

Package ‘smmR’

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Type Package

Title Simulation, Estimation and Reliability of Semi-Markov Models

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Description Performs parametric and non-parametric estimation and simulation for multi-state discrete-time semi-Markov processes. For the parametric estimation, several discrete distributions are considered for the sojourn times: Uniform, Geometric, Poisson, Discrete Weibull and Negative Binomial. The non-parametric estimation concerns the sojourn time distributions, where no assumptions are done on the shape of distributions. Moreover, the estimation can be done on the basis of one or several sample paths, with or without censoring at the beginning or/and at the end of the sample paths. Reliability indicators such as reliability, maintainability, availability, BMP-failure rate, RG-failure rate, mean time to failure and mean time to repair are available as well. The implemented methods are described in Barbu, V.S., Limnios, N. (2008) <doi:10.1007/978-0-387-73173-5>, Barbu, V.S., Limnios, N. (2008) <doi:10.1080/10485250701261913> and Trevezas, S., Limnios, N. (2011) <doi:10.1080/10485252.2011.555543>. Estimation and simulation of discrete-time k-th order Markov chains are also considered.

URL <https://plmlab.math.cnrs.fr/lmrs/statistique/smmR>,
<https://lmrs.pages.math.cnrs.fr/statistique/smmR>

BugReports <https://github.com/corentin-dev/smmR/issues>

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Contents

smmR-package	3
.failureRateBMP	4
availability	6
convolution	7
failureRate	8
fitmm	10
fitsmm	12
get.f	16
get.H	17
get.Kpar	17
get.limitDistribution	18
get.Niuj	18
get.P	19
get.psi	19
get.Py	20
get.qy	20
get.stationaryDistribution	21
getKernel	21
getProcesses	22
is.mm	23
is.mmfit	23
is.smm	24
is.smmfit	24
is.smmnonparametric	25
is.smmparametric	25
maintainability	26
matrixConvolution	27
meanRecurrenceTimes	28
meanSojournTimes	29
mm	30
mtf	31
mtr	32
plot.smm	33
plot.smmfit	34

reliability	35
setSeed	37
simulate.mm	37
simulate.mmfit	38
simulate.smm	39
simulate.smmfit	40
smmnonparametric	41
smmparametric	43

Index	47
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smmR-package	<i>smmR : Semi-Markov Models, Markov Models and Reliability</i>
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Description

This package performs parametric and non-parametric estimation and simulation for multi-state discrete-time semi-Markov processes. For the parametric estimation, several discrete distributions are considered for the sojourn times: Uniform, Geometric, Poisson, Discrete Weibull and Negative Binomial. The non-parametric estimation concerns the sojourn time distributions, where no assumptions are done on the shape of distributions. Moreover, the estimation can be done on the basis of one or several sample paths, with or without censoring at the beginning or/and at the end of the sample paths. Estimation and simulation of discrete-time k-th order Markov chains are also considered.

Semi-Markov models are specified by using the functions `smmparametric()` and `smmnonparametric()` for parametric and non-parametric specifications respectively. These functions return objects of S3 class (`smm`, `smmparametric`) and (`smm`, `smmnonparametric`) respectively (`smm` class inherits from S3 classes `smmparametric` or `smmnonparametric`). Thus, `smm` is like a wrapper class for semi-Markov model specifications.

Based on a model specification (an object of class `smm`), it is possible to:

- **simulate** one or several sequences with the method `simulate.smm()`;
- **plot** conditional sojourn time distributions (method `plot.smm()`);
- compute **log-likelihood**, **AIC** and **BIC** criteria (methods `logLik()`, `AIC()`, `BIC()`);
- compute **reliability**, **maintainability**, **availability**, **failure rates** (methods `reliability()`, `maintainability()`, `availability()`, `failureRate()`).

Estimations of parametric and non-parametric semi-Markov models can be done by using the function `fitsmm()`. This function returns an object of S3 class `smmfit`. The class `smmfit` inherits from classes (`smm`, `smmparametric`) or (`smm`, `smmnonparametric`).

Based on a fitted/estimated semi-Markov model (an object of class `smmfit`), it is possible to:

- **simulate** one or several sequences with the method `simulate.smmfit()`;
- **plot** estimated conditional sojourn time distributions (method `plot.smmfit()`);
- compute **log-likelihood**, **AIC** and **BIC** criteria (methods `logLik()`, `AIC()`, `BIC()`);
- compute estimated **reliability**, **maintainability**, **availability**, **failure rates** and their **confidence intervals** (methods `reliability()`, `maintainability()`, `availability()`, `failureRate()`).

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References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

R.E. Barlow, A.W. Marshall, and F. Prochan. (1963). Properties of probability distributions with monotone hazard rate. Ann. Math. Statist., 34, 375-389.

T. Nakagawa and S. Osaki. (1975). The discrete Weibull distribution. IEEE Trans. Reliabil., R-24, 300-301.

D. Roy and R. Gupta. (1992). Classification of discrete lives. Microelectron. Reliabil., 32 (10), 1459-1473.

I. Votsi & A. Brouste (2019) Confidence interval for the mean time to failure in semi-Markov models: an application to wind energy production, Journal of Applied Statistics, 46:10, 1756-1773.

See Also

Useful links:

- <https://plmlab.math.cnrs.fr/lmrs/statistique/smmR>
- <https://lmrs.pages.math.cnrs.fr/statistique/smmR>
- Report bugs at <https://github.com/corentin-dev/smmR/issues>

.failureRateBMP

BMP-Failure Rate Function

Description

Consider a system S_{system} starting to work at time $k = 0$. The BMP-failure rate at time $k \in N$ is the conditional probability that the failure of the system occurs at time k , given that the system has worked until time $k - 1$.

Usage

```
.failureRateBMP(
  x,
  k,
  upstates = x$states,
  level = 0.95,
  epsilon = 0.001,
  klim = 10000
)
```

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
k	A positive integer giving the period $[0, k]$ on which the BMP-failure rate should be computed.
upstates	Vector giving the subset of operational states U .
level	Confidence level of the asymptotic confidence interval. Helpful for an object <code>x</code> of class <code>smmfit</code> .
epsilon	Value of the reliability above which the latter is supposed to be 0 because of computation errors (see Details).
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the failure rate of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The system starts to work at instant 0 and the state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

The BMP-failure rate at time $k \in N$ is the conditional probability that the failure of the system occurs at time k , given that the system has worked until time $k - 1$.

Let T_D denote the first passage time in subset D , called the lifetime of the system, i.e.,

$$T_D := \inf\{n \in N; Z_n \in D\} \text{ and } \inf \emptyset := \infty.$$

For a discrete-time semi-Markov system, the failure rate at time $k \geq 1$ has the expression:

$$\lambda(k) := P(T_D = k | T_D \geq k)$$

We can rewrite it as follows :

$$\lambda(k) = 1 - \frac{R(k)}{R(k-1)}, \text{ if } R(k-1) \neq 0; \lambda(k) = 0, \text{ otherwise}$$

The failure rate at time $k = 0$ is defined by $\lambda(0) := 1 - R(0)$, with R being the reliability function (see [reliability](#) function).

The calculation of the reliability R involves the computation of many convolutions. It implies that the computation error, may be higher (in value) than the "true" reliability itself for reliability close to 0. In order to avoid inconsistent values of the BMP-failure rate, we use the following formula:

$$\lambda(k) = 1 - \frac{R(k)}{R(k-1)}, \text{ if } R(k-1) \geq \epsilon; \lambda(k) = 0, \text{ otherwise}$$

with ϵ , the threshold, the parameter epsilon in the function `failureRateBMP`.

Value

A matrix with $k + 1$ rows, and with columns giving values of the BMP-failure rate, variances, lower and upper asymptotic confidence limits (if x is an object of class `smmfit`).

availability	<i>Availability Function</i>
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Description

The pointwise (or instantaneous) availability of a system S_{system} at time $k \in N$ is the probability that the system is operational at time k (independently of the fact that the system has failed or not in $[0, k)$).

