Online Quantitative Verification: Capabilities and Challenges

Radu Calinescu

Computing Laboratory, University of Oxford

Outline

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(University of Oxford)

Quantitative verification

Formal technique for establishing quantitative properties of systems that exhibit probabilistic or real-time behaviour

- probability of system being up $\geq$ 99.9% of the time
- expected length of request queue for a disk drive

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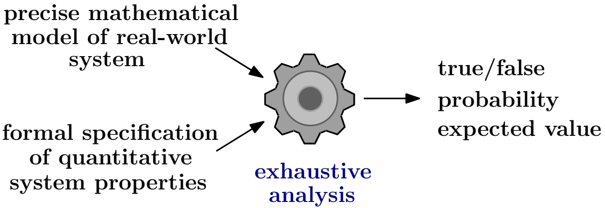
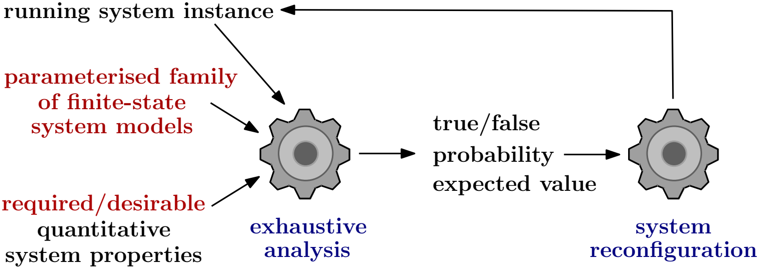


Online quantitative verification

Verification of required/desirable quantitative properties is performed at runtime

- analysed model selected based on actual system state
- verification results used to adjust system configuration



Predictable system adaptiveness

(IT) systems required to self-adapt in predictable ways to rapid changes in their workload, environment and objectives

- guaranteed levels of performance and dependability
- compliance with strict constrains

…properties that are traditionally established using (offline) quantitative verification

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Predictable system adaptiveness

(IT) systems required to self-adapt in predictable ways to rapid changes in their workload, environment and objectives

- context awareness
- synthesis of reconfiguration "policies" from high-level, multi-objective goals

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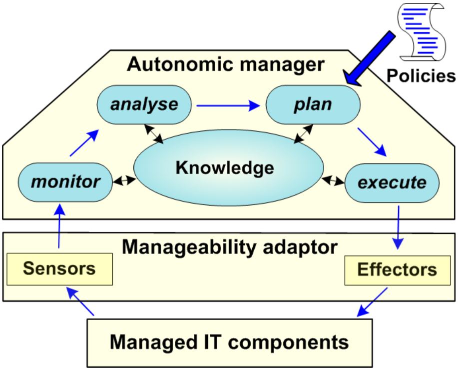
Approach

Integrate existing quantitative verification tool (PRISM) into the standard autonomic computing architecture



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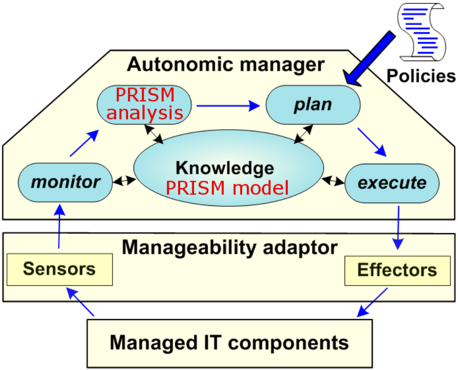
Approach

Integrate existing quantitative verification tool (PRISM) into the standard autonomic computing architecture



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The probabilistic model checker PRISM

Developed by the Oxford Quantitative Analysis and Verification Group

Supports multiple types of probabilistic models

- discrete-time Markov chains
- continuous-time Markov chains
- Markov decision processes

plus extensions of these models with costs and rewards

Used to analyse systems from a wide range of application domains

Discrete-/continuous-time Markov chains

$$\text{DTMC} = (S, s_{\text{init}}, \mathbf{P}, L)$$

- labelling function, $L : S \rightarrow 2^{AP}$
- transition probability matrix, $\mathbf{P} : S \times S \rightarrow [0, 1]$
- initial state, $s_{\text{init}} \in S$
- finite set of states

