Multi-Quality Auto-Tuning by Contract Negotiation

Verteidigung der Dissertation
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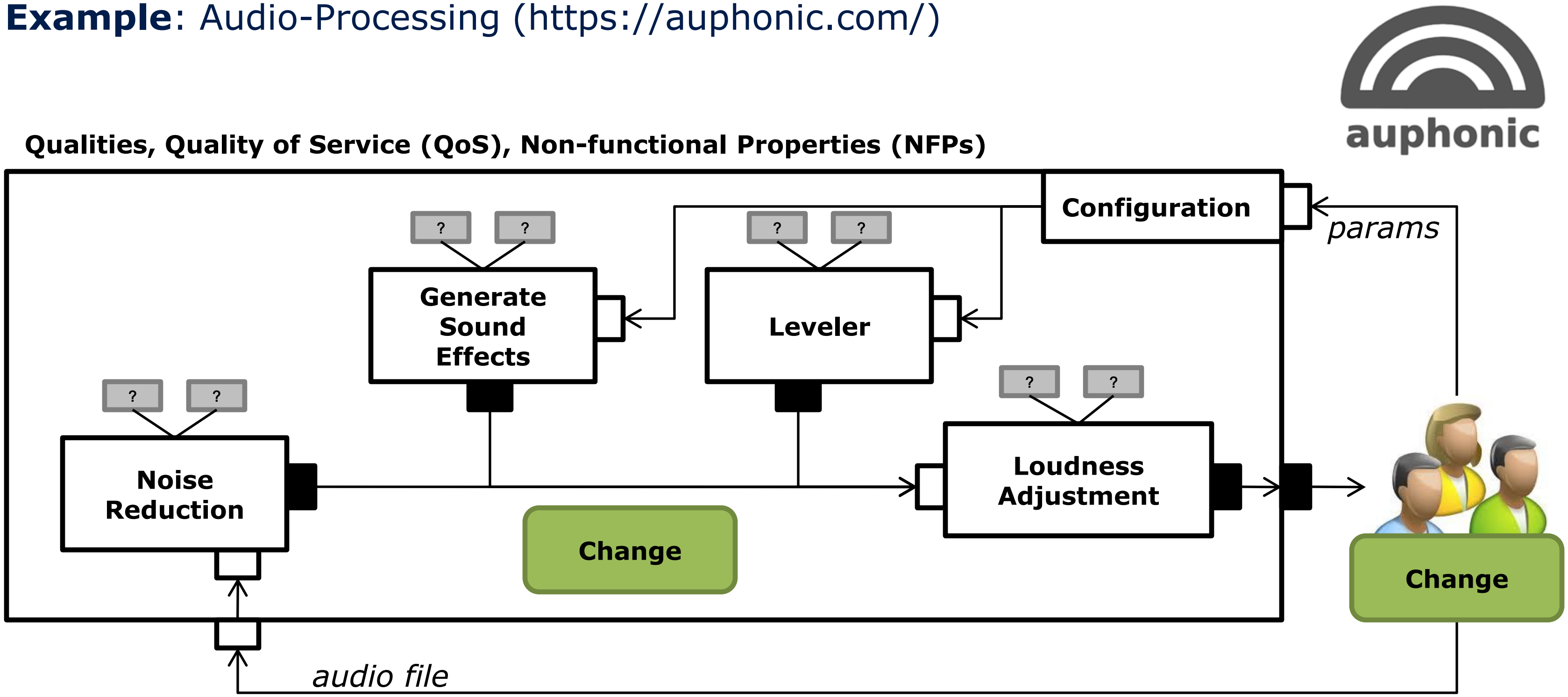
Europa fördert Sachsen. SACHSEN
ESF Europäischer Sozialfonds
Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
DRESDEN concept Exzellenz aus Wissenschaft und Kultur

Motivation

Example: Audio-Processing (https://auphonic.com/)