Usage

```
availability(x, k, upstates = x$states, level = 0.95, klim = 10000)
```

Arguments

<code>x</code>	An object of S3 class <code>smmfit</code> or <code>smm</code> .
<code>k</code>	A positive integer giving the time at which the availability should be computed.
<code>upstates</code>	Vector giving the subset of operational states U .
<code>level</code>	Confidence level of the asymptotic confidence interval. Helpful for an object x of class <code>smmfit</code> .
<code>klim</code>	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the availability of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

The pointwise (or instantaneous) availability of a system S_{system} at time $k \in N$ is the probability that the system is operational at time k (independently of the fact that the system has failed or not in $[0, k)$).

Thus, the pointwise availability of a semi-Markov system at time $k \in N$ is

$$A(k) = P(Z_k \in U) = \sum_{i \in E} \alpha_i A_i(k),$$

where we have denoted by $A_i(k)$ the conditional availability of the system at time $k \in N$, given that it starts in state $i \in E$,

$$A_i(k) = P(Z_k \in U | Z_0 = i).$$

Value

A matrix with $k + 1$ rows, and with columns giving values of the availability, variances, lower and upper asymptotic confidence limits (if x is an object of class `smmf it`).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

convolution

Discrete-time convolution product of f and g (See definition 2.2 p. 20)

Description

Discrete-time convolution product of f and g (See definition 2.2 p. 20)

Usage

```
convolution(f, g)
```

Arguments

f A vector giving the values of the function f for each $k \in N$.
g A vector giving the values of the function g for each $k \in N$.

Value

A vector giving the values of the discrete-time convolution of f and g for each $k \in N$.

failureRate	<i>Failure Rate Function</i>
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Description

Function to compute the BMP-failure rate or the RG-failure rate.

Consider a system S_{system} starting to work at time $k = 0$. The BMP-failure rate at time $k \in N$ is the conditional probability that the failure of the system occurs at time k , given that the system has worked until time $k - 1$.

The RG-failure rate is a discrete-time adapted failure rate, proposed by D. Roy and R. Gupta. Classification of discrete lives. *Microelectronics Reliability*, 32(10):1459–1473, 1992. We call it the RG-failure rate and denote it by $r(k)$, $k \in N$.

Usage

```
failureRate(
  x,
  k,
  upstates = x$states,
  failure.rate = c("BMP", "RG"),
  level = 0.95,
  epsilon = 0.001,
  klim = 10000
)
```

Arguments

x An object of S3 class `smmfit` or `smm`.
k A positive integer giving the period $[0, k]$ on which the BMP-failure rate should be computed.
upstates Vector giving the subset of operational states U .
failure.rate Type of failure rate to compute. If `failure.rate = "BMP"` (default value), then BMP-failure-rate is computed. If `failure.rate = "RG"`, the RG-failure rate is computed.

level	Confidence level of the asymptotic confidence interval. Helpful for an object <code>x</code> of class <code>smmfit</code> .
epsilon	Value of the reliability above which the latter is supposed to be 0 because of computation errors (see Details).
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the failure rate of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The system starts to work at instant 0 and the state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

The BMP-failure rate at time $k \in N$ is the conditional probability that the failure of the system occurs at time k , given that the system has worked until time $k - 1$.

Let T_D denote the first passage time in subset D , called the lifetime of the system, i.e.,

$$T_D := \inf\{n \in N; Z_n \in D\} \text{ and } \inf \emptyset := \infty.$$

For a discrete-time semi-Markov system, the failure rate at time $k \geq 1$ has the expression:

$$\lambda(k) := P(T_D = k | T_D \geq k)$$

We can rewrite it as follows :

$$\lambda(k) = 1 - \frac{R(k)}{R(k-1)}, \text{ if } R(k-1) \neq 0; \lambda(k) = 0, \text{ otherwise}$$

The failure rate at time $k = 0$ is defined by $\lambda(0) := 1 - R(0)$, with R being the reliability function (see [reliability](#) function).

The calculation of the reliability R involves the computation of many convolutions. It implies that the computation error, may be higher (in value) than the "true" reliability itself for reliability close to 0. In order to avoid inconsistent values of the BMP-failure rate, we use the following formula:

$$\lambda(k) = 1 - \frac{R(k)}{R(k-1)}, \text{ if } R(k-1) \geq \epsilon; \lambda(k) = 0, \text{ otherwise}$$

with ϵ , the threshold, the parameter `epsilon` in the function `failureRate`.

Expressing the RG-failure rate $r(k)$ in terms of the reliability R we obtain that the RG-failure rate function for a discrete-time system is given by:

$$r(k) = -\ln \frac{R(k)}{R(k-1)}, \text{ if } k \geq 1; r(k) = -\ln R(0), \text{ if } k = 0$$

for $R(k) \neq 0$. If $R(k) = 0$, we set $r(k) := 0$.

Note that the RG-failure rate is related to the BMP-failure rate by:

$$r(k) = -\ln(1 - \lambda(k)), k \in N$$

Value

A matrix with $k + 1$ rows, and with columns giving values of the BMP-failure rate or RG-failure rate, variances, lower and upper asymptotic confidence limits (if `x` is an object of class `smmfit`).

References

- V. S. Barbu, N. Limnios. (2008). *Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis*. New York: Lecture Notes in Statistics, vol. 191, Springer.
- R.E. Barlow, A.W. Marshall, and F. Prochan. (1963). Properties of probability distributions with monotone hazard rate. *Ann. Math. Statist.*, 34, 375-389.
- D. Roy and R. Gupta. (1992). Classification of discrete lives. *Microelectron. Reliabil.*, 32 (10), 1459-1473.

fitmm

Maximum Likelihood Estimation (MLE) of a k-th order Markov chain

Description

Maximum Likelihood Estimation of the transition matrix and initial distribution of a k-th order Markov chain starting from one or several sequences.

Usage

```
fitmm(sequences, states, k = 1, init.estim = "mle")
```

Arguments

sequences	A list of vectors representing the sequences.
states	Vector of state space (of length s).
k	Order of the Markov chain.
init.estim	Optional. <code>init.estim</code> gives the method used to estimate the initial distribution. The following methods are proposed: <ul style="list-style-type: none"> • <code>init.estim = "mle"</code>: the classical Maximum Likelihood Estimator is used to estimate the initial distribution <code>init</code>; • <code>init.estim = "stationary"</code>: the initial distribution is replaced by the stationary distribution of the Markov chain (if the order of the Markov chain is more than one, the transition matrix is converted into a square block matrix in order to estimate the stationary distribution); • <code>init.estim = "freq"</code>: the initial distribution is estimated by taking the frequencies of the words of length k for all sequences; • <code>init.estim = "prod"</code>: <code>init</code> is estimated by using the product of the frequencies of each letter (for all the sequences) in the word of length k; • <code>init.estim = "unif"</code>: the initial probability of each state is equal to $1/s$, with s the number of states.

Details

Let X_1, X_2, \dots, X_n be a trajectory of length n of the Markov chain $X = (X_m)_{m \in N}$ of order $k = 1$ with transition matrix $p_{trans}(i, j) = P(X_{m+1} = j | X_m = i)$. The maximum likelihood estimation of the transition matrix is $\widehat{p_{trans}}(i, j) = \frac{N_{ij}}{N_i}$, where N_{ij} is the number of transitions from state i to state j and N_i is the number of transition from state i to any state. For $k > 1$ we have similar expressions.

The initial distribution of a k -th order Markov chain is defined as $\mu_i = P(X_1 = i)$. Five methods are proposed for the estimation of the latter :

Maximum Likelihood Estimator: The Maximum Likelihood Estimator for the initial distribution. The formula is: $\widehat{\mu}_i = \frac{N_{start_i}}{L}$, where N_{start_i} is the number of occurrences of the word i (of length k) at the beginning of each sequence and L is the number of sequences. This estimator is reliable when the number of sequences L is high.

Stationary distribution: The stationary distribution is used as a surrogate of the initial distribution. If the order of the Markov chain is more than one, the transition matrix is converted into a square block matrix in order to estimate the stationary distribution. This method may take time if the order of the Markov chain is high (more than three (3)).

Frequencies of each word: The initial distribution is estimated by taking the frequencies of the words of length k for all sequences. The formula is $\widehat{\mu}_i = \frac{N_i}{N}$, where N_i is the number of occurrences of the word i (of length k) in the sequences and N is the sum of the lengths of the sequences.