Discrete-/continuous-time Markov chains

$$\mathrm{DTMC} = (S, s_{\mathrm{init}}, \mathbf{P}, L)$$

- L: labelling function, $L : S \to 2^{AP}$
- $\mathbf{P}$: transition probability matrix, $\mathbf{P} : S \times S \to [0, 1]$
- s_{init}: initial state, $s_{\mathrm{init}} \in S$
- S: finite set of states

$$\mathrm{CTMC} = (S, s_{\mathrm{init}}, \mathbf{R}, L)$$

- $\mathbf{R}$: transition rate matrix, $\mathbf{R} : S \times S \to R_+$

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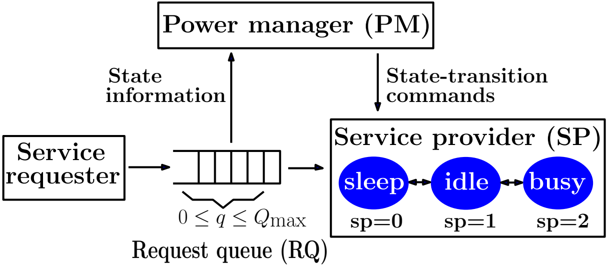
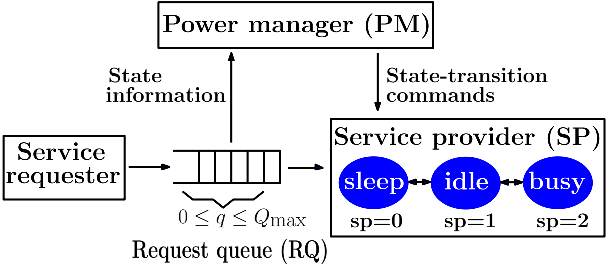
Example: dynamic power management



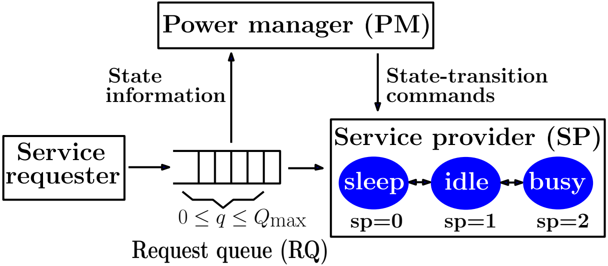
Example: dynamic power management




```
module RQ
  q : [0..Qmax]; // Request queue states

  // State transitions
  [request] true -> 1000/interArrivalTime : (q'=min(q+1,Qmax));
  [serve] q>1 -> (q'=q-1);
endmodule
```

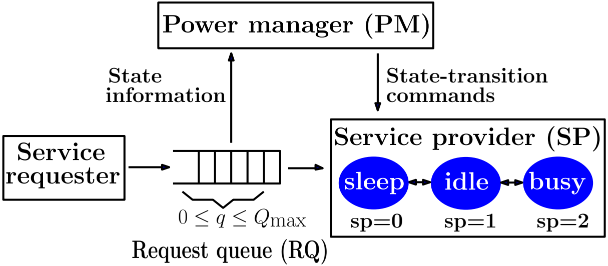
Example: dynamic power management




```
module SP
   sp : [0..2]; // SP states: 0 – sleep, 1 – idle, 2 – busy

   // State transitions
   [sleep2idle] sp=0 & q=0 –> sleep2idleRate : (sp'=1);
   [sleep2idle] sp=0 & q>0 –> sleep2idleRate : (sp'=2);
   [idle2sleep] sp=1 & q=0 –> idle2sleepRate : (sp'=0);
   [request] sp=1 –> (sp'=2);
   [request] !sp=1 –> true;
   [serve] sp=2 & q>1 –> serviceRate : (sp'=2);
   [serve] sp=2 & q=1 –> serviceRate : (sp'=1);
endmodule
```