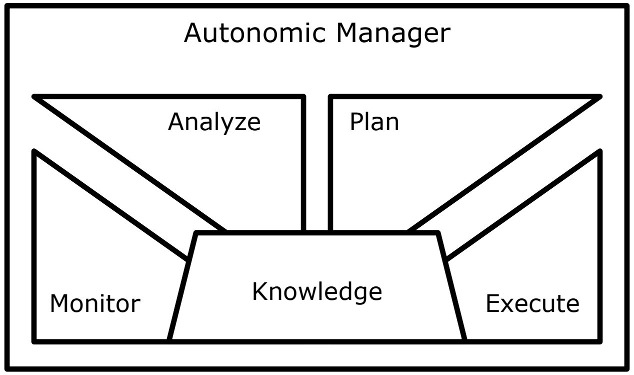


Context: Self-adaptive Systems

Goal: Self-adaptive Systems (SAS)

Robert Laddaga 1997:

> *"Self Adaptive Software **evaluates** its own behavior and **changes behavior** when the evaluation indicates that it is not accomplishing what the software is intended to do, or **when better functionality or performance is possible**."* [L97]



MAPE-K Loop [KC03]

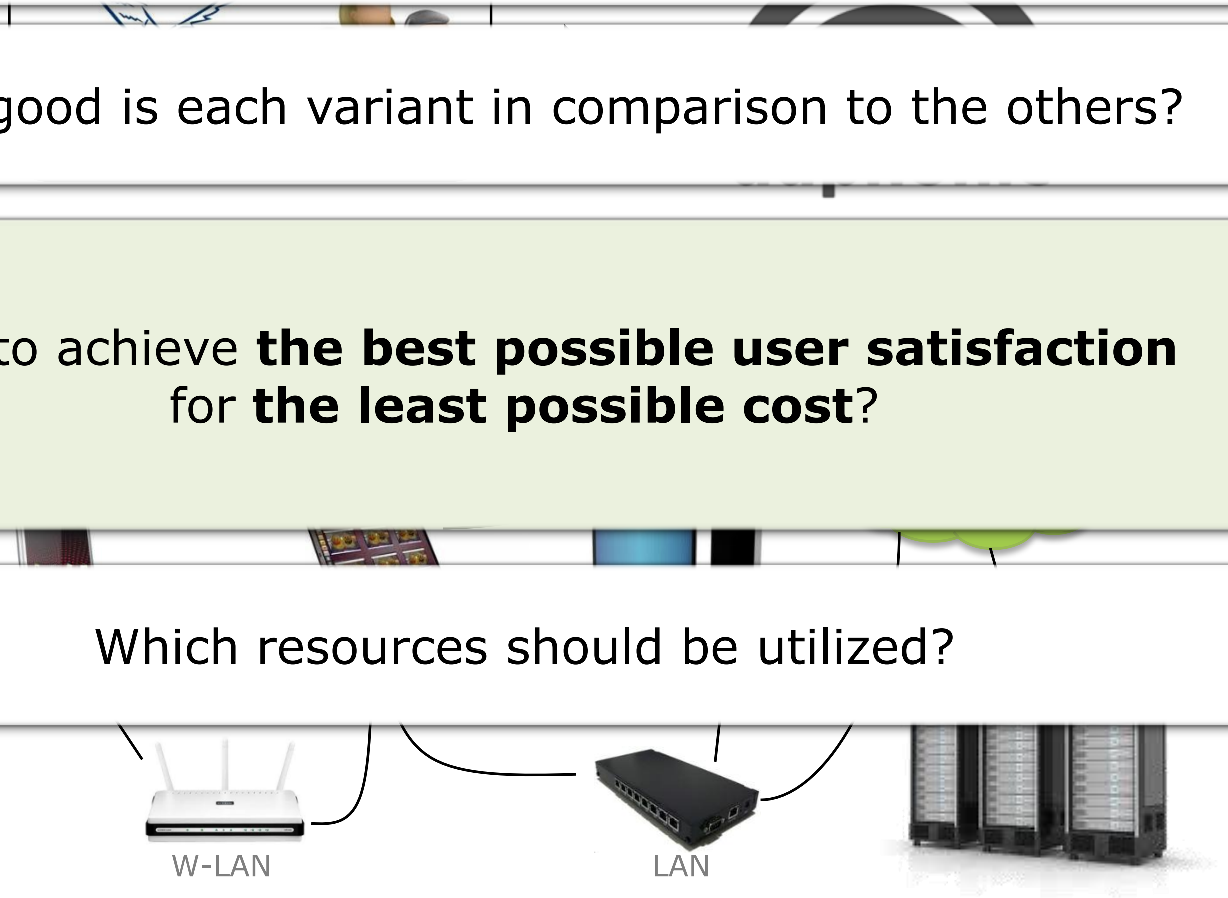
Context

Which variant of which software should be used?