Product of the frequencies of each state: The initial distribution is estimated by using the product of the frequencies of each state (for all the sequences) in the word of length k .

Uniform distribution: The initial probability of each state is equal to $1/s$, with s , the number of states.

Value

An object of class S3 `mmfit` (inheriting from the S3 class `mm`). The S3 class `mmfit` contains:

- All the attributes of the S3 class `mm`;
- An attribute `M` which is an integer giving the total length of the set of sequences `sequences` (sum of all the lengths of the list `sequences`);
- An attribute `logLik` which is a numeric value giving the value of the log-likelihood of the specified Markov model based on the `sequences`;
- An attribute `sequences` which is equal to the parameter `sequences` of the function `fitmm` (i.e. a list of sequences used to estimate the Markov model).

See Also

[mm](#), [simulate.mm](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)
k <- 2
init <- rep.int(1 / s ^ k, s ^ k)
p <- matrix(0.25, nrow = s ^ k, ncol = s)

# Specify a Markov model of order 2
markov <- mm(states = states, init = init, ptrans = p, k = k)

seqs <- simulate(object = markov, nsim = c(1000, 10000, 2000), seed = 150)

est <- fitmm(sequences = seqs, states = states, k = 2)
```

fitsmm

Maximum Likelihood Estimation (MLE) of a semi-Markov chain

Description

Maximum Likelihood Estimation of a semi-Markov chain starting from one or several sequences. This estimation can be parametric or non-parametric, non-censored, censored at the beginning and/or at the end of the sequence, with one or several trajectories. Several parametric distributions are considered (Uniform, Geometric, Poisson, Discrete Weibull and Negative Binomial).

Usage

```
fitsmm(
  sequences,
  states,
  type.sojourn = c("fij", "fi", "fj", "f"),
```

```

distr = "nonparametric",
init.estim = "mle",
cens.beg = FALSE,
cens.end = FALSE
)

```

Arguments

sequences	A list of vectors representing the sequences.
states	Vector of state space (of length s).
type.sojourn	Type of sojourn time (for more explanations, see Details).
distr	By default "nonparametric" for the non-parametric estimation case. If the parametric estimation case is desired, <code>distr</code> should be: <ul style="list-style-type: none"> • A matrix of distributions of dimension (s, s) if <code>type.sojourn = "fij"</code>; • A vector of distributions of length s if <code>type.sojourn = "fi"</code> or <code>"fj"</code>; • A distribution if <code>type.sojourn = "f"</code>. The distributions to be used in <code>distr</code> must be one of "unif", "geom", "pois", "dweibull", "nbinom".
init.estim	Optional. <code>init.estim</code> gives the method used to estimate the initial distribution. The following methods are proposed: <ul style="list-style-type: none"> • <code>init.estim = "mle"</code>: the classical Maximum Likelihood Estimator is used to estimate the initial distribution <code>init</code>; • <code>init.estim = "limit"</code>: the initial distribution is replaced by the limit (stationary) distribution of the semi-Markov chain; • <code>init.estim = "freq"</code>: the initial distribution is replaced by the frequencies of each state in the sequences; • <code>init.estim = "unif"</code>: the initial probability of each state is equal to $1/s$, with s the number of states.
cens.beg	Optional. A logical value indicating whether or not sequences are censored at the beginning.
cens.end	Optional. A logical value indicating whether or not sequences are censored at the end.

Details

This function estimates a semi-Markov model in parametric or non-parametric case, taking into account the type of sojourn time and the censoring described in references. The non-parametric estimation concerns sojourn time distributions defined by the user. For the parametric estimation, several discrete distributions are considered (see below).

The difference between the Markov model and the semi-Markov model concerns the modeling of the sojourn time. With a Markov chain, the sojourn time distribution is modeled by a Geometric distribution (in discrete time). With a semi-Markov chain, the sojourn time can be any arbitrary distribution. In this package, the available distribution for a semi-Markov model are :

- Uniform: $f(x) = \frac{1}{n}$ for $1 \leq x \leq n$. n is the parameter;

- Geometric: $f(x) = \theta(1 - \theta)^{x-1}$ for $x = 1, 2, \dots, n$, $0 < \theta < 1$, θ is the probability of success. θ is the parameter;
- Poisson: $f(x) = \frac{\lambda^x \exp(-\lambda)}{x!}$ for $x = 0, 1, 2, \dots, n$, with $\lambda > 0$. λ is the parameter;
- Discrete Weibull of type 1: $f(x) = q^{(x-1)^\beta} - q^{x^\beta}$, $x = 1, 2, \dots, n$, with $0 < q < 1$, the first parameter and $\beta > 0$ the second parameter. (q, β) are the parameters;
- Negative binomial: $f(x) = \frac{\Gamma(x+\alpha)}{\Gamma(\alpha)x!} p^\alpha (1-p)^x$, for $x = 0, 1, 2, \dots, n$, Γ is the Gamma function, α is the parameter of overdispersion and p is the probability of success, $0 < p < 1$. (α, p) are the parameters;
- Non-parametric.

We define :

- the semi-Markov kernel $q_{ij}(k) = P(J_{m+1} = j, T_{m+1} - T_m = k | J_m = i)$;
- the transition matrix $(p_{trans}(i, j))_{i, j} \in states$ of the embedded Markov chain $J = (J_m)_m$, $p_{trans}(i, j) = P(J_{m+1} = j | J_m = i)$;
- the initial distribution $\mu_i = P(J_1 = i) = P(Z_1 = i)$, $i \in 1, 2, \dots, s$;
- the conditional sojourn time distributions $(f_{ij}(k))_{i, j} \in states$, $k \in N$, $f_{ij}(k) = P(T_{m+1} - T_m = k | J_m = i, J_{m+1} = j)$, f is specified by the argument param in the parametric case and by distr in the non-parametric case.

The maximum likelihood estimation of the transition matrix of the embedded Markov chain is $\widehat{p_{trans}}(i, j) = \frac{N_{ij}}{N_i}$.

Five methods are proposed for the estimation of the initial distribution :

Maximum Likelihood Estimator: The Maximum Likelihood Estimator for the initial distribution. The formula is: $\widehat{\mu}_i = \frac{N_{start_i}}{L}$, where N_{start_i} is the number of occurrences of the word i (of length k) at the beginning of each sequence and L is the number of sequences. This estimator is reliable when the number of sequences L is high.

Limit (stationary) distribution: The limit (stationary) distribution of the semi-Markov chain is used as a surrogate of the initial distribution.

Frequencies of each state: The initial distribution is replaced by taking the frequencies of each state in the sequences.

Uniform distribution: The initial probability of each state is equal to $1/s$, with s , the number of states.

Note that $q_{ij}(k) = p_{trans}(i, j) f_{ij}(k)$ in the general case (depending on the present state and on the next state). For particular cases, we replace $f_{ij}(k)$ by $f_i(k)$ (depending on the present state i), $f_j(k)$ (depending on the next state j) and $f_{..}(k)$ (depending neither on the present state nor on the next state).

In this package we can choose different types of sojourn time. Four options are available for the sojourn times:

- depending on the present state and on the next state (f i j);
- depending only on the present state (f i);
- depending only on the next state (f j);

- depending neither on the current, nor on the next state (f).

If `type.sojourn = "fij"`, `distr` is a matrix of dimension (s, s) (e.g., if the 1st element of the 2nd column is "pois", that is to say we go from the first state to the second state following a Poisson distribution). If `type.sojourn = "fi"` or `"fj"`, `distr` must be a vector (e.g., if the first element of vector is "geom", that is to say we go from (or to) the first state to (or from) any state according to a Geometric distribution). If `type.sojourn = "f"`, `distr` must be one of "unif", "geom", "pois", "dweibull", "nbinom" (e.g., if `distr` is equal to "nbinom", that is to say that the sojourn time when going from one state to another state follows a Negative Binomial distribution). For the non-parametric case, `distr` is equal to "nonparametric" whatever type of sojourn time given.

If the sequence is censored at the beginning and/or at the end, `cens.beg` must be equal to TRUE and/or `cens.end` must be equal to TRUE. All the sequences must be censored in the same way.

Value

Returns an object of S3 class `smmfit` (inheriting from the S3 class `smm` and `smmnonparametric` class if `distr = "nonparametric"` or `smmparametric` otherwise). The S3 class `smmfit` contains:

- All the attributes of the S3 class `smmnonparametric` or `smmparametric` depending on the type of estimation;
- An attribute `M` which is an integer giving the total length of the set of sequences sequences (sum of all the lengths of the list sequences);
- An attribute `logLik` which is a numeric value giving the value of the log-likelihood of the specified semi-Markov model based on the sequences;
- An attribute `sequences` which is equal to the parameter sequences of the function `fitsmm` (i.e. a list of sequences used to estimate the Markov model).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

See Also

[smmnonparametric](#), [smmparametric](#), [simulate.smm](#), [simulate.smmfit](#), [plot.smm](#), [plot.smmfit](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)

# Creation of the initial distribution
vect.init <- c(1 / 4, 1 / 4, 1 / 4, 1 / 4)

# Creation of the transition matrix
pij <- matrix(c(0, 0.2, 0.5, 0.3,
               0.2, 0, 0.3, 0.5,
               0.3, 0.5, 0, 0.2,
               0.4, 0.2, 0.4, 0),
```

```

ncol = s, byrow = TRUE)

# Creation of the distribution matrix

distr.matrix <- matrix(c(NA, "pois", "geom", "nbinom",
                        "geom", NA, "pois", "dweibull",
                        "pois", "pois", NA, "geom",
                        "pois", "geom", "geom", NA),
                      nrow = s, ncol = s, byrow = TRUE)

# Creation of an array containing the parameters
param1.matrix <- matrix(c(NA, 2, 0.4, 4,
                        0.7, NA, 5, 0.6,
                        2, 3, NA, 0.6,
                        4, 0.3, 0.4, NA),
                      nrow = s, ncol = s, byrow = TRUE)

param2.matrix <- matrix(c(NA, NA, NA, 0.6,
                        NA, NA, NA, 0.8,
                        NA, NA, NA, NA,
                        NA, NA, NA, NA),
                      nrow = s, ncol = s, byrow = TRUE)

param.array <- array(c(param1.matrix, param2.matrix), c(s, s, 2))

# Specify the semi-Markov model
semimarkov <- smmparametric(states = states, init = vect.init, ptrans = pij,
                          type.sojourn = "fij", distr = distr.matrix,
                          param = param.array)

seqs <- simulate(object = semimarkov, nsim = c(1000, 10000, 2000), seed = 100)

# Estimation of simulated sequences
est <- fitsmm(sequences = seqs, states = states, type.sojourn = "fij",
             distr = distr.matrix)