Example: dynamic power management




```
module PM
    p : [0..1]; // PM states: 0 – sleep to idle, 1 – idle to sleep

    // State transitions
    [serve] q=1 –> switchToSleepProbability : (p'=1);
    [serve] q=1 –> 1–switchToSleepProbability : (p'=0);
    [serve] q>1 –> true;
    [request] true –> (p'=0);
    [sleep2idle] q=Qmax –> (p'=p);
    [idle2sleep] p=1 –> (p'=0);
endmodule
```

Cost/reward extensions

$$\mathrm{DTMC} = (S, s_{\mathrm{init}}, \mathbf{P}, L)$$

- labelling function, $L : S \rightarrow 2^{AP}$
- transition probability matrix, $\mathbf{P} : S \times S \rightarrow [0, 1]$
- initial state, $s_{\mathrm{init}} \in S$
- finite set of states

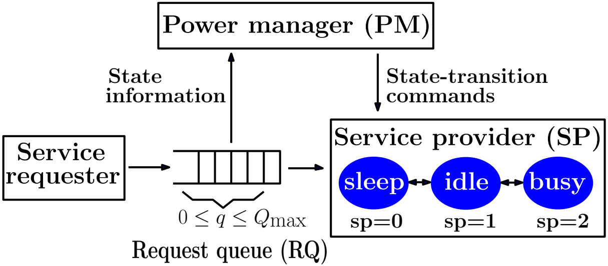
$$\mathrm{CTMC} = (S, s_{\mathrm{init}}, \mathbf{R}, L)$$

- transition rate matrix, $\mathbf{R} : S \times S \rightarrow R_+$

$$\text{reward structure} = (\underline{\rho}, \mathbf{r})$$

- transition reward function, $r : S \times S \rightarrow R_+$
- state reward function, $\underline{\rho} : S \rightarrow R_+$

Example: power utilisation




```
rewards "power"
    sp=0 : 0.13;                      // 0.13W in 'sleep' state
    sp=1 : 0.95;                      // 0.95W in 'idle' state
    sp=2 : 2.15;                      // 2.15W in 'busy' state
    [sleep2idle] true : 7.0;          // 7J 'sleep' → 'idle
    [idle2sleep] true : 0.067;        // 0.067J 'idle' → 'sleep'
endrewards
```

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Quantitative property specification

PCTL—Probabilistic Computational Tree Logic for DTMCs*

CSL—Continuous Stochastic Logic for CTMCs*

Quantitative property specification

PCTL—Probabilistic Computational Tree Logic for DTMCs*

CSL—Continuous Stochastic Logic for CTMCs*

- PCTL syntax:
  - ϕ ::= true | a | $\phi \wedge \phi$ | $\neg\phi$ | $P_{\sim p}[\psi]$ (state formulas)
  - ψ ::= $X\,\phi$ | $\phi\, U^{\leq k}\, \phi$ | $\phi\, U\, \phi$ (path formulas)
  - where a is an atomic proposition, used to identify states of interest, $p \in [0,1]$ is a probability, $\sim \in \{<,>,\leq,\geq\}$, $k \in \mathbb{N}$

$P_{\sim p}[\psi]$: ψ is true with probability ~p

$X\,\phi$: "next"

$\phi\, U^{\leq k}\, \phi$: "bounded until"

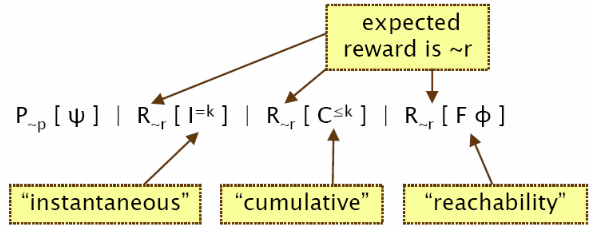
$\phi\, U\, \phi$: "until"