How good is each variant in comparison to the others?

How to achieve **the best possible user satisfaction** for **the least possible cost**?

Which resources should be utilized?



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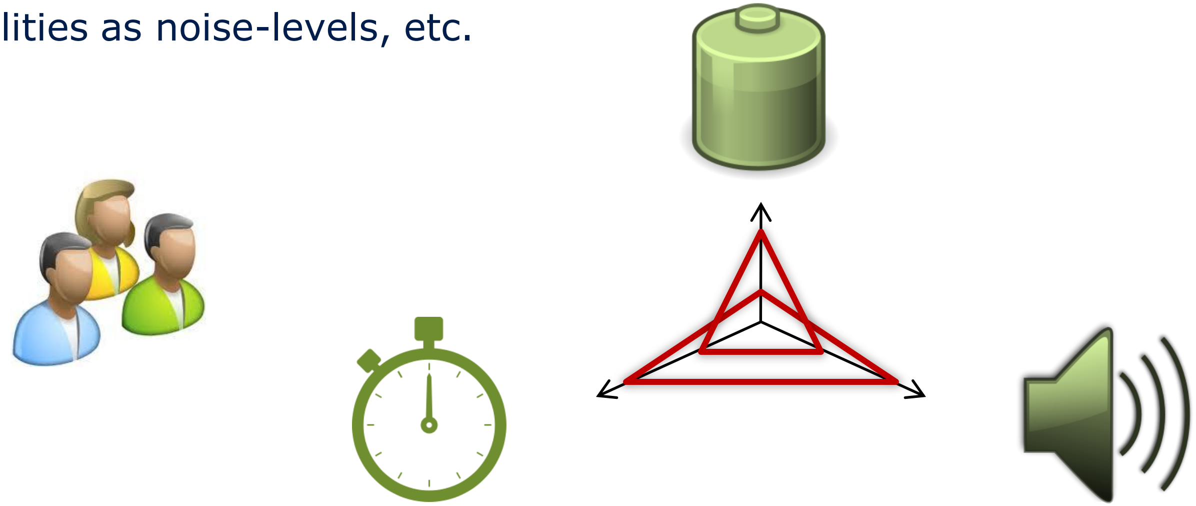
Motivation

- **User objectives relate to qualities**: energy, performance, domain-specific qualities as noise-levels, etc.



- Often **multiple, competing qualities** are to be considered **in combination** [ST09]

A novel approach to **design** & **operate self-optimizing systems** covering **multiple objectives**.

Multi-Quality Auto-Tuning (MQuAT)

Problems / Related Work

Problem 1: Developers **cannot reuse solutions** to build self-optimizing systems although many specific approaches exist.

