MARCIE - Model checking And Reachability analysis done effiCIEntly

[1] Martin Schwarick [2] Christian Rohr [1]Monika Heiner

[1]Brandenburg University of Technology Cottbus (BTU)

[2]Magdeburg Centre for Systems Biology (MaCS)

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M odel checking A and R eachability done effi CIE ntly

- is a tool to validate generalized stochastic Petri nets
- supports qualitative and quantitative analysis of standard properties
- offers qualitative and quantitative model checking capabilities
- implements therefore state of the art techniques,
  most of them in a multi-threaded fashion

Features

- Qualitative analysis of bounded Petri nets
  - symbolic state space computation
  - behavioural properties
  - Computation Tree Logic (CTL) model checker
- "Exact" quantitative analysis of bounded generalized stochastic Petri nets
  - symbolic steady state/transient analysis
  - Continuous Stochastic Logic (CSL) model checker
  - reward computation
- Approximative quantitative analysis of generalized stochastic Petri nets
  - Gillespie's stochastic simulation
  - Fast adaptive uniformization
  - restricted CSL model checker

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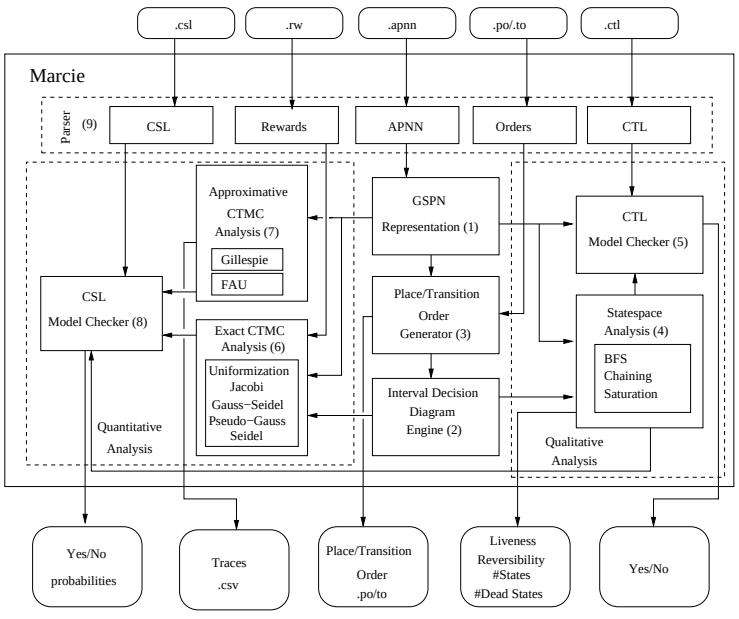
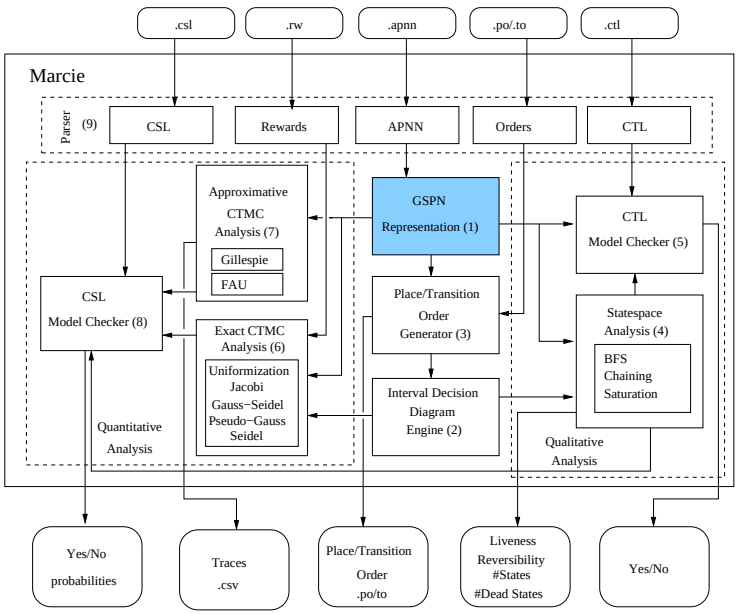
Architecture