Quantitative property specification

PCTL—Probabilistic Computational Tree Logic for DTMCs*

CSL—Continuous Stochastic Logic for CTMCs*

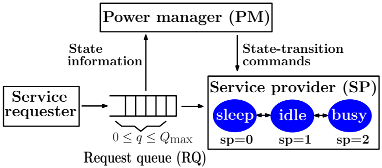
* augmented with costs/rewards

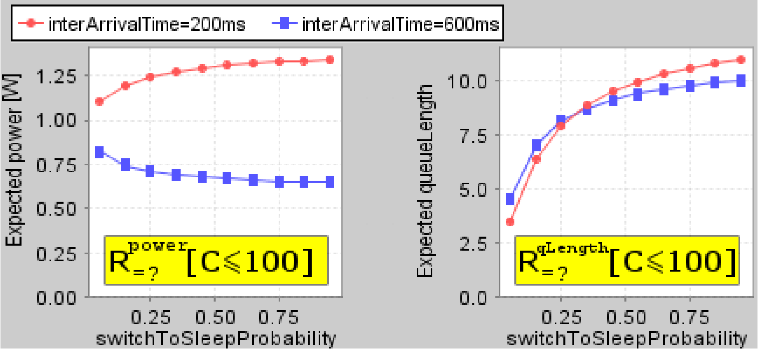


$$\phi ::= \ldots \mid P_{\sim p}[\psi] \mid R_{\sim r}[I^{=k}] \mid R_{\sim r}[C^{\leq k}] \mid R_{\sim r}[F\ \phi]$$

where $r \in \mathbb{R}_{\geq 0}$, $\sim \in \{<,>,\leq,\geq\}$, $k \in \mathbb{N}$

Example: power use; request queue length





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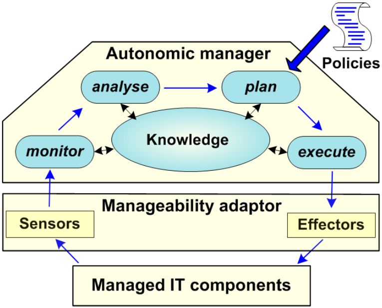
The "knowledge" module



Knowledge=(S, C, f)

- operational model, $f : S \times C \nrightarrow S$
- configuration (modifiable system parameters)
- state ("read-only" system parameters)

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Utility-function autonomic policies

Knowledge=(S, C, f)

- S — state ("read-only" system parameters)
- C — configuration (modifiable system parameters)
- f — operational model, $f : S \times C \nrightarrow S$

Given a utility function

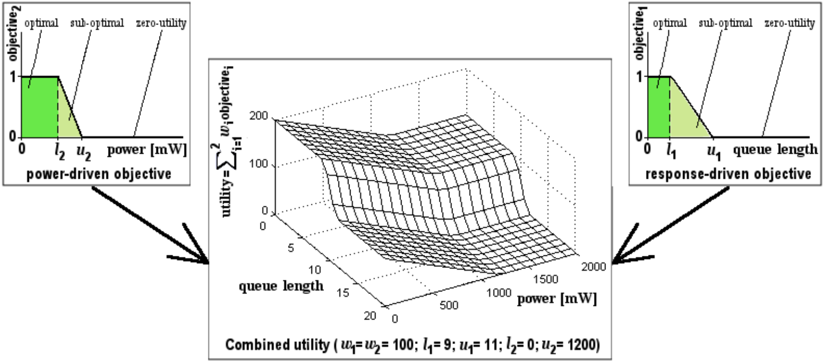
$$utility : S \times C \rightarrow R_+,$$

adjust the configurable system parameters such as to maximise the system utility "at all times"