```

get.f

Method to get the conditional sojourn time distribution f

Description

Computes the conditional sojourn time distribution $f(k)$, $f_i(k)$, $f_j(k)$ or $f_{ij}(k)$.

Usage

```
get.f(x, k)
```

Arguments

- x An object of S3 class `smmfit` or `smm`.
- k A strictly positive integer giving the time horizon (k must be different from 0 since we assume that there are not instantaneous transitions).

Value

A vector, matrix or array giving the value of f at each time between 1 and k.

get.H	<i>Function to compute the value of the sojourn time cumulative distribution H</i>
-------	---

Description

Function to compute the value of H (See equation (3.4) p.46).

Usage

get.H(q)

Arguments

- q An array giving the values of the kernel for a giving time horizon $[0, \dots, k]$ (This kernel q is the output of the method `getKernel` or `get.qy`).

Value

An array giving the value of $H(k)$ at each time between 0 and k.

get.Kpar	<i>Method to get the number of parameters of a Markov or semi-Markov chain</i>
----------	--

Description

Method to get the number of parameters of a Markov or such as AIC and BIC.

Usage

get.Kpar(x)

Arguments

- x An object for which the number of parameters can be returned (An object of class `smm` or `mm`).

Value

A positive integer giving the number of parameters.

get.limitDistribution *Method to get the limit (stationary) distribution*

Description

Method to get the limit (stationary) distribution of a semi-Markov chain.

Usage

```
get.limitDistribution(x, klim = 10000)
```

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function).

Value

A vector of length $\text{card}(E)$ giving the values of the limit distribution.

get.Niuj	<i>Function giving the value of the counting process N_{iuj} used in the estimation of the kernel and the transition matrix of censored and non-parametric semi-markov chains (cf. article Exact MLE and asymptotic properties for nonparametric semi-Markov models)</i>
----------	---

Description

Function giving the value of the counting process N_{iuj} used in the estimation of the kernel and the transition matrix of censored and non-parametric semi-markov chains (cf. article Exact MLE and asymptotic properties for nonparametric semi-Markov models)

Usage

```
get.Niuj(sequences)
```

Arguments

sequences	A list of sequences of states.
-----------	--------------------------------

Value

An array giving the values of the counting process N_{iuj} .

get.P *Method to compute the value of P*

Description

Method to compute the value of P (See equation (3.33) p.59).

Usage

```
get.P(x, k, states = x$states, var = FALSE, klim = 10000)
```

Arguments

x An object of S3 class `smmfit` or `smm`.

k A positive integer giving the time horizon.

states Vector giving the states for which the mean sojourn time should be computed. `states` is a subset of E .

var Logical. If TRUE the asymptotic variance is computed.

klim Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. [meanSojournTimes](#) function) for the asymptotic variance.

Value

An array giving the value of $P_{i,j}(k)$ at each time between 0 and k if `var = FALSE`. If `var = TRUE`, a list containing the following components:

x: an array giving the value of $P_{i,j}(k)$ at each time between 0 and k ;

sigma2: an array giving the asymptotic variance of the estimator $\sigma_P^2(i, j, k)$.

get.psi *Function to compute the value of the matrix-valued function ψ*

Description

Function to compute the value of ψ , the matrix-valued function (See equation (3.16) p.53).

Usage

```
get.psi(q)
```

Arguments

q An array giving the values of the kernel for a given time horizon $[0, \dots, k]$ (This kernel `q` is the output of the method `getKernel` or `.get.qy`).

Value

An array giving the value of $\psi(k)$ at each time between 0 and k.

get.Py

Method to compute the value of P_Y

Description

Method to compute the value of P_Y (See Proposition 5.1 p.105-106).

Usage

get.Py(x, k, upstates = x\$states)

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
k	A positive integer giving the time horizon.
upstates	Vector giving the subset of operational states U .

Value

An array giving the value of $P_Y(k)$ at each time between 0 and k.

get.qy

Method to get the semi-Markov kernel q_Y

Description

Computes the semi-Markov kernel $q_Y(k)$ (See proposition 5.1 p.106).

Usage

get.qy(x, k, upstates = x\$states)

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
k	A positive integer giving the time horizon.
upstates	Vector giving the subset of operational states U .

Value

An array giving the value of $q_Y(k)$ at each time between 0 and k.

 get.stationaryDistribution

Method to get the stationary distribution

Description

Method to get the stationary distribution of a Markov chain. If the order of the Markov chain is higher than one, a block matrix is computed to get the stationary distribution.

Usage

```
get.stationaryDistribution(x)
```

Arguments

x An object of S3 class mm or mmfit.

Value

A vector of length $\text{card}(E)$ giving the values of the stationary distribution.

 getKernel

Method to get the semi-Markov kernel q

Description

Computes the semi-Markov kernel $q_{ij}(k)$.

Usage

```
getKernel(x, k, var = FALSE, klim = 10000)
```

Arguments

x An object of S3 class smmfit or smm.

k A positive integer giving the time horizon.

var Logical. If TRUE the asymptotic variance is computed.

klim Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. [meanSojournTimes](#) function) for the asymptotic variance.

Value

An array giving the value of $q_{ij}(k)$ at each time between 0 and k if var = FALSE. If var = TRUE, a list containing the following components:

x: an array giving the value of $q_{ij}(k)$ at each time between 0 and k;

sigma2: an array giving the asymptotic variance of the estimator $\sigma_q^2(i, j, k)$.

 getProcesses

Function to compute processes based on a list of sequences

Description

Function to compute processes based on a list of sequences

Usage

```
getProcesses(sequences)
```

Arguments

sequences A list of sequences of states.