Characteristics

- command line tool
- entirely written in C++
- about 40,000 LOC
- libraries: *flex*/*bison*, *GMP*, *phtreads*, *boost*
- available for Linux and MAC OS

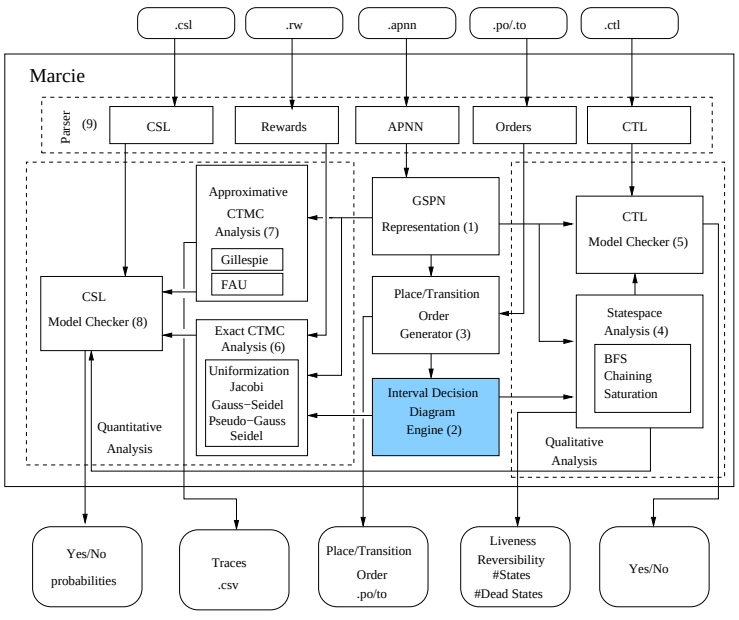
Architecture



GSPN Representation

- stochastic transitions with marking-dependent rate functions
- immediate transitions with weights
- extended arcs (read arcs, inhibitor arcs, reset arcs)

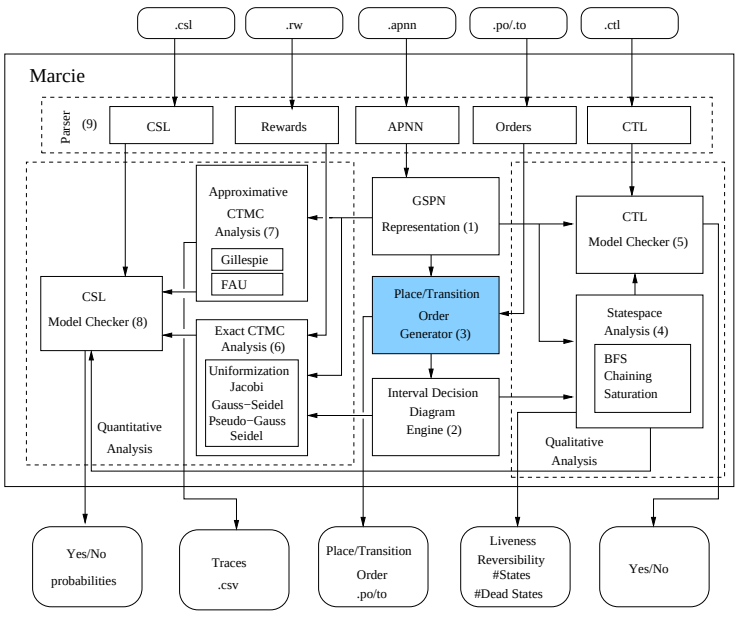
Architecture



IDD Engine

- Interval Decision Diagram (BDD generalization)
- implementation characteristics
  - shared IDDs
  - fast unique tables and operation caches
  - garbage collection
  - dedicated operations to fire *PN* transitions