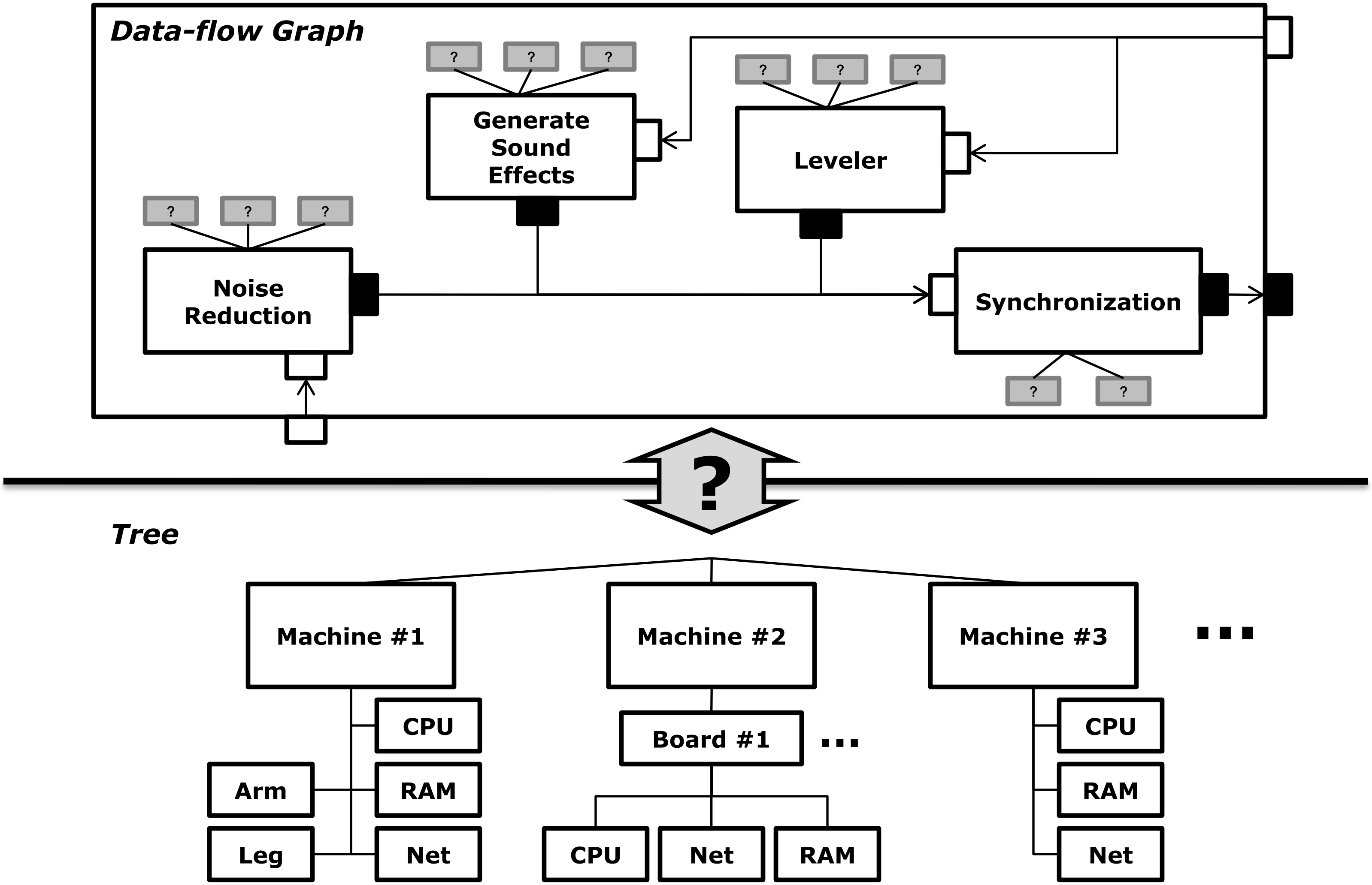
- Fixed set of considered properties (e.g., bandwidth, response time)
- Fixed architecture (e.g., specific to servers, mobile phones or cars)
- Fixed optimization technique (e.g., integer linear programming)

Goal: A generic approach to self-optimizing systems.

Solution: A **model-driven development approach** to self-optimization

- A **component-based metamodel** enabling the developer to specify the properties of interest and the system‘s architecture.
- **Technology bridges** to utilize multiple optimization techniques (generation of optimization problems).

Optimization Problem Description



Problems / Related Work

Problem 2: Existing (specific) approaches **do not cover dependencies between qualities.**

- Quality-contract-based approaches
  - COMQUAD → QoS characteristics (e.g., `response_time < 5ms`) [RZ03]
  - THESEUS → SLAs; QoS intervals (e.g., `2ms < response_time < 5ms`) [S10]
  - No context-dependent QoS statements (e.g., `response_time(size) = f(size)`)
  - Both projects identified the need to cover QoS dependencies [ZM03, S10]

Goal: Explicit coverage of (context-dependent) interaction between qualities.

Solution:

- An extended notion of quality contracts and
- A process for quality contract refinement.

Problems / Related Work

Problem 3: Competing qualities demand for **multi-objective optimization** having a **high computational complexity** (NP-hard) [NW99]

- Multi-objective approaches (e.g., OCTOPUS)
  - **„a priori":** aggregation of objectives prior to optimization
  - **„a posteriori":** optimization delivers set of multi-dimensional solutions (Pareto front)
- **Optimization at runtime** requires feasible, assessable time requirements

Goal: A generic, *assessable* runtime multi-objective optimization approach.

