf{B}^{-1}$ and $v = \mathbf{B}a$. Then,

$$f_T(t) = \alpha e^{At}a = \alpha\mathbf{B}^{-1}e^{\Lambda t}\mathbf{B}a = ue^{\Lambda t}v.$$

190 At this point, we distinguish two cases.

191 – The eigenvalues of A are different and Λ is a diagonal matrix. In this case, $f_T(t)$
192 is a sum of exponential functions because

$$f_T(t) = ue^{\Lambda t}v = \sum_i u_i v_i e^{\lambda_i t} = \sum_i c_i e^{\lambda_i t},$$

195 where $c_i = u_i v_i$ is a constant coefficient of the exponential function.
196 Here the eigenvalues (λ_i) as well as the associated coefficients (c_i) can be real
197 or complex conjugate pairs. For a complex conjugate pair of eigenvalues, we
198 have

$$c_i e^{\lambda_i t} + \bar{c}_i e^{\bar{\lambda}_i t} = 2|c_i|e^{\mathcal{R}(\lambda_i)t}\cos(\mathcal{I}(\lambda_i)t - \varphi_i),$$

200 where $c_i = |c_i|e^{\imath\varphi_i}$, $\mathcal{R}(\lambda_i)$ and $\mathcal{I}(\lambda_i)$ are the real and the imaginary part of λ_i
201 and $\imath$ is the imaginary unit.

202 – There are eigenvalues of A with higher multiplicity and Λ contains real Jordan
203 blocks. The matrix exponent of a Jordan block is

$$\exp\left[\begin{pmatrix} \lambda & 1 & & \\ & \lambda & 1 & \\ & & \ddots & \ddots \\ & & & \lambda \end{pmatrix}t\right] = \begin{pmatrix} e^{\lambda t} & te^{\lambda t} & \frac{1}{2!}t^2 e^{\lambda t} & \frac{1}{3!}t^3 e^{\lambda t} \\ & e^{\lambda t} & te^{\lambda t} & \frac{1}{2!}t^2 e^{\lambda t} \\ & & \ddots & \ddots \\ & & & e^{\lambda t} \end{pmatrix}.$$

---

[1]The case of different Jordan blocks with identical eigenvalue is not considered here, because it cannot occur in non-redundant PH representations.

Consequently, the density function takes the form

$$f_T(t) = \sum_{i=1}^{\#\lambda} \sum_{j=1}^{\#\lambda_i} c_{ij} t^{j-1} e^{\lambda_i t},$$

where $\#\lambda$ is the number of different eigenvalues and $\#\lambda_i$ is the multiplicity of λ_i. Similar to the previous case, the eigenvalues (λ_i) as well as the associated coefficients ($c_{i,j}$) can be real or complex conjugate pairs. For a complex conjugate pair of eigenvalues, we have

$$c_{i,j} t^{j-1} e^{\lambda_i t} + \bar{c}_{i,j} t^{j-1} e^{\bar{\lambda}_i t} = 2|c_{i,j}| t^{j-1} e^{\mathcal{R}(\lambda_i)t} \cos(\mathcal{I}(\lambda_i)t - \varphi_{i,j}),$$

where $c_{i,j} = |c_{i,j}| e^{\imath \varphi_{i,j}}$.

As a result of all of these cases, the density function of a PH distribution possesses the form

$$f_T(t) = \sum_{i=1}^{\#\lambda_R} \sum_{j=1}^{\#\lambda_i^R} c_{ij} t^{j-1} e^{\lambda_i^R t} + \sum_{i=1}^{\#\lambda_C} \sum_{j=1}^{\#\lambda_i^C} 2|c_{i,j}| t^{j-1} e^{\mathcal{R}(\lambda_i^C)t} \cos(\mathcal{I}(\lambda_i^C)t - \varphi_{i,j})$$

$$(3)$$

where $\#\lambda_R$ is the number of different real eigenvalues and $\#\lambda_C$ is the number of different complex conjugate eigenvalue pairs.

• In general, infinitely many Markov chains can represent the same PH distribution.

– The following *similarity transformation* generates representations with identical size.
 Let $\mathbf{T}$ be a non-singular matrix with unit row sums ($\mathbf{T1} = \mathbf{1}$). The vector–matrix pairs ($\boldsymbol{\alpha}$, A) and ($\boldsymbol{\alpha}\mathbf{T}$, $\mathbf{T}^{-1}A\mathbf{T}$) are two different vector–matrix representations of the same PH distribution, since

$$F_T(t) = 1 - \boldsymbol{\alpha}\mathbf{T} e^{\mathbf{T}^{-1}A\mathbf{T}t} \mathbf{1} = 1 - \boldsymbol{\alpha}\mathbf{T}\mathbf{T}^{-1} e^{At} \mathbf{T1} = 1 - \boldsymbol{\alpha} e^{At} \mathbf{1}.$$

– Representations with different sizes can be obtained as follows.
 Let matrix $\mathbf{V}$ of size $m \times n$ be such that $\mathbf{V1} = \mathbf{1}$.
 The vector–matrix pairs ($\boldsymbol{\alpha}$, A) of size n and ($\boldsymbol{\gamma}$, $\mathbf{G}$) of size m are two different vector–matrix representations of the same PH distribution if $A\mathbf{V} = \mathbf{V}\mathbf{G}$ and $\boldsymbol{\alpha}\mathbf{V} = \boldsymbol{\gamma}$ because

$$F_T(t) = 1 - \boldsymbol{\gamma} e^{\mathbf{G}t} \mathbf{1} = 1 - \boldsymbol{\alpha}\mathbf{V} e^{\mathbf{G}t} \mathbf{1} = 1 - \boldsymbol{\alpha} e^{At} \mathbf{V1} = 1 - \boldsymbol{\alpha} e^{At} \mathbf{1}$$

in this case.

3 Matrix Exponential Distributions and Their Basic Properties

In the definition of PH distributions, vector $\boldsymbol{\alpha}$ is a probability vector with nonnegative elements and matrix $\boldsymbol{A}$ is a generator matrix with negative diagonal and nonnegative off-diagonal elements. Relaxing these sign constraints for the vector and matrix elements and maintaining the matrix exponential distribution (and density) function results in the set of matrix exponential (ME) distributions.