Architecture



Order Generator

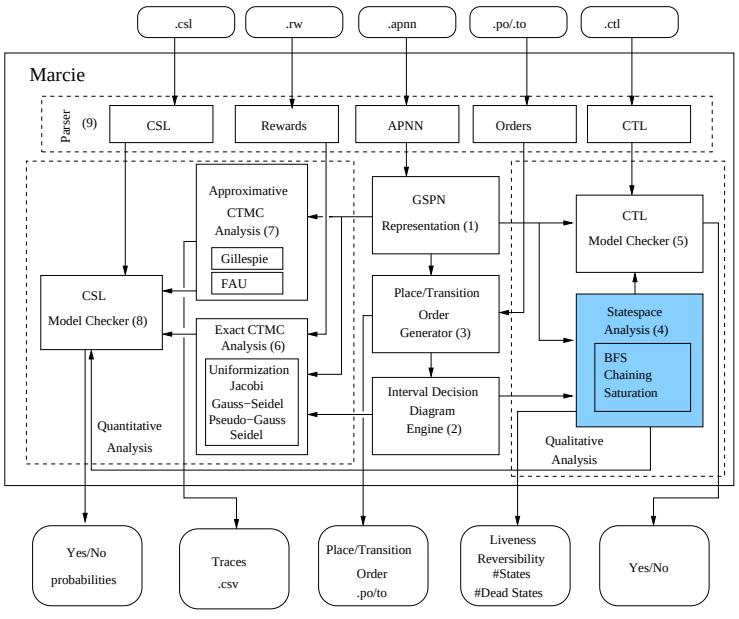
Pre-computation of static

- variable orders
  - small sized IDDs
- transition orders
  - reducing the number of computation steps for Transition Chaining and Saturation

based on the net structure

(heuristics)

Architecture



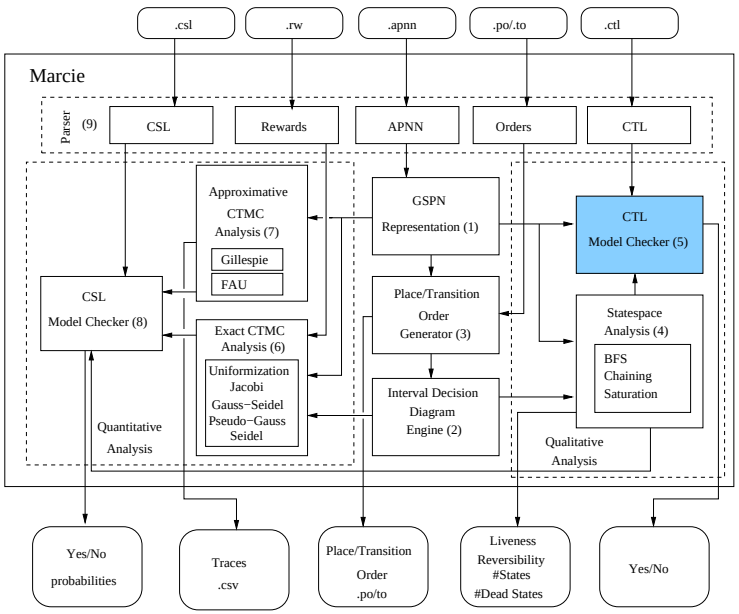
State Space Analysis
of bounded Petri nets
generation algorithms:

- Breath-First-Search
- Transition Chaining
- Saturation

behavioural properties:

- dead states
- reversibility
- liveness

Architecture



CTL Model Checker

efficient symbolic implementation of the standard CTL model checking algorithm

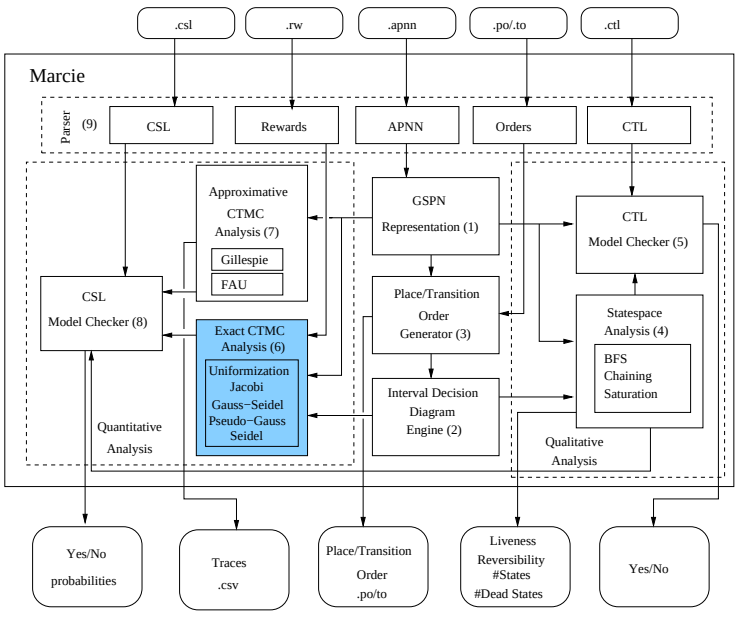
- atomic propositions: arithmetic and boolean expressions over the marking of places
- state formulas:

$$\phi :\equiv \phi \vee \phi \mid \neg\phi \mid \phi \wedge \phi \mid \phi \Leftrightarrow \phi \mid \phi \Rightarrow \phi \mid A\psi \mid E\psi$$

- path formulas:

$$\psi :\equiv X\phi \mid \phi U\phi \mid F\phi \mid G\phi$$

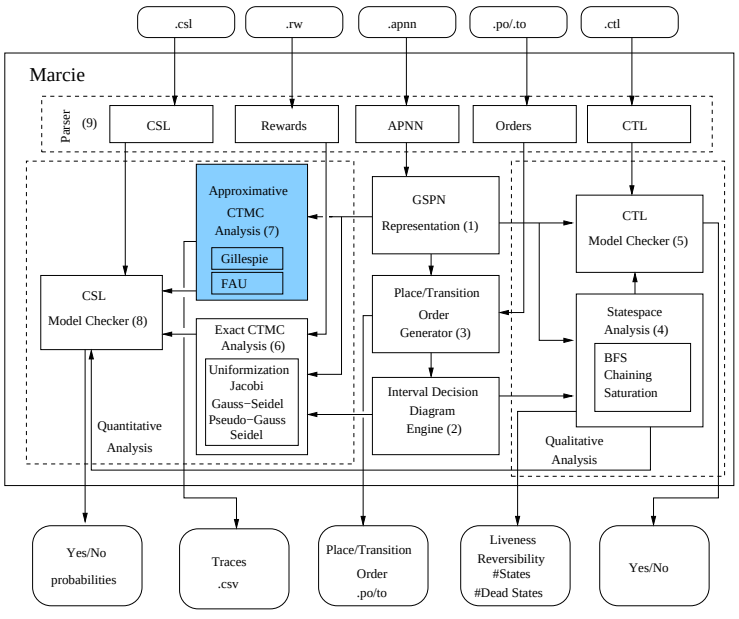
Architecture



"Exact" CTMC Analysis

- computation of probability distributions
  - transient analysis - uniformization method
  - steady state analysis - iterative methods – Jacobi and (Pseudo-) Gauss-Seidel
- basic operation is a matrix-vector multiplication
  - "on-the-fly" computation of the matrix based on the symbolic state space representation (IDD)
  - *multi-threaded*