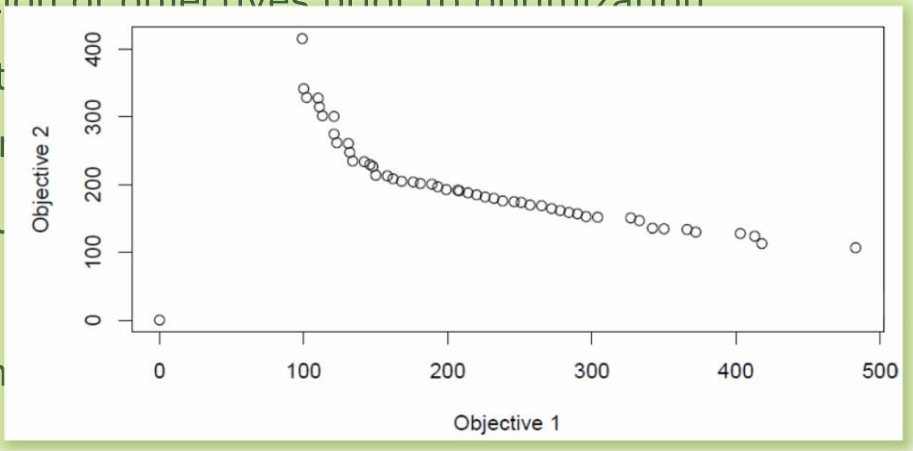
Solution:

- **4 runtime technology bridges** to multi-objective optimization techiques.
- **Scalability analysis** of supported techniques.

Problems / Related Work

Problem 3: Competing qualities demand for **multi-objective optimization** having a **high computational complexity** (NP-hard) [NW99]

- Multi-objective approaches (e.g., OCTOPUS)
  - **„a priori“:** aggregation of objectives prior to optimization
  - **„a posteriori“:** optimizat
    (Pareto fr
- **Optimization at runtime** requ