Definition 2 Random variable T with distribution function

$$F_T(t) = 1 - \boldsymbol{\alpha}\mathrm{e}^{\boldsymbol{A}t}\mathbf{1},$$

where $\boldsymbol{\alpha}$ is a finite real vector and $\boldsymbol{A}$ is a finite real matrix, is matrix exponentially distributed.

The size of $\boldsymbol{\alpha}$ and $\boldsymbol{A}$ plays the same role as the number of transient states in case of PH distributions. By definition, the set of PH distributions with a given size is a subset of the set of PH distributions with the same size.

ME distributions share the following basic properties with PH distributions: matrix exponential distribution function, matrix exponential density function, moments, rational Laplace transform, the same set of functions as in (3), and non-unique representation. The main difference between the matrix exponential and the PH classes comes from the fact that the sign constraints on the elements of generator matrixes restrict the eigenvalue structure of such matrixes, while such restrictions do not apply in case of ME distributions. For example, the eigenvalues of an order three PH distribution with dominant eigenvalue θ satisfy $\mathcal{R}(\lambda_i) \leq \theta$ and $|\mathcal{I}(\lambda_i)| \leq (\theta - \mathcal{R}(\lambda_i))/\sqrt{3}$, while the eigenvalues of an order three ME distribution with dominant eigenvalue θ satisfy $\mathcal{R}(\lambda_i) \leq \theta$ only. This flexibility of the eigenvalues has significant consequence on the flexibility of the set of order three PH and ME distributions. For example, the minimal squared coefficient of variation among the order three PH and ME distributions are $1/3$ and 0.200902, respectively.

The main difficulty encountered when working with ME distributions is that a general vector–matrix pair does not always define a nonnegative density function, while a vector–matrix pair with the sign constraints of PH distributions does. Efficient numerical methods have been proposed recently to check the nonnegativity of a matrix exponential function defined by a general vector–matrix pair, but general symbolic conditions are still missing.

4 Analysis of Models with PH Distributed Durations

If all durations (service times, interarrival times, repair times, etc.) in a system are distributed according to PH distributions, then its overall behavior can be captured by a continuous time Markov chain, referred to as extended Markov chain (EMC).

274 In this section, we show how to derive the infinitesimal generator of this EMC using
275 Kronecker operations. The methodology here described has been originally presented
276 in the case of Discrete PHs in [17] and more recently in the case of Continuous PHs
277 in [13]

278   To this end we first introduce the notation used to describe the model. By $\mathcal{S}$, we
279 denote the set of states and by $N = |\mathcal{S}|$ the number of states. The states themselves
280 are denoted by $s_1, s_2, ..., s_N$. The set of activities is denoted by $\mathcal{A}$ and the set of those
281 that are active in state s_i is denoted by $\mathcal{A}_i$. The activities are denoted by $a_1, a_2, ..., a_M$
282 with $M = |\mathcal{A}|$. When activity a_i is completed in state s_j then the system moves from
283 state s_j to state $n(j, i)$, i.e., n is the function that provides the next state. We assume
284 that the next state is a deterministic function of the current state and the activity that
285 completes. We further assume that there does not exist a triple, k, i, j, for which
286 $s_k \in \mathcal{S}, a_i \in \mathcal{A}, a_j \in \mathcal{A}$ and $n(k, i) = n(k, j)$. These two assumptions, which make
287 the formulas simpler, are easy to relax in practice. There can be activities that end
288 when the system moves from state s_i to state s_j even if they do not complete and are
289 active both in s_i and in s_j. These activities are collected in the set $e(i, j)$. The PH
290 distribution that is associated with activity a_i is characterized by the initial vector
291 $\boldsymbol{\alpha}_i$ and matrix $\boldsymbol{A}_i$. As before, we use the notation $\boldsymbol{a}_i = -\boldsymbol{A}_i \mathbf{1}$ to refer to the vector
292 containing the intensities that lead to completion of activity a_i. The number of phases
293 of the PH distribution associated with activity a_i is denoted by n_i.

294 *Example 1 PH/PH/1/K queue with server break-downs.* As an example, we consider,
295 using the above-described notation, a queue in which the server is subject to failure
296 only if the queue is not empty. The set of states is $\mathcal{S} = \{s_1, s_2, ..., s_{2K+1}\}$ where s_1
297 represents the empty queue, s_{2i} with $1 \leq i \leq K$ represents the state with i clients
298 in the queue and the server up, and s_{2i+1} with $1 \leq i \leq K$ represents the state with
299 i clients and the server down. There are four activities in the system: a_1 represents
300 the arrival activity, a_2 the service activity, a_3 the failure activity,[2] and a_4 the repair
301 activity. The vectors and matrices that describe the associated PH distributions are
302 $\boldsymbol{\alpha}_1, \boldsymbol{\alpha}_2, \boldsymbol{\alpha}_3, \boldsymbol{\alpha}_4$ and $\boldsymbol{A}_1, \boldsymbol{A}_2, \boldsymbol{A}_3, \boldsymbol{A}_4$. In this example, we assume that the arrival
303 activity is active if the system is not full and it is inactive if the system is full.
304 The service and the failure activities are active if the queue is not empty and the
305 server is up. The repair activity is active if the queue is not empty and the server is
306 down. Accordingly, we have $\mathcal{A}_1 = \{a_1\}$, $\mathcal{A}_{2i} = \{a_1, a_2, a_3\}$ for $1 \leq i \leq K - 1$,
307 $\mathcal{A}_{2i+1} = \{a_1, a_4\}$ for $1 \leq i \leq K - 1$, $\mathcal{A}_{2K} = \{a_2, a_3\}$, and $\mathcal{A}_{2K+1} = \{a_4\}$. The next
308 state function is as follows: for arrivals we have $n(1, 1) = s_2$ and $n(i, 1) = s_{i+2}$ with
309 $2 \leq i \leq 2K - 1$; for services $n(2, 2) = s_1$ and $n(2i, 2) = s_{2i-2}$ with $2 \leq i \leq K$;
310 for failures $n(2i, 3) = s_{2i+1}$ with $1 \leq i \leq K$; for repairs $n(2i + 1, 4) = s_{2i}$ with
311 $1 \leq i \leq K$. We assume that the failure activity ends every time when a service
312 activity completes, i.e., failure is connected to single jobs and not to the aging of the
313 server. Other activities end only when they complete or when such a state is reached
314 in which they are not active. Accordingly, $e(2i, 2i - 2) = \{a_3\}$ for $2 \leq i \leq K$.