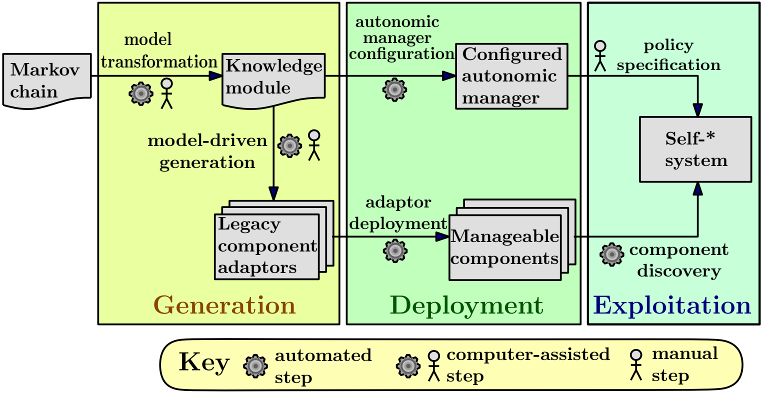
$$\left[\text{for } \mathbf{s}_0 \in S, \text{ find } \mathbf{c} \in C \text{ s.t. } \mathbf{c} = \operatorname*{\mathbf{argmax}}_{\mathbf{x} \in C} utility(f(\mathbf{s}_0, \mathbf{x}), \mathbf{x})\right]$$

Example: multi-objective utility function

$$utility = \sum^{n} w_i objective_i$$



Self-* system development



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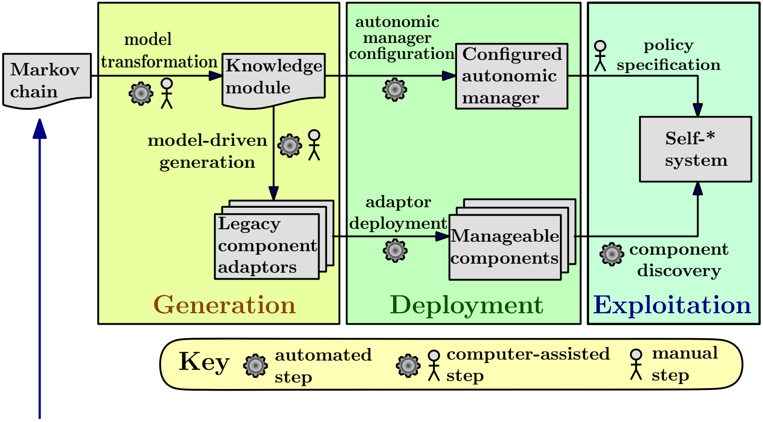
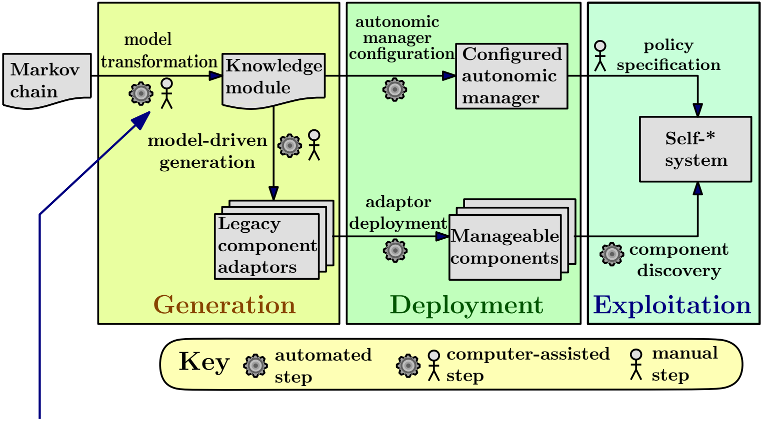
Self-* system development



PRISM discrete-/continuous-time Markov chain

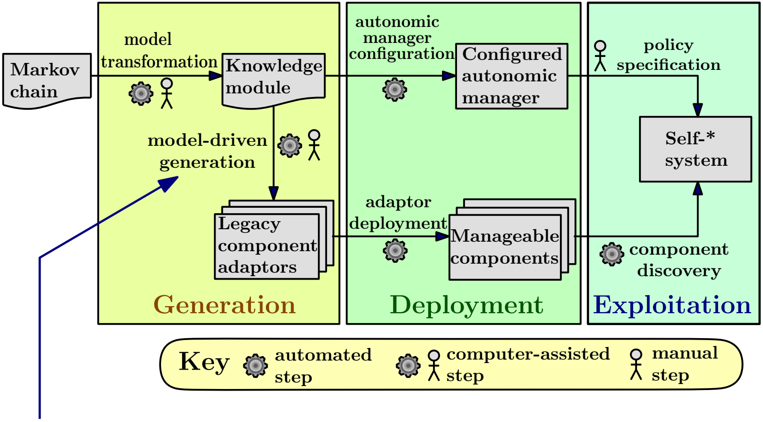
- available from the formal verification of the system
- newly developed