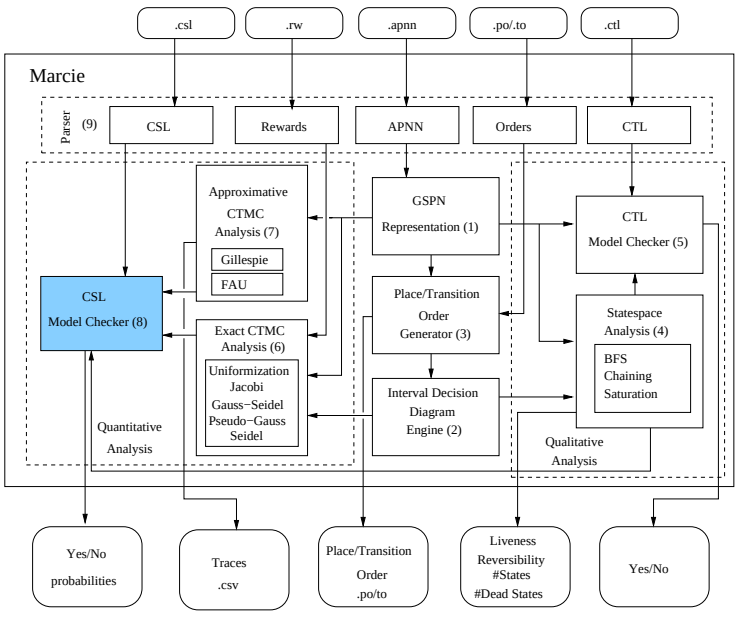
Architecture



Approximative CTMC Analysis

1. Stochastic Simulation
   - single trajectories
   - modified Gillespie algorithm
   - confidence intervals
   - *multi-threaded*
2. Fast Adaptive Uniformization
   - adaptive uniformization
   - state pruning
   - produces often a very small part of the state space

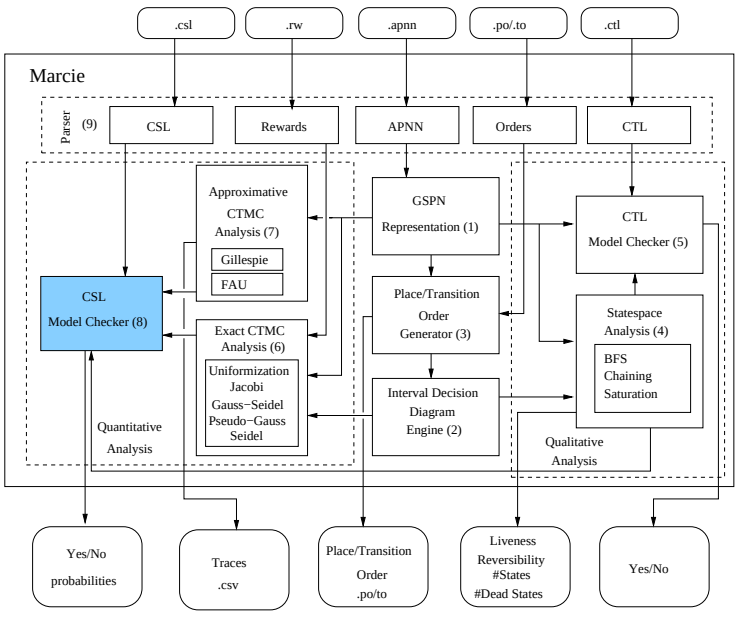
Architecture



CSL Model Checker

- CSL is a stochastic extension of CTL
- $\mathcal{P}_{\circ p}$ replaces E and A
- $\mathcal{S}_{\circ p}$ allows to reason about steady state behaviour
- temporal operators are decorated with time intervals

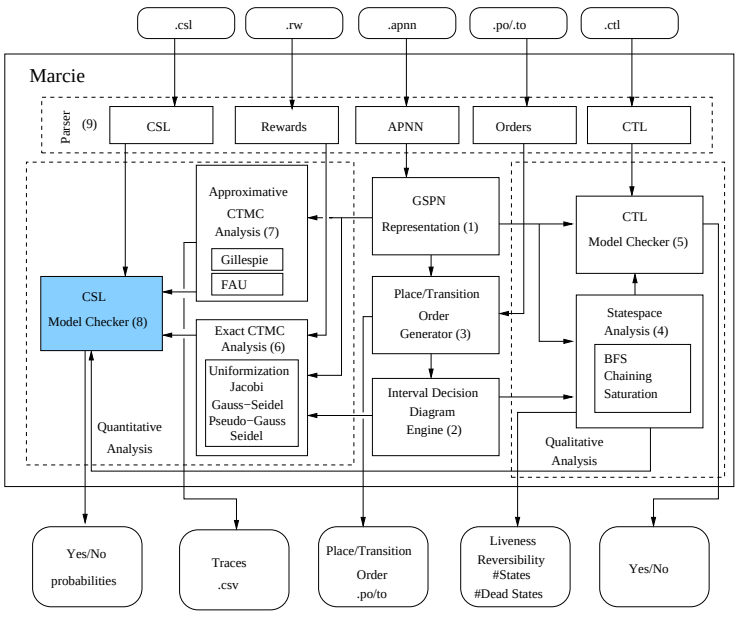
Architecture



CSL Model Checker

- CSL model checking algorithm is similar to CTL
- but the evaluation of $\mathcal{P}$ and $\mathcal{S}$ requires the computation of a probability distribution
- standard CTMC analysis techniques can be applied
- for unnested and time-bounded formulas approximation or simulation can be used
- *multi-threaded*