---

[2]Failure is more like an event than an activity but, in order to keep the discussion clearer, we refer
to it as failure activity.

Based on the description of the ingredients of the model, it is possible to derive blocks of the initial probability vector and the blocks of the infinitesimal generator of the corresponding CTMC. Let us start with the infinitesimal generator, which we denote by Q, composed of $N \times N$ blocks. The block of Q that is situated in the ith row of blocks and in the jth column of blocks is denoted by Q_{ij}. A block in the diagonal, Q_{ii} describes the parallel execution of the activities that are active in s_i. The parallel execution of CTMCs can be captured by the Kronecker-sum operator ($\oplus$), and thus we have

$$Q_{ii} = \bigoplus_{j : s_j \in \mathcal{A}_i} A_j .$$

An off-diagonal block, Q_{ij}, is not a zero matrix only if there exists an activity whose completion moves the system from state s_i to state s_j. Let us assume that the completion of activity a_k moves the system from state s_i to state s_j, i.e., $n(i, k) = s_j$. The corresponding block, Q_{ij}, must

- reflect the fact that activity a_k completes and restarts if a_k is active in s_j,
- reflect the fact that activity a_k completes and does not restart if a_k is not active in s_j,
- end activities that are active in s_i but not in s_j,
- start those activities that are not active in s_i but are active in s_j,
- end and restart those activities that are active both in s_i and in s_j but are in e(i, j),
- and maintain the phase of those that are active both in s_i and in s_j and are not in e(i, j).

The joint treatment of the above cases can be carried out by the Kronecker-product operator and thus we have

$$Q_{ij} = \bigotimes_{l : 1 \le l \le M} R_l$$

with

$$R_l = \begin{cases} a_k & \text{if } l = k \text{ and } k \notin \mathcal{A}_j \\ a_k \alpha_k & \text{if } l = k \text{ and } k \in \mathcal{A}_j \\ \mathbf{1}_{n_l} & \text{if } l \neq k \text{ and } k \in \mathcal{A}_i \text{ and } k \notin \mathcal{A}_j \\ \alpha_l & \text{if } l \neq k \text{ and } k \notin \mathcal{A}_i \text{ and } k \in \mathcal{A}_j \\ \mathbf{1}_{n_l} \alpha_l & \text{if } l \neq k \text{ and } k \in \mathcal{A}_i \text{ and } k \in \mathcal{A}_j \text{ and } k \in e(i, j) \\ \mathbf{I}_{n_l} & \text{if } l \neq k \text{ and } k \in \mathcal{A}_i \text{ and } k \in \mathcal{A}_j \text{ and } k \notin e(i, j) \\ 1 & \text{otherwise} \end{cases}$$

where the subscripts to $\mathbf{1}$ and $\mathbf{I}$ indicate their size.

The initial probability vector of the CTMC, π, is a row vector composed of N blocks which must reflect the initial probabilities of the states of the system and the initial probabilities of the PH distributions of the active activities. Denoting by π_i the initial probability of state s_i, the ith block of the initial probability vector, π_i, is given as

$$347 \qquad \boldsymbol{\pi}_i = \bigotimes_{j:s_j \in \mathcal{A}_i} \boldsymbol{\alpha}_j \ .$$

348   *Example 2* For the previous example, the diagonal blocks, which must reflect the
349   ongoing activities, are the following:

$$350 \qquad \boldsymbol{Q}_{1,1} = \boldsymbol{A}_1, \ \ \boldsymbol{Q}_{2i,2i} = \boldsymbol{A}_1 \bigoplus \boldsymbol{A}_2 \bigoplus \boldsymbol{A}_3, \ \ \boldsymbol{Q}_{2i+1,2i+1} = \boldsymbol{A}_1 \bigoplus \boldsymbol{A}_4,$$

$$\begin{matrix} 351 \\ 352 \end{matrix} \qquad \boldsymbol{Q}_{2K,2K} = \boldsymbol{A}_2 \bigoplus \boldsymbol{A}_3, \ \ \boldsymbol{Q}_{2K+1,2K+1} = \boldsymbol{A}_4 \ \ \text{with } 1 \le i \le K-1$$

353   Arrival in state s_1 takes the system to state s_2. The corresponding block must complete
354   and restart the arrival activity and must restart both the service and the failure activity:

$$\begin{matrix} 355 \\ 356 \end{matrix} \qquad \boldsymbol{Q}_{12} = \boldsymbol{a}_1 \boldsymbol{\alpha}_1 \bigotimes \boldsymbol{\alpha}_2 \bigotimes \boldsymbol{\alpha}_3 \qquad (4)$$

357   Arrival in state s_{2i} (server up) takes the system to state s_{2i+2}. If the system does
358   not become full then the corresponding block must complete and restart the arrival
359   activity and must maintain the phase of both the service and the failure activity. If
360   the system becomes full, the arrival activity is not restarted. Accordingly, we have

$$361 \qquad \boldsymbol{Q}_{2i,2i+2} = \boldsymbol{a}_1 \boldsymbol{\alpha}_1 \bigotimes \mathbf{I}_{n_2} \bigotimes \mathbf{I}_{n_3} \ \ \text{with } 1 \le i \le K-2$$

$$\begin{matrix} 362 \\ 363 \end{matrix} \qquad \boldsymbol{Q}_{2K-2,2K} = \boldsymbol{a}_1 \bigotimes \mathbf{I}_{n_2} \bigotimes \mathbf{I}_{n_3}$$

364   An arrival in state s_{2i+1} (server down) takes the system to state s_{2i+3}. If the system
365   does not become full then the corresponding block must complete and restart the
366   arrival activity and must maintain the phase of the repair activity. If the system
367   becomes full, the arrival activity is not restarted. Accordingly, we have

$$368 \qquad \boldsymbol{Q}_{2i+1,2i+3} = \boldsymbol{a}_1 \boldsymbol{\alpha}_1 \bigotimes \mathbf{I}_{n_4} \ \ \text{with } 1 \le i \le K-2$$

$$\begin{matrix} 369 \\ 370 \end{matrix} \qquad \boldsymbol{Q}_{2K-1,2K+1} = \boldsymbol{a}_1 \bigotimes \mathbf{I}_{n_4}$$