Self-* system development



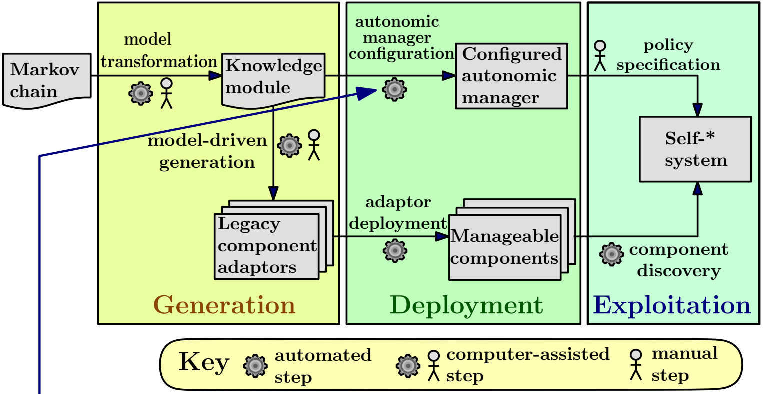
Automated transformation, except for the partition of the Markov chain parameters into state and configuration

Self-* system development



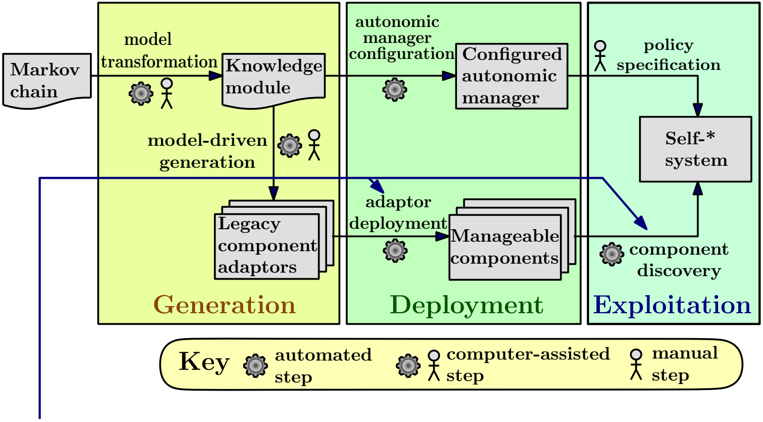
Off-the-shelf tools (XSLT engine, data type generator) used to generate most adaptor code

Self-* system development



Knowledge module supplied at runtime to autonomic manager instance

Self-* system development



Adaptor deployment leads to automatic component discovery by the autonomic manager

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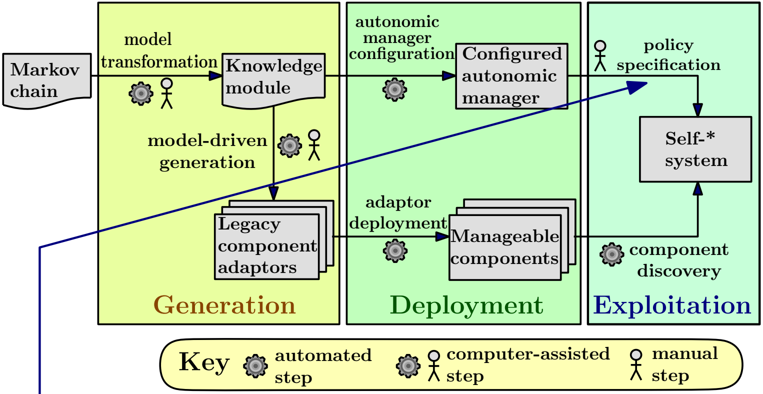
Self-* system development