Value

A list giving:

s: Cardinal of the states space;

states: Vector of state space of length s ;

M: The total length (sum of the length of each sequence);

L: The number of sequences;

kmax : Maximum length of the sojourn times;

Ym: List of semi-Markov chains;

Jm: List of successively visited states for each sequence;

Tm: List of successive time points when state changes for each sequence;

Lm: List of sojourn time for each sequence;

Um: List of backward recurrence time for each sequence;

counting: List giving the counting processes such as $N_{ij}(k)$, $N_i(k)$, $N_j(k)$...

is.mm	<i>Function to check if an object is of class mm</i>
-------	--

Description

is.mm returns TRUE if x is an object of class mm.

Usage

```
is.mm(x)
```

Arguments

x An arbitrary R object.

Value

is.mm returns TRUE or FALSE depending on whether x is an object of class mm or not.

is.mmfit	<i>Function to check if an object is of class mmfit</i>
----------	---

Description

is.mmfit returns TRUE if x is an object of class mmfit.

Usage

```
is.mmfit(x)
```

Arguments

x An arbitrary R object.

Value

is.mmfit returns TRUE or FALSE depending on whether x is an object of class mmfit or not.

is.smm	<i>Function to check if an object is of class smm</i>
--------	---

Description

is.smm returns TRUE if x is an object of class smm.

Usage

```
is.smm(x)
```

Arguments

x An arbitrary R object.

Value

is.smm returns TRUE or FALSE depending on whether x is an object of class smm or not.

is.smmfit	<i>Function to check if an object is of class smmfit</i>
-----------	--

Description

is.smmfit returns TRUE if x is an object of class smmfit.

Usage

```
is.smmfit(x)
```

Arguments

x An arbitrary R object.

Value

is.smmfit returns TRUE or FALSE depending on whether x is an object of class smmfit or not.

`is.smmnonparametric` *Function to check if an object is of class smmnonparametric*

Description

`is.smmnonparametric` returns TRUE if `x` is an object of class `smmnonparametric`.

Usage

`is.smmnonparametric(x)`

Arguments

`x` An arbitrary R object.

Value

`is.smmnonparametric` returns TRUE or FALSE depending on whether `x` is an object of class `smmnonparametric` or not.

`is.smmparametric` *Function to check if an object is of class smmparametric*

Description

`is.smmparametric` returns TRUE if `x` is an object of class `smmparametric`.

Usage

`is.smmparametric(x)`

Arguments

`x` An arbitrary R object.

Value

`is.smmparametric` returns TRUE or FALSE depending on whether `x` is an object of class `smmparametric` or not.

maintainability	<i>Maintainability Function</i>
-----------------	---------------------------------

Description

For a reparable system S_{system} for which the failure occurs at time $k = 0$, its maintainability at time $k \in N$ is the probability that the system is repaired up to time k , given that it has failed at time $k = 0$.

Usage

```
maintainability(x, k, upstates = x$states, level = 0.95, klim = 10000)
```

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
k	A positive integer giving the period $[0, k]$ on which the maintainability should be computed.
upstates	Vector giving the subset of operational states U .
level	Confidence level of the asymptotic confidence interval. Helpful for an object <code>x</code> of class <code>smmfit</code> .
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the maintainability of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The system starts to fail at instant 0 and the state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

Thus, we take $(\alpha_i := P(Z_0 = i))_{i \in U} = 0$ and we denote by T_U the first hitting time of subset U , called the duration of repair or repair time, that is,

$$T_U := \inf\{n \in N; Z_n \in U\} \text{ and } \inf \emptyset := \infty.$$

The maintainability at time $k \in N$ of a discrete-time semi-Markov system is

$$M(k) = P(T_U \leq k) = 1 - P(T_U > k) = 1 - P(Z_n \in D, n = 0, \dots, k).$$

Value

A matrix with $k + 1$ rows, and with columns giving values of the maintainability, variances, lower and upper asymptotic confidence limits (if x is an object of class `smmfit`).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

matrixConvolution	<i>Discrete-time matrix convolution product (See definition 3.5 p. 48)</i>
-------------------	--

Description

Discrete-time matrix convolution product (See definition 3.5 p. 48)

Usage

```
matrixConvolution(a, b)
```

Arguments

a An array of dimension $(S, S, k + 1)$.
b An array of dimension $(S, S, k + 1)$.

Value

An array of dimension $(S, S, k + 1)$ giving the discrete-time matrix convolution product for each $k \in N$.

meanRecurrenceTimes *Method to get the mean recurrence times μ*

Description

Method to get the mean recurrence times μ .

Usage

```
meanRecurrenceTimes(x, klim = 10000)
```

Arguments

x An object of S3 class `smmfit` or `smm`.

klim Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. [meanSojournTimes](#) function).

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$.

We are interested in investigating the mean recurrence times of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$.

Let $T = (T_n)_{n \in N}$ denote the successive time points when state changes in $(Z_n)_{n \in N}$ occur and let also $J = (J_n)_{n \in N}$ denote the successively visited states at these time points.

The mean recurrence of an arbitrary state $j \in E$ is given by:

$$\mu_{jj} = \frac{\sum_{i \in E} \nu(i) m_i}{\nu(j)}$$

where $(\nu(1), \dots, \nu(s))$ is the stationary distribution of the embedded Markov chain $(J_n)_{n \in N}$ and m_i is the mean sojourn time in state $i \in E$ (see [meanSojournTimes](#) function for the computation).

Value

A vector giving the mean recurrence time $(\mu_i)_{i \in [1, \dots, s]}$.

meanSojournTimes	<i>Mean Sojourn Times Function</i>
------------------	------------------------------------

Description

The mean sojourn time is the mean time spent in each state.

Usage

```
meanSojournTimes(x, states = x$states, klim = 10000)
```

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
states	Vector giving the states for which the mean sojourn time should be computed. states is a subset of E .
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function).

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$.

We are interested in investigating the mean sojourn times of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$.

Let $T = (T_n)_{n \in N}$ denote the successive time points when state changes in $(Z_n)_{n \in N}$ occur and let also $J = (J_n)_{n \in N}$ denote the successively visited states at these time points.

The mean sojourn times vector is defined as follows:

$$m_i = E[T_1 | Z_0 = j] = \sum_{k \geq 0} (1 - P(T_{n+1} - T_n \leq k | J_n = j)) = \sum_{k \geq 0} (1 - H_j(k)), \quad i \in E$$

Value

A vector of length $\text{card}(E)$ giving the values of the mean sojourn times for each state $i \in E$.

mm	<i>Markov model specification</i>
----	-----------------------------------

Description

Creates a model specification of a Markov model.

Usage

```
mm(states, init, ptrans, k = 1)
```

Arguments

states	Vector of state space of length s .
init	Vector of initial distribution of length s^k .
ptrans	Matrix of transition probabilities of dimension (s, s) .
k	Order of the Markov chain.

Value

An object of class `mm`.

See Also

[simulate.mm](#), [fitmm](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)
k <- 1
init <- rep.int(1 / s, s)
p <- matrix(c(0, 0, 0.3, 0.4, 0, 0, 0.5, 0.2, 0.7, 0.5,
             0, 0.4, 0.3, 0.5, 0.2, 0), ncol = s)

# Specify a Markov model of order 1
markov <- mm(states = states, init = init, ptrans = p, k = k)
```

mttf

*Mean Time To Failure (MTTF) Function***Description**

Consider a system S_{system} starting to work at time $k = 0$. The mean time to failure (MTTF) is defined as the mean lifetime.

Usage