371   Service completion can take place in three different situations. If the system becomes
372   empty then the phase of the arrival activity is maintained, the service activity is
373   completed and the failure activity is put to an end. If the system neither becomes
374   empty nor was full then the phase of the arrival activity is maintained, the service
375   activity is completed and restarted, and the failure activity ends and restarts. Finally, if
376   the queue was full then the arrival activity is restarted, the service activity is completed
377   and restarted, and the failure activity is put to an end and restarted. Accordingly, we
378   have

$$379 \qquad \boldsymbol{Q}_{2,1} = \mathbf{I}_{n_1} \bigotimes \boldsymbol{a}_2 \bigotimes \mathbf{1}_{n_3}$$

$$\boldsymbol{Q}_{2i,2i-1} = \mathbf{I}_{n_1} \bigotimes \boldsymbol{a}_2\boldsymbol{\alpha}_2 \bigotimes \mathbf{1}_{n_3}\boldsymbol{\alpha}_3 \quad \text{with } 1 < i < K$$

$$\boldsymbol{Q}_{2K,2K-2} = \boldsymbol{\alpha}_1 \bigotimes \boldsymbol{a}_2\boldsymbol{\alpha}_2 \bigotimes \mathbf{1}_{n_3}\boldsymbol{\alpha}_3 \tag{5}$$

The failure activity can be completed in two different situations. If the system is not full, then the phase of the arrival activity is maintained. If the system is full then the arrival activity is not active. In both cases, the service activity ends, the failure activity is completed and the repair activity is initialized.

$$\boldsymbol{Q}_{2i,2i+1} = \mathbf{I}_{n_1} \bigotimes \mathbf{1}_{n_2} \bigotimes \boldsymbol{a}_3 \bigotimes \boldsymbol{\alpha}_4 \quad \text{with } 1 \leq i < K$$

$$\boldsymbol{Q}_{2K,2K+1} = \mathbf{1}_{n_2} \bigotimes \boldsymbol{a}_3 \bigotimes \boldsymbol{\alpha}_4$$

Similarly to the failure activity, also the repair activity can be completed in two different situations because the arrival activity can be active or inactive. In both cases, the service activity and the failure activity must be initialized and the repair activity completes.

$$\boldsymbol{Q}_{2i+1,2i} = \mathbf{I}_{n_1} \bigotimes \boldsymbol{\alpha}_2 \bigotimes \boldsymbol{\alpha}_3 \bigotimes \boldsymbol{a}_4 \quad \text{with } 1 \leq i < K$$

$$\boldsymbol{Q}_{2K+1,2K} = \boldsymbol{\alpha}_2 \bigotimes \boldsymbol{\alpha}_3 \bigotimes \boldsymbol{a}_4$$

5 Analysis of Stochastic Systems with ME Distributed Durations

The most important observation to take from this section is that all steps of the method of EMCs (as explained in the previous section) remain directly applicable in case of ME distributed durations (where the $(\boldsymbol{\alpha}_i, \boldsymbol{A}_i)$ vector–matrix pairs describe ME distributions). In that case, the only difference is that the signs of the vector and matrix elements are not restricted to be nonnegative in case of the vector elements and off-diagonal matrix elements and to be negative in case of the diagonal matrix elements. Consequently, the model description does not allow a probabilistic interpretation via Markov chains.

This general conclusion was obtained through serious research efforts. Following the results in [12], it was suspected that in a stochastic model ME distributions could be used in place of PH distributions and several results would carry over, but it was not easy to prove these conjectured results in the general setting because probabilistic arguments associated with PH distributions no longer hold. In [1], it was shown that matrix geometric methods can be applied for quasi-birth–death processes (QBDs) with rational arrival processes (RAPs) [3], which can be viewed as an extension of ME distributions to arrival processes. To prove that the matrix geometric relations hold, the authors of [1] use an interpretation of RAPs proposed in [3]. However, the models considered are limited to QBDs. For the model class of SPNs with ME

417 distributed firing times, the applicability of the EMC-like analysis was proved in [2]
418 and refined for the special case when the ME distribution has no PH representation
419 in [4].

6 Analysis tools

421 Based on the common representation of the EMC through the Kronecker algebra,
422 smart algorithms have been developed recently to optimize memory usage. These
423 algorithms build the EMC in a completely symbolic way, both at the process state
424 space level and at the expanded state space level, as deeply explained in [13] that we
425 use as reference.

426   The algorithm presented in [13] is based on two high level steps:

427 1. to generate the reachability graph of the model (which collects the system states
428   in a graph according to their reachability from an initial set of states) using a
429   symbolic technique;
430 2. to enrich the symbolically stored reachability graph with all the necessary infor-
431   mation to evaluate Kronecker expressions representing the expanded state space.

432 Step 1 is performed using symbolic technique based on complex data structures like
433 Multi-Valued Decision Diagram (MDD) [18] to encode the model state space; step
434 2 adds information related to each event memory policy to the encoded state space.
435 In manner it is possible to use on the fly expressions introduced in Sects. 4 and 5 to
436 compute various probability measures of the model.

6.1 Symbolic Generation of Reachability Graph

438 Both traditional performance or dependability evaluation techniques and more recent
439 model checking-based approaches are grounded in the knowledge of the set of states
440 that the system considered can reach starting from a particular initial state (or in
441 general from a set of initial states). Symbolic techniques [5] focus on generating
442 a compact representation of huge state spaces by exploiting a model's structure
443 and regularity. A model has a structure when it is composed of K sub-models, for
444 some $K \in \mathbb{N}$. In this case, a global system state can be represented as a K-tuple
445 $(q^1, \ldots, q^K)$, where q^k is the local state of sub-model k (having some finite size n^k).
446   The use of (MDDs) for the encoding of model state spaces was introduced by
447 Miner and Ciardo in [14]. MDDs are rooted, directed, acyclic graphs associated with
448 a finite ordered set of integer variables. When used to encode a state space, an MDD
449 has the following structure:

450 • nodes are organized into $K + 1$ levels, where K is the number of sub-models;

451 • level K contains only a single non-terminal node, the root, whereas levels $K - 1$
452 through 1 contain one or more non-terminal nodes;

453 • a non-terminal node at level k has n^k arcs pointing to nodes at level $k - 1$;

454 A state $s = (q^1, \ldots, q^K)$ belongs to S if and only if a path exists from the root node
455 to the terminal node 1 such that, at each node, the arc corresponding to the local
456 state q^k is followed. In [6], and then in [7], Ciardo et al. proposed the *Saturation*
457 algorithm for the generation of reachability graphs using MDDs. Such an iteration
458 strategy improves both memory and execution time efficiency.