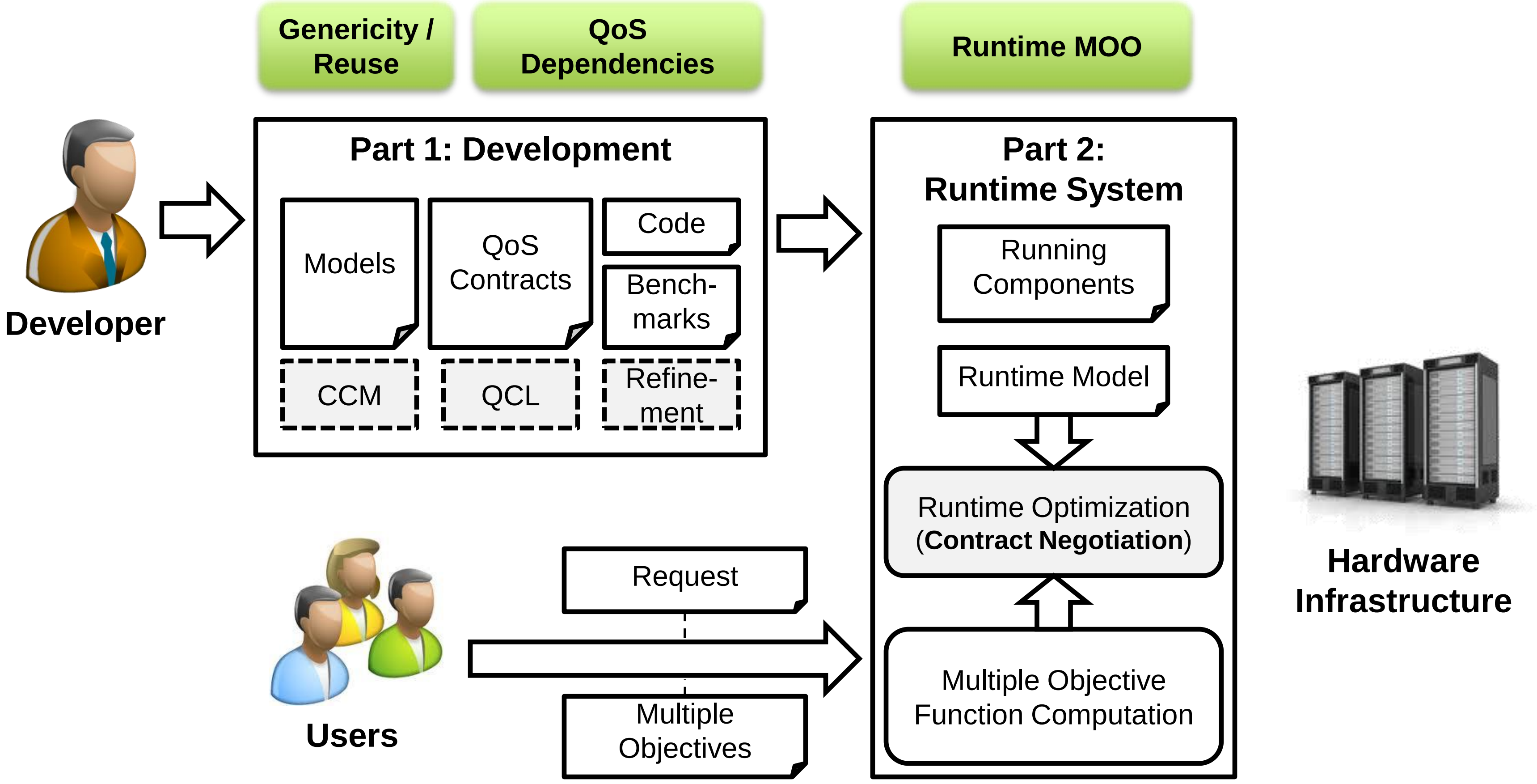


Goal: A generic, *assessable* runtim

Solution:

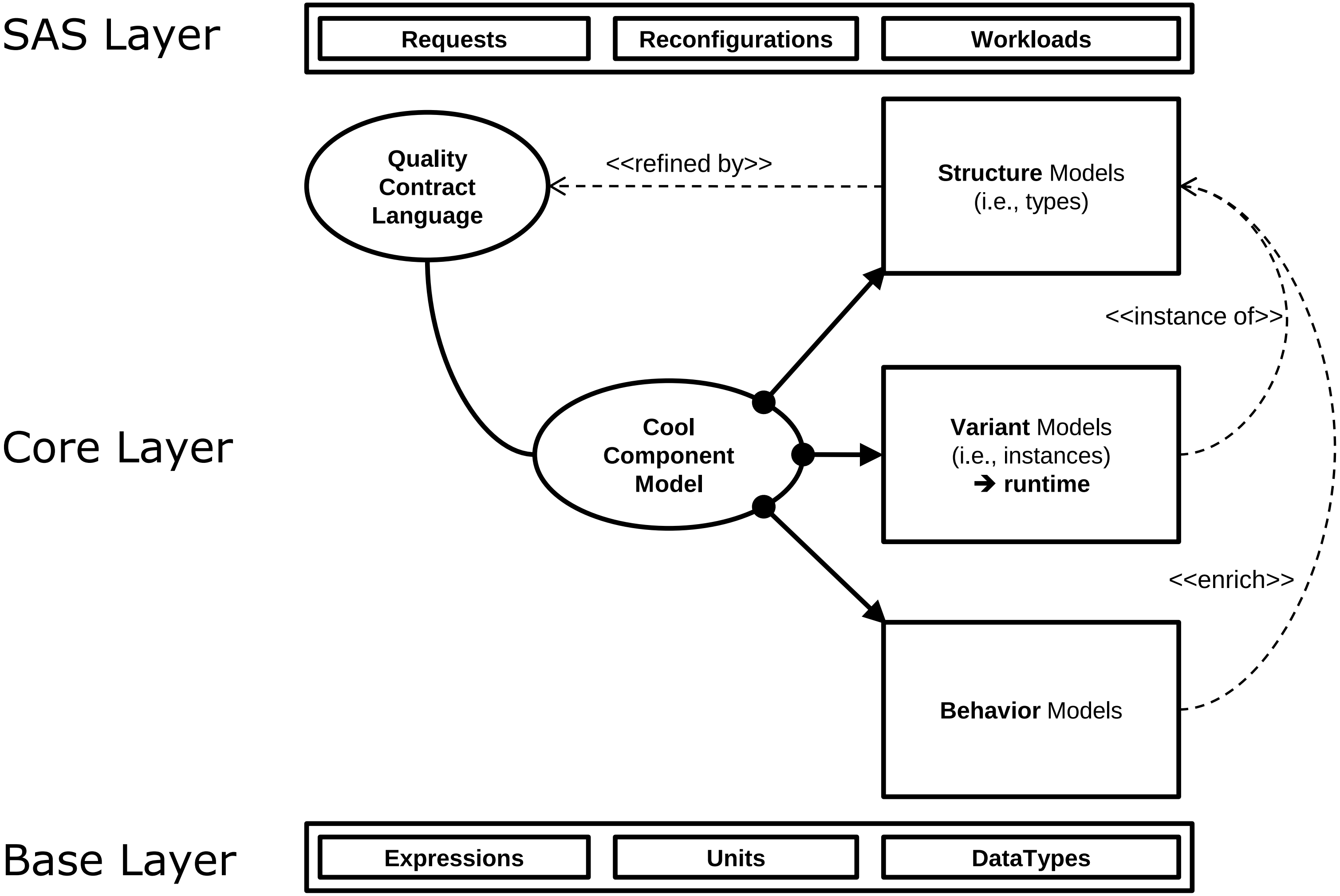
- **4 runtime technology bridges** to multi-objective optimization techiques.
- **Scalability analysis** of supported techniques.