```
mttf(x, upstates = x$states, level = 0.95, klim = 10000)
```

Arguments

<code>x</code>	An object of S3 class <code>smmfit</code> or <code>smm</code> .
<code>upstates</code>	Vector giving the subset of operational states U .
<code>level</code>	Confidence level of the asymptotic confidence interval. Helpful for an object <code>x</code> of class <code>smmfit</code> .
<code>klim</code>	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the mean time to failure of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The system starts to work at instant 0 and the state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

Let T_D denote the first passage time in subset D , called the lifetime of the system, i.e.,

$$T_D := \inf\{n \in N; Z_n \in D\} \text{ and } \inf \emptyset := \infty.$$

The mean time to failure (MTTF) is defined as the mean lifetime, i.e., the expectation of the hitting time to down set D ,

$$MTTF = E[T_D]$$

Value

A matrix with $\text{card}(U) = s_1$ rows, and with columns giving values of the mean time to failure for each state $i \in U$, variances, lower and upper asymptotic confidence limits (if x is an object of class `smmfit`).

References

V. S. Barbu, N. Limnios. (2008). *Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis*. New York: Lecture Notes in Statistics, vol. 191, Springer.

I. Votsi & A. Brouste (2019) Confidence interval for the mean time to failure in semi-Markov models: an application to wind energy production, *Journal of Applied Statistics*, 46:10, 1756-1773

 mttr

Mean Time To Repair (MTTR) Function

Description

Consider a system S_{system} that has just failed at time $k = 0$. The mean time to repair (MTTR) is defined as the mean of the repair duration.

Usage

```
mttr(x, upstates = x$states, level = 0.95, klim = 10000)
```

Arguments

<code>x</code>	An object of S3 class <code>smmfit</code> or <code>smm</code> .
<code>upstates</code>	Vector giving the subset of operational states U .
<code>level</code>	Confidence level of the asymptotic confidence interval. Helpful for an object x of class <code>smmfit</code> .
<code>klim</code>	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the mean time to repair of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in \mathbb{N}}$. The system has just failed at instant 0 and the state of the

system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

Let T_U denote the first passage time in subset U , called the duration of repair or repair time, i.e.,

$$T_U := \inf\{n \in N; Z_n \in U\} \text{ and } \inf \emptyset := \infty.$$

The mean time to repair (MTTR) is defined as the mean of the repair duration, i.e., the expectation of the hitting time to up set U ,

$$MTTR = E[T_U]$$

Value

A matrix with $\text{card}(U) = s_1$ rows, and with columns giving values of the mean time to repair for each state $i \in U$, variances, lower and upper asymptotic confidence limits (if x is an object of class `smmfit`).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

I. Votsi & A. Brouste (2019) Confidence interval for the mean time to failure in semi-Markov models: an application to wind energy production, Journal of Applied Statistics, 46:10, 1756-1773

plot.smm

Plot function for an object of class smm

Description

Displays the densities for the conditional sojourn time distributions depending on the current state i and on the next state j .

Usage

```
## S3 method for class 'smm'
plot(x, i, j, klim = NULL, ...)
```

Arguments

x	An object of S3 class <code>smm</code> (inheriting from the S3 class <code>smmnonparametric</code> or <code>smmparametric</code>).
i	An element of the state space vector <code>x\$states</code> giving the current state in the following cases: <code>type.sojourn = "fij"</code> or <code>type.sojourn = "fi"</code> , otherwise, <code>i</code> is ignored.
j	An element of the state space vector <code>x\$states</code> giving the next state in the following cases: <code>type.sojourn = "fij"</code> or <code>type.sojourn = "fj"</code> , otherwise, <code>j</code> is ignored.
klim	An integer giving the limit value for which the density will be plotted. If <code>klim</code> is <code>NULL</code> , then quantile or order 0.95 is used.
...	Arguments passed to <code>plot</code> .

Value

None.

`plot.smmfit`

Plot function for an object of class `smmfit`

Description

Displays the densities for the conditional sojourn time distributions depending on the current state `i` and on the next state `j`.

Usage

```
## S3 method for class 'smmfit'
plot(x, i, j, klim = NULL, ...)
```

Arguments

x	An object of class <code>smmfit</code> (inheriting from the S3 classes <code>smm</code> , <code>smmnonparametric</code> or <code>smmparametric</code>).
i	An element of the state space vector <code>x\$states</code> giving the current state in the following cases: <code>type.sojourn = "fij"</code> or <code>type.sojourn = "fi"</code> , otherwise, <code>i</code> is ignored.
j	An element of the state space vector <code>x\$states</code> giving the next state in the following cases: <code>type.sojourn = "fij"</code> or <code>type.sojourn = "fj"</code> , otherwise, <code>j</code> is ignored.
klim	An integer giving the limit value for which the density will be plotted. If <code>klim</code> is <code>NULL</code> , then quantile or order 0.95 is used.
...	Arguments passed to <code>plot</code> .

Value

None.

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

Examples

```

states <- c("a", "c", "g", "t")
s <- length(states)

# Creation of the initial distribution
vect.init <- c(1 / 4, 1 / 4, 1 / 4, 1 / 4)

# Creation of the transition matrix
pij <- matrix(c(0, 0.2, 0.3, 0.4, 0.2, 0, 0.5, 0.2, 0.5,
               0.3, 0, 0.4, 0.3, 0.5, 0.2, 0), ncol = s)

# Creation of the distribution matrix
distr.vec <- c("pois", "geom", "geom", "geom")
parameters <- matrix(c(2, 0.6, 0.8, 0.8, NA, NA, NA, NA),
                    ncol = 2, byrow = FALSE)

# Specify the semi-Markov model
smm <- smmparametric(states = states, init = vect.init, ptrans = pij,
                    type.sojourn = "fi", distr = distr.vec, param = parameters)

seqs <- simulate(object = smm, nsim = rep(5000, 100), seed = 10)

est <- fitsmm(sequences = seqs, states = states, type.sojourn = "fi", distr = distr.vec)

class(est)

plot(x = est, i = "a", col = "blue", pch = "+")

```

reliability

*Reliability Function***Description**

Consider a system S_{system} starting to function at time $k = 0$. The reliability or the survival function of S_{system} at time $k \in N$ is the probability that the system has functioned without failure in the period $[0, k]$.

Usage

```
reliability(x, k, upstates = x$states, level = 0.95, klim = 10000)
```

Arguments

x	An object of S3 class <code>smmfit</code> or <code>smm</code> .
k	A positive integer giving the period $[0, k]$ on which the reliability should be computed.
upstates	Vector giving the subset of operational states U .
level	Confidence level of the asymptotic confidence interval. Helpful for an object <code>x</code> of class <code>smmfit</code> .
klim	Optional. The time horizon used to approximate the series in the computation of the mean sojourn times vector m (cf. meanSojournTimes function) for the asymptotic variance.

Details

Consider a system (or a component) S_{system} whose possible states during its evolution in time are $E = \{1, \dots, s\}$. Denote by $U = \{1, \dots, s_1\}$ the subset of operational states of the system (the up states) and by $D = \{s_1 + 1, \dots, s\}$ the subset of failure states (the down states), with $0 < s_1 < s$ (obviously, $E = U \cup D$ and $U \cap D = \emptyset$, $U \neq \emptyset$, $D \neq \emptyset$). One can think of the states of U as different operating modes or performance levels of the system, whereas the states of D can be seen as failures of the systems with different modes.

We are interested in investigating the reliability of a discrete-time semi-Markov system S_{system} . Consequently, we suppose that the evolution in time of the system is governed by an E-state space semi-Markov chain $(Z_k)_{k \in N}$. The system starts to work at instant 0 and the state of the system is given at each instant $k \in N$ by Z_k : the event $\{Z_k = i\}$, for a certain $i \in U$, means that the system S_{system} is in operating mode i at time k , whereas $\{Z_k = j\}$, for a certain $j \in D$, means that the system is not operational at time k due to the mode of failure j or that the system is under the repairing mode j .

Let T_D denote the first passage time in subset D , called the lifetime of the system, i.e.,

$$T_D := \inf\{n \in N; Z_n \in D\} \text{ and } \inf \emptyset := \infty.$$

The reliability or the survival function at time $k \in N$ of a discrete-time semi-Markov system is:

$$R(k) := P(T_D > k) = P(Z_n \in U, n = 0, \dots, k)$$

which can be rewritten as follows:

$$R(k) = \sum_{i \in U} P(Z_0 = i)P(T_D > k | Z_0 = i) = \sum_{i \in U} \alpha_i P(T_D > k | Z_0 = i)$$

Value

A matrix with $k + 1$ rows, and with columns giving values of the reliability, variances, lower and upper asymptotic confidence limits (if `x` is an object of class `smmfit`).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

setSeed	<i>Set the RNG Seed from within Rcpp</i>
---------	--

Description

Set the RNG Seed from within Rcpp

Usage