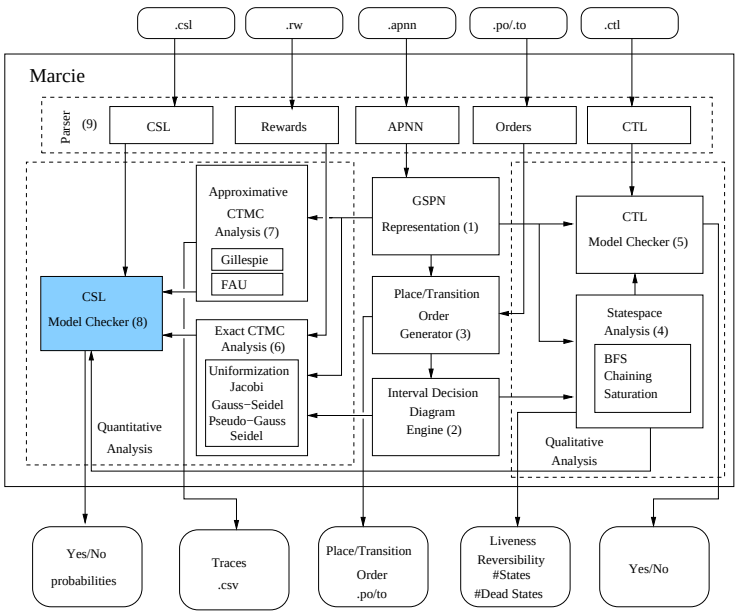
Architecture



CSL Model Checker

- extensions to reason about expectations of rewards
- new operator $\mathcal{R}_{\circ\nabla}$ with
  - $[C_{<=t}]$ the cumulative reward
  - $[I_{=t}]$ the instaneous reward
  - $[F(sp)]$ the cumulative reward until the first occurence of a state satisfying sp
  - $[\mathcal{S}]$ expected reward at steady state

Architecture

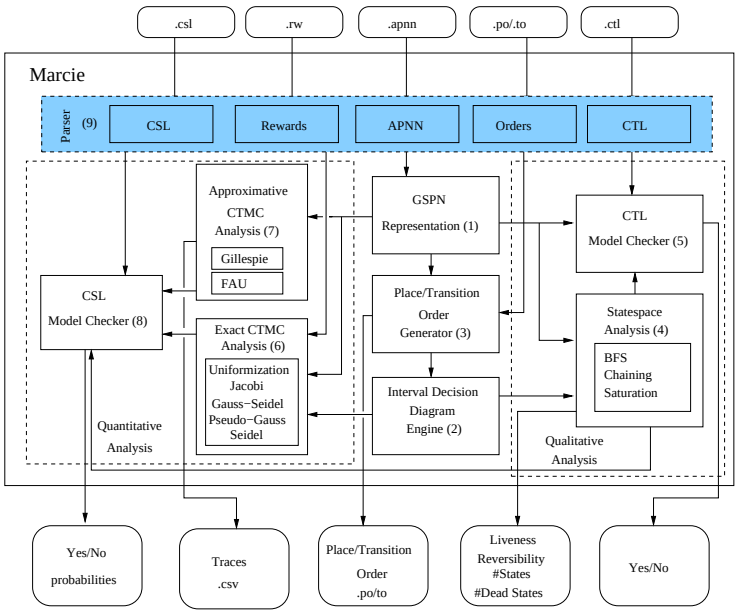


CSRL Model Checker

- Continuous Stochastic Reward Logic
- temporal operators are decorated with a time *and* a reward interval
- performability:

$$\mathcal{P}_{=?}[true\mathbf{U}_{[t,t][0,r]}\psi]$$

Architecture



Parser

component to allow the input of

- the GSPN in an adaption of *APNN*
- reward structures as in the PRISM language
- CSL/CTL formulas
- place/transition orders in simple text format