459 An efficient encoding of the reachability graph is built in the form of a set of
460 Kronecker matrices $\mathbf{W}_{e,k}$ with $e \in \mathcal{A}$ and $k = 1, \ldots, K$, where $\mathcal{A}$ is the set collecting
461 all the system events or activities. $\mathbf{W}_{e,k}[i_k, j_k] = 1$ if state j_k of sub-model k is
462 reachable from state i_k due to event e. According to such a definition, the next
463 state function of the model can be encoded as the incidence matrix given by the
464 boolean sum of Kronecker products $\sum_{e \in \mathcal{A}} \bigotimes_{K \geq k \geq 1} \mathbf{W}_{e,k}$. As a consequence, the
465 matrix representation $\mathbf{R}$ of the reachability graph of the model can be obtained by
466 filtering the rows and columns of such a matrix corresponding to the reachable global
467 states encoded in the MDD and replacing each non-null element with the labels of
468 the events that cause the corresponding state transition.

469 Saturation Unbound is a very effective way to represent the model state space
470 and the related reachability graph of a model. In any case, the methodology we are
471 dealing with is not strictly dependent on any particular algorithm to efficiently store
472 the reachability graph. We refer to the *Saturation Unbound* algorithm simply because
473 its efficiency is well known [7].

6.2 Annotating the Reachability Graph

475 The use of Saturation together with the Kronecker representation presented in previ-
476 ous sections enable solution of the derived stochastic process. However, knowledge
477 of the reachability graph of the untimed system as produced by Saturation is not
478 sufficient to manage the infinitesimal generator matrix $\mathbf{Q}$ on the fly according to the
479 symbolic representation. Considering that the information about the enabled events
480 for all the system states is contained in the high level description of the model and it
481 can be evaluated on the fly when needed with a negligible overhead, the only addi-
482 tional information needed is knowledge about the sets of active but not enabled events
483 in each state s ($T_a^{(s)}$). Using Saturation for the evaluation of the reachability graph
484 requires an additional analysis step for the computation of such an information and
485 use of a different data structure for storage. Multi Terminal Multi-Valued Decision
486 Diagram (MTMDD) [15] is used for this purpose.

487 The main differences with respect to MDDs are that: (1) more than two terminal
488 nodes are present in an MTMDD and (2) such nodes can be labeled with arbitrary
489 integer values, rather than just 0 and 1. An MTMDD can efficiently store both the

490 system state space S and the sets $T_a^{(s)}$ of active but not enabled events for all $s \in \mathcal{S}$;
491 this is necessary, in our approach, to correctly evaluate non-null blocks of **Q** matrix.
492 In fact, while an MDD is only able to encode a state space, an MTMDD is also
493 able to associate an integer to each state. Thus, the encoding of sets $T_a^{(s)}$ can be
494 done associating to each possible set of events an integer code that unambiguously
495 represents it. Let us associate to each event an unique index n such that $1 \leq n \leq \|\mathcal{A}\|$.
496 Then the integer value associated to one of the possible sets $T_a^{(s)}$ is computed starting
497 from the indices associated with the system events that belong to it in the following
498 way:

$$b_M \cdot 2^A + \cdots + b_n \cdot 2^n + \cdots b_1 \cdot 2^1 + 1 = \sum_{i=1}^M b_i 2^i + 1$$

500 where

$$b_i = \begin{cases} 1, & \text{if event } e_i \in T_a^{(s)} \\ 0, & \text{otherwise} \end{cases}$$

502 In this manner all the necessary information to apply the Kronecker-based expres-
503 sions on the fly are provided; the only remaining need is a method to evaluate the set
504 $T_a^{(s)}$ given a referring state s.
505   In [13], the following theorem has been proved.

506 **Theorem 1** *Given a model $\mathcal{M}$, a state $s_0 \in S$ and an event $\overline{e} \in \mathcal{A}$ with an age*
507 *memory policy associated, then $\overline{e} \in T_a^{(s_0)}$ iff $\overline{e} \notin T_e^{(s_0)}$ and one of the following*
508 *statements holds:*

509 *1. $\exists s_1 \in \mathcal{S}, \exists e_1 \in \mathcal{A}, s_1 \neq s_0, e_1 \neq \overline{e} \mid s_0 \in \mathcal{N}_{e_1}(s_1) \land \overline{e} \in T_e^{(s_1)}$*
510 *2. $\exists s_1 \in \mathcal{S}, s_1 \neq s_0 \mid s_0 \in \mathcal{N}(s_1) \land \overline{e} \in T_a^{(s_1)}$*

511 *where $\mathcal{N}_{e_1}$ is the next state function associated to event e_1.*

512 Note that function $\mathcal{N}$ is the equivalent to the $n(\cdot, \cdot)$ defined in Sect. 4; function $\mathcal{N}_e$
513 instead differs for the restriction to the firing of a specific event e. We use this notation
514 because it is less cumbersome in this specific context.
515   Theorem 1 gives a way to evaluate if an event e belongs to the set $T_a^{(s_0)}$ or not.
516 In fact, according to the statements proved, it is possible to characterize a state
517 s_0 with respect to the system event memory policies by exploring its reachability
518 graph. Exploration can be performed using classical bread-first search and depth-
519 first search algorithms, easily applicable to an explicitly stored reachability graph; it
520 is more complicated to apply classical search algorithms when the graph is stored in
521 implicit manner as is the case when MTMDD data structures are used.
522   In this case, a different approach can be used by resorting to Computational Tree
523 Logic (CTL) formulas that have been shown to be very efficient for data structures
524 like MDD and MTMDD. The use of CTL formulas to evaluate sets $T_a^{(s)}$ is justified
525 by a theorem introduced in [13]. Before recalling this theorem, we need to introduce
526 a CTL operator.