```
setSeed(seed)
```

Arguments

seed An unsigned int that is the seed one wishes to use.

Value

A set RNG scope.

Examples

```
set.seed(10)
x <- rnorm(5, 0, 1)
setSeed(10)
y <- rnorm(5, 0, 1)
all.equal(x, y, check.attributes = FALSE)
```

simulate.mm	<i>Simulates k-th order Markov chains</i>
-------------	---

Description

Simulates k-th order Markov chains.

Usage

```
## S3 method for class 'mm'
simulate(object, nsim = 1, seed = NULL, ...)
```

Arguments

object	An object of class mm .
nsim	An integer or vector of integers (for multiple sequences) specifying the length of the sequence(s).
seed	Optional. seed for the random number generator. If no seed is given, then seed is set by using the command <code>set.seed(round(as.numeric(Sys.time())))</code> .
...	further arguments passed to or from other methods.

Details

If `nsim` is a single integer then a chain of that length is produced. If `nsim` is a vector of integers, then `length(nsim)` sequences are generated with respective lengths.

Value

A list of vectors representing the sequences.

See Also

[mm](#), [fitmm](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)
k <- 2
init <- rep.int(1 / s ^ k, s ^ k)
p <- matrix(0.25, nrow = s ^ k, ncol = s)

# Specify a Markov model of order 1
markov <- mm(states = states, init = init, ptrans = p, k = k)

seqs <- simulate(object = markov, nsim = c(1000, 10000, 2000), seed = 150)
```

simulate.mmfit

Simulates Markov chains

Description

Simulates sequences from a fitted Markov model.

Usage

```
## S3 method for class 'mmfit'
simulate(object, nsim = 1, seed = NULL, ...)
```

Arguments

object	An object of class <code>mmfit</code> .
nsim	An integer or vector of integers (for multiple sequences) specifying the length of the sequence(s).
seed	Optional. seed for the random number generator. If no seed is given, then seed is set by using the command <code>set.seed(round(as.numeric(Sys.time())))</code> .
...	further arguments passed to or from other methods.

Details

If `nsim` is a single integer then a chain of that length is produced. If `nsim` is a vector of integers, then `length(nsim)` sequences are generated with respective lengths.

Value

A list of vectors representing the sequences.

See Also

[mm](#), [fitmm](#)

simulate.smm

Simulates semi-Markov chains

Description

Simulates sequences from a semi-Markov model.

Usage

```
## S3 method for class 'smm'
simulate(object, nsim = 1, seed = NULL, ...)
```

Arguments

object	An object of S3 class <code>smm</code> (inheriting from the S3 class smmnonparametric or smmparametric).
nsim	An integer or vector of integers (for multiple sequences) specifying the length of the sequence(s).
seed	Optional. seed for the random number generator. If no seed is given, then seed is set by using the command <code>set.seed(round(as.numeric(Sys.time())))</code> .
...	further arguments passed to or from other methods.

Details

If `nsim` is a single integer then a chain of that length is produced. If `nsim` is a vector of integers, then `length(nsim)` sequences are generated with respective lengths.

Value

A list of vectors representing the sequences.

References

V. S. Barbu, N. Limnios. (2008). *Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis*. New York: Lecture Notes in Statistics, vol. 191, Springer.

See Also

[smpparametric](#), [smpnonparametric](#), [fitsmp](#)

simulate.smmfit	<i>Simulates semi-Markov chains</i>
-----------------	-------------------------------------

Description

Simulates sequences from a fitted semi-Markov model.

Usage

```
## S3 method for class 'smmfit'  
simulate(object, nsim = 1, seed = NULL, ...)
```

Arguments

object	An object of class <code>smmfit</code> (inheriting from the S3 classes <code>smp</code> , smpnonparametric or smpparametric).
nsim	An integer or vector of integers (for multiple sequences) specifying the length of the sequence(s).
seed	seed for the random number generator.
...	further arguments passed to or from other methods.

Details

If `nsim` is a single integer then a chain of that length is produced. If `nsim` is a vector of integers, then `length(nsim)` sequences are generated with respective lengths.

Value

A list of vectors representing the sequences.

References

V. S. Barbu, N. Limnios. (2008). *Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis*. New York: Lecture Notes in Statistics, vol. 191, Springer.

See Also

[smmnonparametric](#), [smmparametric](#), [fitsmm](#)

smmnonparametric	<i>Non-parametric semi-Markov model specification</i>
------------------	---

Description

Creates a non-parametric model specification for a semi-Markov model.

Usage

```
smmnonparametric(
  states,
  init,
  ptrans,
  type.sojourn = c("fij", "fi", "fj", "f"),
  distr,
  cens.beg = FALSE,
  cens.end = FALSE
)
```

Arguments

states	Vector of state space of length s .
init	Vector of initial distribution of length s .
ptrans	Matrix of transition probabilities of the embedded Markov chain $J = (J_m)_m$ of dimension (s, s) .
type.sojourn	Type of sojourn time (for more explanations, see Details).
distr	<ul style="list-style-type: none"> • Array of dimension $(s, s, kmax)$ if type.sojourn = "fij"; • Matrix of dimension $(s, kmax)$ if type.sojourn = "fi" or "fj"; • Vector of length $kmax$ if the type.sojourn = "f". <p>$kmax$ is the maximum length of the sojourn times.</p>
cens.beg	Optional. A logical value indicating whether or not sequences are censored at the beginning.
cens.end	Optional. A logical value indicating whether or not sequences are censored at the end.

Details

This function creates a semi-Markov model object in the non-parametric case, taking into account the type of sojourn time and the censoring described in references. The non-parametric specification concerns sojourn time distributions defined by the user.

The difference between the Markov model and the semi-Markov model concerns the modeling of the sojourn time. With a Markov chain, the sojourn time distribution is modeled by a Geometric

distribution (in discrete time). With a semi-Markov chain, the sojourn time can be any arbitrary distribution.

We define :

- the semi-Markov kernel $q_{ij}(k) = P(J_{m+1} = j, T_{m+1} - T_m = k | J_m = i)$;
- the transition matrix $(p_{trans}(i, j))_{i,j} \in \text{states}$ of the embedded Markov chain $J = (J_m)_m$, $p_{trans}(i, j) = P(J_{m+1} = j | J_m = i)$;
- the initial distribution $\mu_i = P(J_1 = i) = P(Z_1 = i)$, $i \in 1, 2, \dots, s$;
- the conditional sojourn time distributions $(f_{ij}(k))_{i,j} \in \text{states}$, $k \in N$, $f_{ij}(k) = P(T_{m+1} - T_m = k | J_m = i, J_{m+1} = j)$, f is specified by the argument `distr` in the non-parametric case.

In this package we can choose different types of sojourn time. Four options are available for the sojourn times:

- depending on the present state and on the next state (f_{ij});
- depending only on the present state (f_i);
- depending only on the next state (f_j);
- depending neither on the current, nor on the next state (f).

Let define `kmax` the maximum length of the sojourn times. If `type.sojourn = "fij"`, `distr` is an array of dimension $(s, s, kmax)$. If `type.sojourn = "fi"` or `"fj"`, `distr` must be a matrix of dimension $(s, kmax)$. If `type.sojourn = "f"`, `distr` must be a vector of length `kmax`.

If the sequence is censored at the beginning and/or at the end, `cens.beg` must be equal to TRUE and/or `cens.end` must be equal to TRUE. All the sequences must be censored in the same way.