Related Tools

short selection of widely used tools

- PRISM - University of Oxford
  `http://www.prismmodelchecker.org`
- MRMC - RWTH Aachen
  `http://www.mrmc-tool.org`
- SMART - University of California at Riverside
  `http://www.cs.ucr.edu/~ciardo/SMART/`

Related Tools

Features

	MARCIE	PRISM	MRMC	SMART

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high level description	GSPN	GCL		GSPN*

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formalism		DTMC	DTMC/DMRM	DTMC
	CTMC	CTMC	CTMC/CMRM	CTMC
		MDP	MDP	

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model checking	CTL			CTL
		LTL		
	CS(R)L	PCTL/CSL	PCTL/CS(R)L	

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exact engine		explicit	explicit	explicit
	IDD	(MT)BDD		(MT)MDD,MD,EVDD

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simulative engine	yes	yes	yes	yes

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simulative engine	yes	yes	yes	yes
multi-threading	yes	no	no	no

PRISM vs. MARCIE

Exact Quantitative Analysis

Similarities

- based on Decision Diagrams (DD)
- multiplication by DD traversal,
  state indices are computed using offsets during the traversal
- explicit storage of probability vectors and the diagonal entries
- similar caching strategies

PRISM vs. MARCIE

Exact Quantitative Analysis

Differences

	PRISM	MARCIE

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Exact Quantitative Analysis

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state space	BDD	IDD

PRISM vs. MARCIE

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rate matrix	MTBDD or BDD+SM	IDD + GSPN

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rates	terminal nodes or SM	on-the-fly computation

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multi-threading	no	yes

Experimental Results

Case studies

- Flexible Manufacturing System
- Kanban
- Polling Server System
- AKAP scaffold-mediated crosstalk
- Angiogenetic process

Test system

- $8 \times 2.2 Ghz$ MAC Pro
- 32GB RAM
- Cent OS 5.5

Experiments

- transient analysis
- steady state analysis
- simulative analysis

State space size

Size of the reachability graphs for different model configurations.

model	N	states	transitions
FMS	2	810	3,699
	4	35,910	237,120
	6	537,768	4,205,670
	8	4,459,455	38,533,968
	10	25,397,658	234,523,289
	12	111,414,940	1,078,917,632
	14	403,259,040	4,047,471,180
Kanban	2	4,600	28,120
	4	454,475	3,979,850
	6	11,261,376	115,708,992
	8	133,865,325	1,507,898,700
PSS	5	240	800
	10	15,360	89,600
	15	737,280	6,144,000
	20	31,457,280	340,787,200
AKAP	3	1,632,240	12,691,360
	4	15,611,175	141,398,580
	5	74,612,328	734,259,344
	6	386,805,104	4,116,788,172
ANG	2	5,384	26,193
	4	2,413,480	21,810,412
	6	277,789,578	24,813,347,031

Transient analysis

Total run-time including state space generation, initialization and probability computation.
The column *iter* gives the number of required iterations.

model			MARCIE				PRISM	
	N	iter	1	2	4	8	hybrid	sparse
FMS	8	202	2m27s	2m28s	1m51s	1m28s	3m47s	2m50s
	10	202	13m11s	9m44s	7m51s	8m22s	27m39s	15m57s
	12	208	55m54s	42m41s	31m56s	29m57s	2h10m47s	1h39m05s
	14	208	4h07m51s	3hm35ms07s	2h48m59s	2h41m41s	8h26m38s	‡
Kanban	4	181	6s	3s	2s	2s	12s	8s
	6	181	1m57s	1m34s	48s	34s	5m16s	3m09s
	8	181	23m59	17m53s	9m18s	6m41s	1h08m15s	43m23s
PSS	10	377	$\ll$1s	$\ll$1s	$\ll$1s	$\ll$1s	2s	2s
	15	377	17s	7s	4s	3s	33s	17s
	20	377	9m02s	5m32s	2m59s	2m06s	29m18s	14m22s
AKAP	4	1,532	25m15s	17m09s	7m49s	5m13s	52m20s	24m12s
	5	1,850	2h40m14s	1h34m36s	47m54s	30m26s	–	–
	6	2,218	–	–	5h44m53s	3h49m45s	†	†
ANG	4	547	1m53s	1m18s	54s	44s	2m27s	7m24s
	5	794	31m08s	20m50s	13m45s	11m46s	34m06s	4h25m34s
	6	1,093	7h36m57s	4h39m52s	3h17m47s	3h00m16s	†	†