527 **Definition 3** Let $s_0 \in \mathcal{S}$ be a state of a discrete state process with state space $\mathcal{S}$, and
528 let p and q be two logical conditions on the states. Let also $\mathcal{F}(s) \subseteq \mathcal{N}(s) \cup \mathcal{N}^{-1}(s)$ be
529 a reachability relationship between two states in $\mathcal{S}$ that defines a desired condition

530 over the paths. Then s_0 satisfies the formula $E_{\mathcal{F}}[pUq]$, and we will write $s_0 \models$
531 $E_{\mathcal{F}}[pUq]$, iff $\exists\, n \geq 0, \exists\, s_1 \in \mathcal{F}(s_0), \ldots, \exists\, s_n \in \mathcal{F}(s_{n-1}) \mid (s_n \models q) \wedge (\forall m <$
532 $n, s_m \models p)$.

533 In definition above, we used the path quantifier E with the meaning *there exists a*
534 *path* and the tense operator U with the meaning *until*, as usually adopted in CTL
535 formulas.

536   Given Definition 3, the following theorem holds:

537 **Theorem 2** *An event $\overline{e} \in \mathcal{E}$, with an age memory policy associated, belongs to*
538 $T_a^{(s_0)}$, *with $s_0 \in \mathcal{S}$, iff $s_0 \models E_{\mathcal{F}}[pUq]$ over a path at least one long, where*
539 *p and q are the statements "$\overline{e}$ is not enabled" and "$\overline{e}$ is enabled," respectively,*
540 *and $\mathcal{F}(s) = \mathcal{N}^{-1}(s) \setminus \mathcal{N}_{\overline{e}}^{-1}(s)$.*

541   Thanks to Theorem 2, evaluation of the CTL formula $E_{\mathcal{F}}[pUq]$ makes possible
542 to evaluate whether an event $\overline{e}$ is active but not enabled in state s_0 or not by setting
543 condition p as $\overline{e}$ *is not enable* and q as $\overline{e}$ *is enabled*. This is the last brick to build
544 an algorithm able to compute state probabilities of a model, where the event are PH
545 or ME distributed; in fact, it is possible to characterize all the active and/or enabled
546 events in all the different states and to apply the Kronecker expressions with this
547 information to solve the derived EMC.

548 ## 7 Examples

549 In this section, we present two examples where non-exponentially distributed dura-
550 tions are present. In the first example, these durations are approximated by PH dis-
551 tributions, while in the second example they are described by ME distributions.

552 ### 7.1 Reliability Model of Computer System

553 We introduce a reliability model where we use PH distributions as failure times.
554 The model is specified according to the Petri net depicted in Fig. 1, where the usual
555 graphical notation for the places, transitions, and arcs has been adopted.

556   The system under study is a distributed computing system composed of a cluster
557 of two computers. Each of them has three main weak points: the motherboard, CPU,
558 and disk. Interconnections inside the cluster are provided by a manager in such a
559 way that the overall system is seen as a single unit. In the distributed system, the two
560 computers work independently, driven by the manager that acts as a load balancer to
561 split the work between them. Since the manager represents a single point of failure, a
562 second instance is deployed for redundancy in the system; this latter instance operates
563 in cold standby when the main computer manager works and it is powered on when
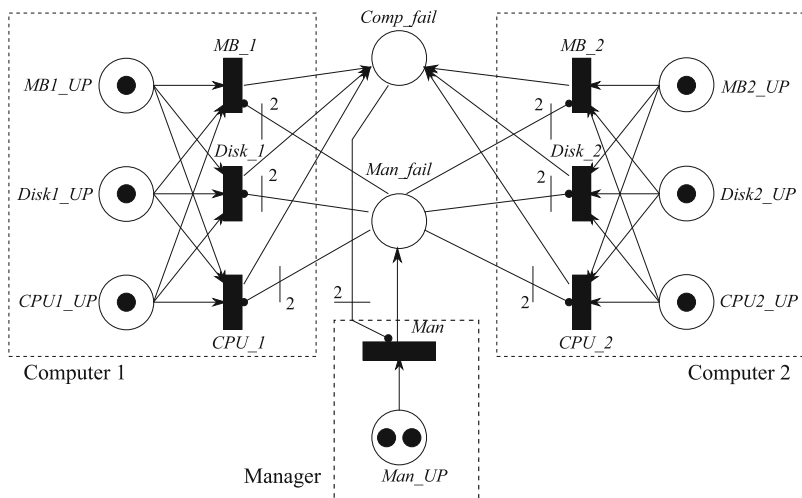564 it fails.

Fig. 1 Computer system reliability model

Due to this configuration, the distributed system works when at least one of the two computers works and the computer manager properly operates. The main components of each computational unit (CPU, motherboard, and disk) may fail rendering the unit inoperable. In the Petri net model, faults in the CPU, motherboard, and disk are modeled by the timed transitions MB_i, $Disk\_i$, and CPU_i whose firing represents the respective faulty event in the i-th Computer; the operating conditions of components are represented by a token in the places $CPUi\_UP$, MBi_UP, and $Diski\_UP$. When one of the transitions above fires a token is flushed out of the place and a token is put in the place $Comp\_fail$. At the same time, all the other transitions related to the faulty events in the same unit become disabled because the unit is considered down and thus no more faults can occur. Two tokens in the place $Comp\_fail$ means that the two computational units are both broken and the overall distributed system is not operational. Similarly, transition Man models the fault of a manager unit. Its firing flushes a token out of the place Man_UP and puts a token in the place Man_fail. Thanks to the redundancy, the first manager unit fault is tolerated whereas the system goes down when a second fault occurs. This state is represented in the Petri net by two tokens in the place Man_fail. In both faulty states, all the transitions are disabled and an absorbing state is reached. In terms of Petri net objects, the not operational condition is expressed by the following statement:

$$(\#Comp\_fail = 2) \vee (\#Man\_fail = 2) , \tag{6}$$

where the symbol $\#P$ states the number of token in place P.

Table 1 Failure time distribution parameters

Transition	Weibull			
	β_f	η_f	E	λ
MB_1, MB_2	0.5965	1.20	1.82	0.55
$Disk\_1, Disk\_2$	0.5415	1.00	1.71	0.59
CPU_1, CPU_2	0.399	1.46	3.42	0.29
Man	0.5965	1.20	1.82	0.55

As usual in reliability modeling, the time to failure of the components has been modeled using Weibull distributions whose cumulative distribution function is

$$F(t) = 1 - \mathrm{e}^{(1/\eta_f)^{\beta_f}}.$$

This choice has been also supported by measures done on real systems such as those analyzed in [9]. The parameters of the Weibull distributions used for the Petri net transitions of Fig. 1 are reported in Table 1.