Value

Returns an object of class `smm`, [smmnonparametric](#).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

See Also

[simulate](#), [fitsmm](#), [smmparametric](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)

# Creation of the initial distribution
vect.init <- c(1 / 4, 1 / 4, 1 / 4, 1 / 4)

# Creation of the transition matrix
pij <- matrix(c(0, 0.2, 0.5, 0.3,
```

```

      0.2, 0, 0.3, 0.5,
      0.3, 0.5, 0, 0.2,
      0.4, 0.2, 0.4, 0),
      ncol = s, byrow = TRUE)

# Creation of a matrix corresponding to the
# conditional sojourn time distributions
kmax <- 6
nparam.matrix <- matrix(c(0.2, 0.1, 0.3, 0.2,
                          0.2, 0, 0.4, 0.2,
                          0.1, 0, 0.2, 0.1,
                          0.5, 0.3, 0.15, 0.05,
                          0, 0, 0.3, 0.2,
                          0.1, 0.2, 0.2, 0),
                        nrow = s, ncol = kmax, byrow = TRUE)

semimarkov <- smmnonparametric(states = states, init = vect.init, ptrans = pij,
                              type.sojourn = "fj", distr = nparam.matrix)

semimarkov

```

smmparametric

Parametric semi-Markov model specification

Description

Creates a parametric model specification for a semi-Markov model.

Usage

```

smmparametric(
  states,
  init,
  ptrans,
  type.sojourn = c("fij", "fi", "fj", "f"),
  distr,
  param,
  cens.beg = FALSE,
  cens.end = FALSE
)

```

Arguments

states	Vector of state space of length s .
init	Vector of initial distribution of length s .
ptrans	Matrix of transition probabilities of the embedded Markov chain $J = (J_m)_m$ of dimension (s, s) .

type.sojourn	Type of sojourn time (for more explanations, see Details).
distr	<ul style="list-style-type: none"> • Matrix of distributions of dimension (s, s) if type.sojourn = "fij"; • Vector of distributions of length s if type.sojourn = "fi" or "fj"; • A distribution if type.sojourn = "f". <p>where the distributions to be used can be one of unif, geom, pois, dweibull or nbinom.</p>
param	<p>Parameters of sojourn time distributions:</p> <ul style="list-style-type: none"> • Array of distribution parameters of dimension $(s, s, 2)$ (2 corresponds to the maximal number of distribution parameters) if type.sojourn = "fij"; • Matrix of distribution parameters of dimension $(s, 2)$ if type.sojourn = "fi" or "fj"; • Vector of distribution parameters of length 2 if type.sojourn = "f". <p>When parameters/values are not necessary (e.g. the Poisson distribution has only one parameter that is λ, leave the value NA for the second parameter in the argument param).</p>
cens.beg	Optional. A logical value indicating whether or not sequences are censored at the beginning.
cens.end	Optional. A logical value indicating whether or not sequences are censored at the end.

Details

This function creates a semi-Markov model object in the parametric case, taking into account the type of sojourn time and the censoring described in references. For the parametric specification, several discrete distributions are considered (see below).

The difference between the Markov model and the semi-Markov model concerns the modeling of the sojourn time. With a Markov chain, the sojourn time distribution is modeled by a Geometric distribution (in discrete time). With a semi-Markov chain, the sojourn time can be any arbitrary distribution. In this package, the available distribution for a semi-Markov model are :

- Uniform: $f(x) = 1/n$ for $a \leq x \leq b$, with $n = b - a + 1$;
- Geometric: $f(x) = \theta(1 - \theta)^x$ for $x = 0, 1, 2, \dots, n$, $0 < \theta < 1$, with $n > 0$ and θ is the probability of success;
- Poisson: $f(x) = (\lambda^x \exp(-\lambda))/x!$ for $x = 0, 1, 2, \dots, n$, with $n > 0$ and $\lambda > 0$;
- Discrete Weibull of type 1: $f(x) = q^{(x-1)^\beta} - q^{x^\beta}$, $x = 1, 2, 3, \dots, n$, with $n > 0$, q is the first parameter and β is the second parameter;
- Negative binomial: $f(x) = \frac{\Gamma(x+\alpha)}{\Gamma(\alpha)x!} p^\alpha (1-p)^x$, for $x = 0, 1, 2, \dots, n$, Γ is the Gamma function, α is the parameter of overdispersion and p is the probability of success, $0 < p < 1$;
- Non-parametric.

We define :

- the semi-Markov kernel $q_{ij}(k) = P(J_{m+1} = j, T_{m+1} - T_m = k | J_m = i)$;
- the transition matrix $(p_{trans}(i, j))_{i, j} \in states$ of the embedded Markov chain $J = (J_m)_m$, $p_{trans}(i, j) = P(J_{m+1} = j | J_m = i)$;

- the initial distribution $\mu_i = P(J_1 = i) = P(Z_1 = i), i \in 1, 2, \dots, s;$
- the conditional sojourn time distributions $(f_{ij}(k))_{i,j} \in \text{states}, k \in N, f_{ij}(k) = P(T_{m+1} - T_m = k | J_m = i, J_{m+1} = j), f$ is specified by the argument `param` in the parametric case.

In this package we can choose different types of sojourn time. Four options are available for the sojourn times:

- depending on the present state and on the next state (f_{ij});
- depending only on the present state (f_i);
- depending only on the next state (f_j);
- depending neither on the current, nor on the next state (f).

If `type.sojourn = "fij"`, `distr` is a matrix of dimension (s, s) (e.g., if the row 1 of the 2nd column is "pois", that is to say we go from the first state to the second state following a Poisson distribution). If `type.sojourn = "fi"` or `"fj"`, `distr` must be a vector (e.g., if the first element of vector is "geom", that is to say we go from the first state to any state according to a Geometric distribution). If `type.sojourn = "f"`, `distr` must be one of "unif", "geom", "pois", "dweibull", "nbinom" (e.g., if `distr` is equal to "nbinom", that is to say that the sojourn times when going from any state to any state follows a Negative Binomial distribution). For the non-parametric case, `distr` is equal to "nonparametric" whatever type of sojourn time given.

If the sequence is censored at the beginning and/or at the end, `cens.beg` must be equal to TRUE and/or `cens.end` must be equal to TRUE. All the sequences must be censored in the same way.

Value

Returns an object of class [smmparametric](#).

References

V. S. Barbu, N. Limnios. (2008). Semi-Markov Chains and Hidden Semi-Markov Models Toward Applications - Their Use in Reliability and DNA Analysis. New York: Lecture Notes in Statistics, vol. 191, Springer.

See Also

[simulate](#), [fitsmm](#), [smmnonparametric](#)

Examples

```
states <- c("a", "c", "g", "t")
s <- length(states)

# Creation of the initial distribution
vect.init <- c(1 / 4, 1 / 4, 1 / 4, 1 / 4)

# Creation of the transition matrix
pij <- matrix(c(0, 0.2, 0.5, 0.3,
               0.2, 0, 0.3, 0.5,
               0.3, 0.5, 0, 0.2,
               0.4, 0.2, 0.4, 0),
```


Index

- * **Markov**
 - smmR-package, 3
- * **availability**
 - smmR-package, 3
- * **censored**
 - smmR-package, 3
- * **estimation**
 - smmR-package, 3
- * **failure**
 - smmR-package, 3
- * **maintainability**
 - smmR-package, 3
- * **reliability**
 - smmR-package, 3
- * **semi-Markov**
 - smmR-package, 3
- * **simulation**
 - smmR-package, 3
- .failureRateBMP, 4
- availability, 6
- convolution, 7
- failureRate, 8
- fitmm, 10, 30, 38, 39
- fitsmm, 12, 40–42, 45
- get.f, 16
- get.H, 17
- get.Kpar, 17
- get.limitDistribution, 18
- get.Niuj, 18
- get.P, 19
- get.psi, 19
- get.Py, 20
- get.qy, 20
- get.stationaryDistribution, 21
- getKernel, 21
- getProcesses, 22
- is.mm, 23
- is.mmfit, 23
- is.smm, 24
- is.smmfit, 24
- is.smmnonparametric, 25
- is.smmparametric, 25
- maintainability, 26
- matrixConvolution, 27
- meanRecurrenceTimes, 28
- meanSojournTimes, 5, 6, 9, 18, 19, 21, 26, 28, 29, 29, 31, 32, 36
- mm, 12, 30, 30, 38, 39
- mttf, 31
- mttr, 32
- plot.smm, 15, 33
- plot.smmfit, 15, 34
- reliability, 6, 9, 35
- setSeed, 37
- simulate, 42, 45
- simulate.mm, 12, 30, 37
- simulate.mmfit, 38
- simulate.smm, 15, 39
- simulate.smmfit, 15, 40
- smmnonparametric, 15, 34, 39–41, 41, 42, 45
- smmparametric, 15, 34, 39–42, 43, 45
- smmR (smmR-package), 3
- smmR-package, 3