Utility-function policy specified by system administrator
- multi-objective utility function defined in terms of cost/reward structures from the PRISM Markov chain

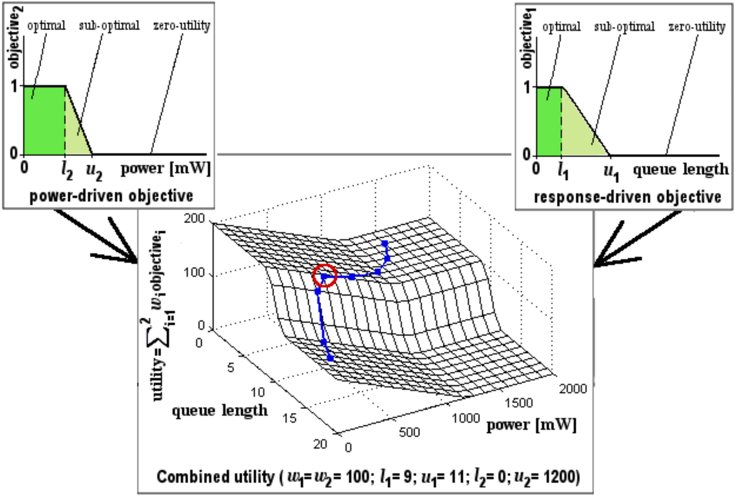
utility function example

Policy implementation

Periodically and/or when the autonomic manager is notified about system changes:

1 **foreach** component *c* in the policy scope **do**
2 extract parameterised model of *c* from the knowledge module
3 get state parameters of *c* from the manageability adaptors
4 evaluate quantitative properties used in the utility function
5 choose configuration parameters that maximise the utility of *c*

Example: dynamic power management



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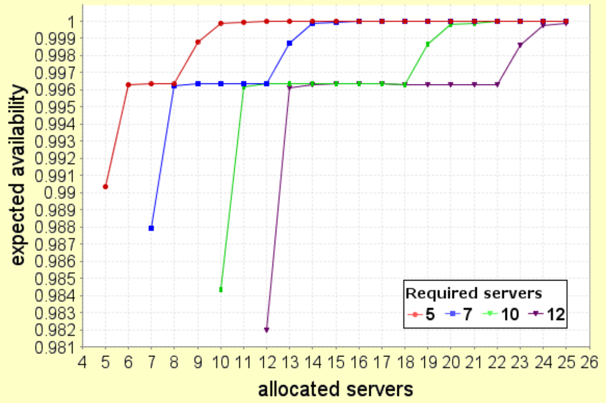
Example 2: cluster availability management

Multi-objective utility function:

1. achieve target availability in the presence of failures and variations in the number of requested servers
2. minimise number of allocated servers



Challenges: inherited from offline verification

State-space explosion

- new model checking techniques still needed

Expert knowledge required to produce "good" models

- more models should be built as part of the system development process

Challenges: specific to online verification

Model checkers not typically intended for online use

- use command-line interfaces (lower-level APIs better)

Prohibitive analysis time

- pre-compute/cache analysis results; hybrid approaches

Local optima (unless all possible configurations verified)

- offline assessment to ensure solution is effective

Utility-function definition

- close to natural language property/utility specification?

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Summary

Increasing need for IT systems to adapt in predictable, dependable ways to changes in their state, objectives and environment

Quantitative verification reached a level of maturity that enables its online use to achieve such adaptiveness in certain scenarios

Interesting research work required to address challenges posed by online quantitative verification

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Thank you

Questions?

Further reading

R. Calinescu – General-Purpose Autonomic Computing, In: M. Denko et al., *Autonomic Computing and Networking*, Springer, April 2009, pp. 3–29.

R. Calinescu and M. Kwiatkowska – Using Quantitative Analysis to Implement Autonomic IT Systems, *Proc. 31st Intl. Conf. Software Eng.* (ICSE 2009).