Weibull distributions have been introduced in the model through the use of 10-phase PH distributions, approximating them by evaluating the formula (6). The results obtained are depicted in Fig. 2. To better highlight the usefulness of the modeling approach presented here, the Petri net model was solved by imposing exponential distributions as transition firing times. In fact, the use of exponential distributions is quite common to obtain a more tractable model. The value of the parameters λ used in this second run was computed as the reciprocal of the expected value, E, of the corresponding Weibull distributions (listed in Table 1). The result obtained are also depicted in Fig. 2. As can be easily noted, the use of exponential distributions produces optimistic results compared to the use of Weibull distributions, making the system appear more reliable than it is in reality.
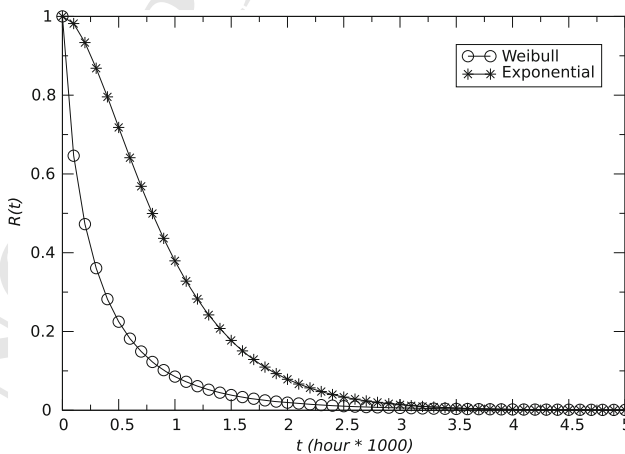
Fig. 2 Computer system reliability $R(t)$

7.2 Numerical Example with "Oscillating" ME Distribution

For our second example, we consider the Activity Network depicted in Fig. 3, which represents a "mission" composed of five activities and the constraints on the order in which the five activities can be carried out. Initially, activities 1 and 2 are active. If activity 1 finishes then activities 3 and 4 start and thus there are three activities under execution, namely, activities 2, 3, and 4. If activity 3 is the first first among these three activities to finish then no new activity starts because in order to start activity 5, both activity 2 and 3 must finish. The graph of all the possible states of the Activity Network is shown in Fig. 4, where in every node we report the activities that are under execution in the node. The label on the edges indicates the activity whose completion triggers the edge. The duration of the activities are modeled with ME distributions and we denote the vector and matrix that represent the duration of activity i by $\boldsymbol{\alpha}_i$ and $\boldsymbol{A}_i$, respectively. Further, we use the notation $\boldsymbol{a}_i = (-\boldsymbol{A}_i)\boldsymbol{1}$ and denote by I_i the identity matrix whose dimension is equal to that of $\boldsymbol{A}_i$.

Following the approach described in Sect. 4, one can determine the infinitesimal generator of the model. Its first seven block-columns are given as (the left side of the matrix)

$$
\begin{vmatrix}
A_1 \bigoplus A_2 & a_1 \bigotimes I_2 \bigotimes A_3 \bigotimes A_4 & 0 & 0 & I_1 \bigotimes a_2 & 0 & 0 \\
0 & A_2 \bigoplus A_3 \bigoplus A_4 & I_2 \bigotimes I_3 \bigotimes a_4 & 0 & 0 & I_2 \bigotimes a_3 \bigotimes I_4 & a_2 \bigotimes I_3 \bigotimes I_4 \\
0 & 0 & A_2 \bigoplus A_3 & I_2 \bigotimes a_3 & 0 & 0 & 0 \\
0 & 0 & 0 & A_2 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & A_1 & 0 & a_1 \bigotimes A_3 \bigotimes A_4 \\
0 & 0 & 0 & I_2 \bigotimes a_4 & 0 & A_2 \bigoplus A_4 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & A_3 \bigoplus A_4 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{vmatrix}
$$

and the remaining five block-columns are (the right side of the matrix)
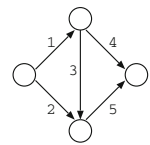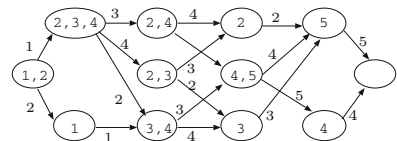
Fig. 3 An activity network

Fig. 4 CTMC of the activity network in Fig. 3

$$\begin{vmatrix}
0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
\boldsymbol{a}_2 \otimes I_3 & 0 & 0 & 0 & 0 \\
0 & \boldsymbol{a}_2 \otimes A_5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 \\
0 & 0 & \boldsymbol{a}_2 \otimes I_4 \otimes A_5 & 0 & 0 \\
I_3 \otimes \boldsymbol{a}_4 & 0 & \boldsymbol{a}_3 \otimes I_4 \otimes A_5 & 0 & 0 \\
A_3 & \boldsymbol{a}_3 \otimes A_5 & 0 & 0 & 0 \\
0 & A_5 & 0 & 0 & \boldsymbol{a}_5 \\
0 & \boldsymbol{a}_4 \otimes I_5 & A_4 \oplus A_5 & I_4 \otimes \boldsymbol{a}_5 & 0 \\
0 & 0 & 0 & A_4 & \boldsymbol{a}_4 \\
0 & 0 & 0 & 0 & 0
\end{vmatrix}$$

The vector that provides the initial configuration is $|A_1 \otimes A_2, 0, ..., 0|$.