– means that the experiment was canceled after 12 hours
† means that the CTMC could not be created using the default tool settings ‡ means that we ran out of memory

Steady state analysis

Total run-time including state space generation, initialization, reward computation - if necessary, and probability computation. The number of required iterations is given in the columns *iter*. If possible we used the Jacobi solvers. For the Kanban and ANG models we used the Gauss-Seidel solvers. The number of iterations required by the Gauss-Seidel solvers differ between MARCIEand PRISM because of different variable orders.

model		MARCIE					PRISM		
	N	iter	1	2	4	8	iter	hybrid	sparse
FMS	2	378	$\ll$1s	$\ll$1s	$\ll$1s	$\ll$1	378	2s	3s
	6	1,084	59s	42s	57s	34s	1,084	41s	30s
	10	1,812	1h11m15s	45m07s	30m31s	24m47s	1,812	2h25m42s	37m15s
	12	2,193	6h13m53s	3h52m32s	2h26m17s	2h04m45s	2,193	–	3h32m11s
	14	2,589	–	–	–	9h10m04s	†	†	†
Kanban	2	48	$\ll$1s	Gauss-Seidel			189	2	2s
	4	122	15s				323	12s	10s
	6	224	11m07s	no multi-threading support			622	9m48s	6m18s
	8	356	3h57m23s				999	3h27m27s	1h59m59s
PSS	10	406	$\ll$1s	$\ll$1s	$\ll$1s	$\ll$1s	406	2s	2s
	15	657	14s	9s	5s	3s	657	24s	21s
	20	920	16m16s	10m58s	6m21s	3m08s	920	31m28s	26m31s
AKAP	4	1,433	21m17s	13m07s	7m04s	4m40s	1,433	17m37s	17m08s
	5	1,348	1h46m52s	1h05m12s	37m39s	23m03s	–	–	–
	6	1,659	–	8h00m02s	3h53m29s	2h43m48s	–	–	†
ANG	2	*n.a.*	48s	Gauss-Seidel			*n.a.*	4m05s	28s
	3	*n.a.*	1s24m55s				†	†	†
	4	*n.a.*	–	no multi-threading support			†	†	†

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Simulative analysis

Total run-time for simulations done with MARCIEand PRISM.
The confidence level is 99%, the desired accuracy 1×10^{-5}, which leads to 66, 348, 303 simulation runs.

model	N	t	Threads	MARCIE	PRISM
FMS	14	1	1	40m43s	3h24m13s
			8	5m4s	*n.a.*
Kanban	10	10	1	13m48s	2h23m58s
			8	1m58s	*n.a.*
PSS	20	1	1	4h10m4s	62h32m33s
			8	31m53s	*n.a.*
AKAP	6	1	1	2m37s	10m23s
			8	25s	*n.a.*
ANG	6	1	1	38m48s	8h26m57s
			8	5m20s	*n.a.*

Conclusions

MARCIE is an analysis tool for generalized stochastic Petri nets which

- is easy to use
  - flat Petri net models
  - no prior knowledge of the boundedness degree
  - automatic computation of variable orders
- assures high performance
  - efficient IDD engine
  - efficient simulation engine
- offers model checking of branching time logic
  - qualitative: Computation Tree Logic
  - quantitative: Continuous Stochastic Logic

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Work in Progress

- PLTLc model checking
- steady state simulation
- parallel simulative model checking on Graphical Processing Units
- parallelization of the (Pseudo-)Gauss-Seidel solver
- completion of the CSRL model checker

Thanks for your attention.

Questions?

Demonstration?

http://www-dssz.informatik.tu-cottbus.de/software/MARCIE