In order to illustrate a feature of ME distributions that cannot be exhibited by PH distributions, we applied an ME distribution with "oscillating" PDF to describe the duration of activities 1, 2, 4, and 5. The vector–matrix pair of this ME distribution is

$$A_1 = A_2 = A_4 = A_5 = |1.04865, -0.0340166, -0.0146293|\,,$$

$$A_1 = A_2 = A_4 = A_5 = \begin{vmatrix} -1 & 0 & 0 \\ 0 & -1 & -20 \\ 0 & 20 & -1 \end{vmatrix}\,,$$

and its PDF is depicted in Fig. 5. The duration of the remaining activity, namely activity 3, is distributed according to an Erlang distribution with four phases and average execution time equal to 1, i.e.,
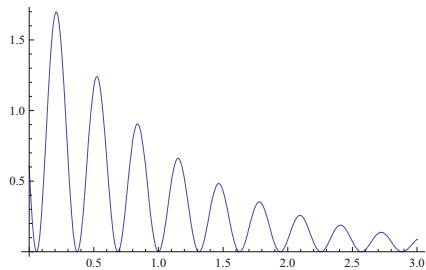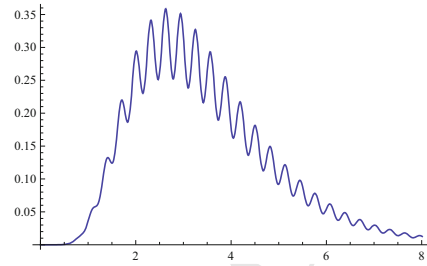
$$A_3 = |1, 0, 0, 0|\,, \quad A_3 = \frac{1}{4}\begin{vmatrix} -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ 0 & 0 & -1 & 1 \\ 0 & 0 & 0 & -1 \end{vmatrix}\,.$$

Fig. 5 Oscillating activity duration pdf

Fig. 6 Overall accomplishment time pdf

⁶³⁵ The model was then used to characterize the PDF of the time that is needed to ⁶³⁶ accomplish the whole mission. The resulting PDF is shown in Fig. 6 and one can ⁶³⁷ observe that the oscillating nature of the distribution of the activity durations carries ⁶³⁸ over into the overall completion time distribution.

8 Conclusions

⁶⁴⁰ While the evolution of computing devices and analysis methods resulted in a sharp ⁶⁴¹ increase in the complexity of computable CTMC models, CTMC-based analysis ⁶⁴² had been restricted to the analysis of stochastic models with exponentially distrib- ⁶⁴³ uted duration times. A potential extension of CTMC-based analysis is the inclusion ⁶⁴⁴ of PH distributed duration times, which enlarges the state space, but still has a fea- ⁶⁴⁵ sible computational complexity. We surveyed the basics of PH distributions and the ⁶⁴⁶ analysis approach to generate the EMC.

⁶⁴⁷ A more recent development in this field is the extension of the EMC-based analy- ⁶⁴⁸ sis with ME distributed duration times. With respect to the steps of the analysis ⁶⁴⁹ method, the EMC-based analysis and its extension with ME distributions are identi- ⁶⁵⁰ cal. However, because ME distributions are more flexible than the PH distributions ⁶⁵¹ (more precisely, the set of PH distributions of a given size is a subset of the set of ⁶⁵² ME distributions of the same size) this extension increases the modeling flexibility ⁶⁵³ of the set of models which can be analyzed with a given computational complexity.

⁶⁵⁴ Apart of the steps of the EMC-based analysis method, we discussed the tool sup- ⁶⁵⁵ port available for the automatic execution of the analysis method. Finally, application ⁶⁵⁶ examples demonstrate the abilities of the modeling and analysis methods.

References

⁶⁵⁸ 1. Asmussen S, Bladt M (1999) Point processes with finite-dimensional conditional probabilities. ⁶⁵⁹ Stoch Process Appl 82:127–142
⁶⁶⁰ 2. Bean NG, Nielsen BF (2010) Quasi-birth-and-death processes with rational arrival process ⁶⁶¹ components. Stoch Models 26(3):309–334

3. Buchholz P, Horvath A, Telek M (2011) Stochastic Petri nets with low variation matrix exponentially distributed firing time. Int J Perform Eng 7:441–454, 2011 (Special issue on performance and dependability modeling of dynamic systems)

4. Buchholz P, Telek M (2010) Stochastic petri nets with matrix exponentially distributed firing times. Perform Eval 67:1373–1385

5. Burch JR, Clarke EM, McMillan KL, Dill DL, Hwang LJ (1990) Symbolic model checking: 1020 states and beyond. In: Fifth annual IEEE symposium on logic in computer science, 1990. LICS '90, Proceedings, pp 428–439

6. Ciardo G, Luttgen G, Siminiceanu R (2001) Saturation: an efficient iteration strategy for symbolic state space generation. In: Proceedings of tools and algorithms for the construction and analysis of systems (TACAS), LNCS 2031. Springer, pp 328–342

7. Ciardo G, Marmorstein R, Siminiceanu R (2003) Saturation unbound. In: Proceedings of TACAS. Springer, pp 379–393

8. Cox DR (1955) The analysis of non-markovian stochastic processes by the inclusion of supplementary variables. Proc Cambridge Philos Soc 51(3):433–441

9. Distefano S, Longo F, Scarpa M, Trivedi KS (2014) Non-markovian modeling of a bladecenter chassis midplane. In: Computer performance engineering, vol 8721 of Lecture Notes in Computer Science. Springer International Publishing, pp 255–269

10. Kleinrock L (1975) Queuing systems, vol 1: theory. Wiley Interscience, New York

11. Kulkarni VG (1995) Modeling and analysis of stochastic systems. Chapman & Hall

12. Lipsky L (2008) Queueing theory: a linear algebraic approach. Springer

13. Longo F, Scarpa M (2015) Two-layer symbolic representation for stochastic models with phase-type distributed events. Int J Syst Sci 46(9):1540–1571

14. Miner AS, Ciardo G (1999) Efficient reachability set generation and storage using decision diagrams. In: Application and Theory of Petri Nets 1999 (Proceedings 20th international conference on applications and theory of Petri Nets. Springer, pp 6–25)

15. Miner A, Parker D (2004) Symbolic representations and analysis of large state spaces. In: Validation of stochastic systems, LNCS 2925, Dagstuhl (Germany). Springer, pp 296–338

16. Neuts M (1975) Probability distributions of phase type. In: Amicorum L, Florin EH (eds) University of Louvain, pp 173–206

17. Scarpa M, Bobbio A (1998) Kronecker representation of stochastic petri nets with discrete ph distributions. In: Proceedings of IEEE international computer performance and dependability symposium, 1998. IPDS'98. pp 52–62

18. Srinivasan A, Ham T, Malik S, Brayton RK (1990) Algorithms for discrete function manipulation. In: IEEE international conference on computer-aided design, 1990. ICCAD-90. Digest of technical papers, pp 92–95

19. Trivedi K (1982) Probability and statistics with reliability, queueing and computer science applications. Prentice-Hall, Englewood Cliffs

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