Overview


Genericity / Reuse
QoS Dependencies
Runtime MOO
Developer
Part 1: Development
Models
QoS Contracts
Code
Bench-marks
CCM
QCL
Refine-ment
Part 2: Runtime System
Running Components
Runtime Model
Runtime Optimization (Contract Negotiation)
Multiple Objective Function Computation
Hardware Infrastructure
Users
Request
Multiple Objectives

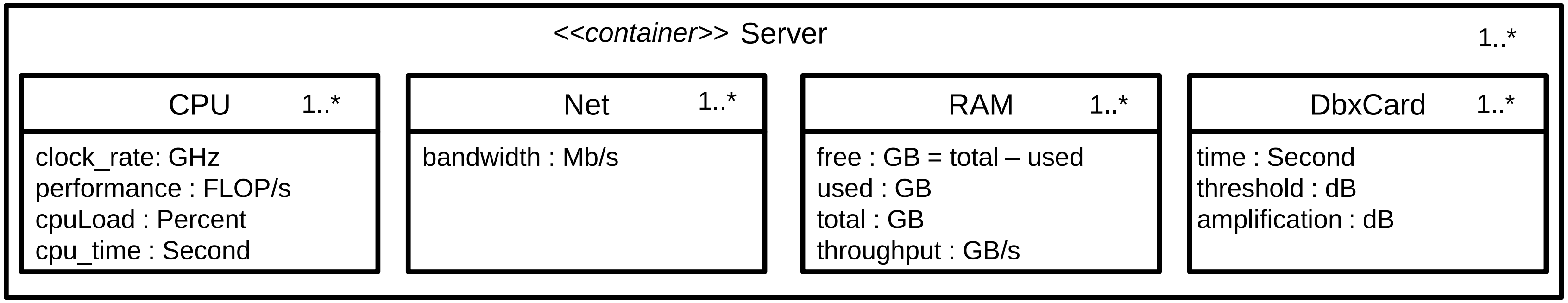
PART 1: DEVELOPMENT

Cool Component Model [GWS+10]



Cool Component Model [GWS+10]

- Example CCM Structure Model for Servers:



<<*container*>> Server 1..*

CPU 1..*
clock_rate: GHz
performance : FLOP/s
cpuLoad : Percent
cpu_time : Second

Net 1..*
bandwidth : Mb/s

RAM 1..*
free : GB = total – used
used : GB
total : GB
throughput : GB/s

DbxCard 1..*
time : Second
threshold : dB
amplification : dB

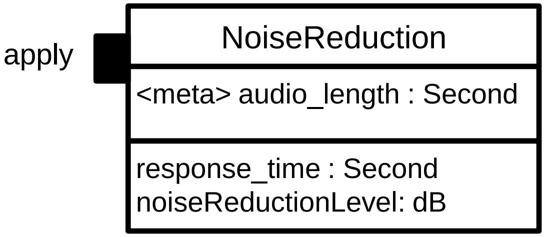
- Example Unit Library

```
library {
  simple unit Watt : Integer
  simple unit Second : Integer;
  simple unit dB : Real;

  complex unit Joule = Watt Second;

  factor KW = 1000 Watt;
}
```

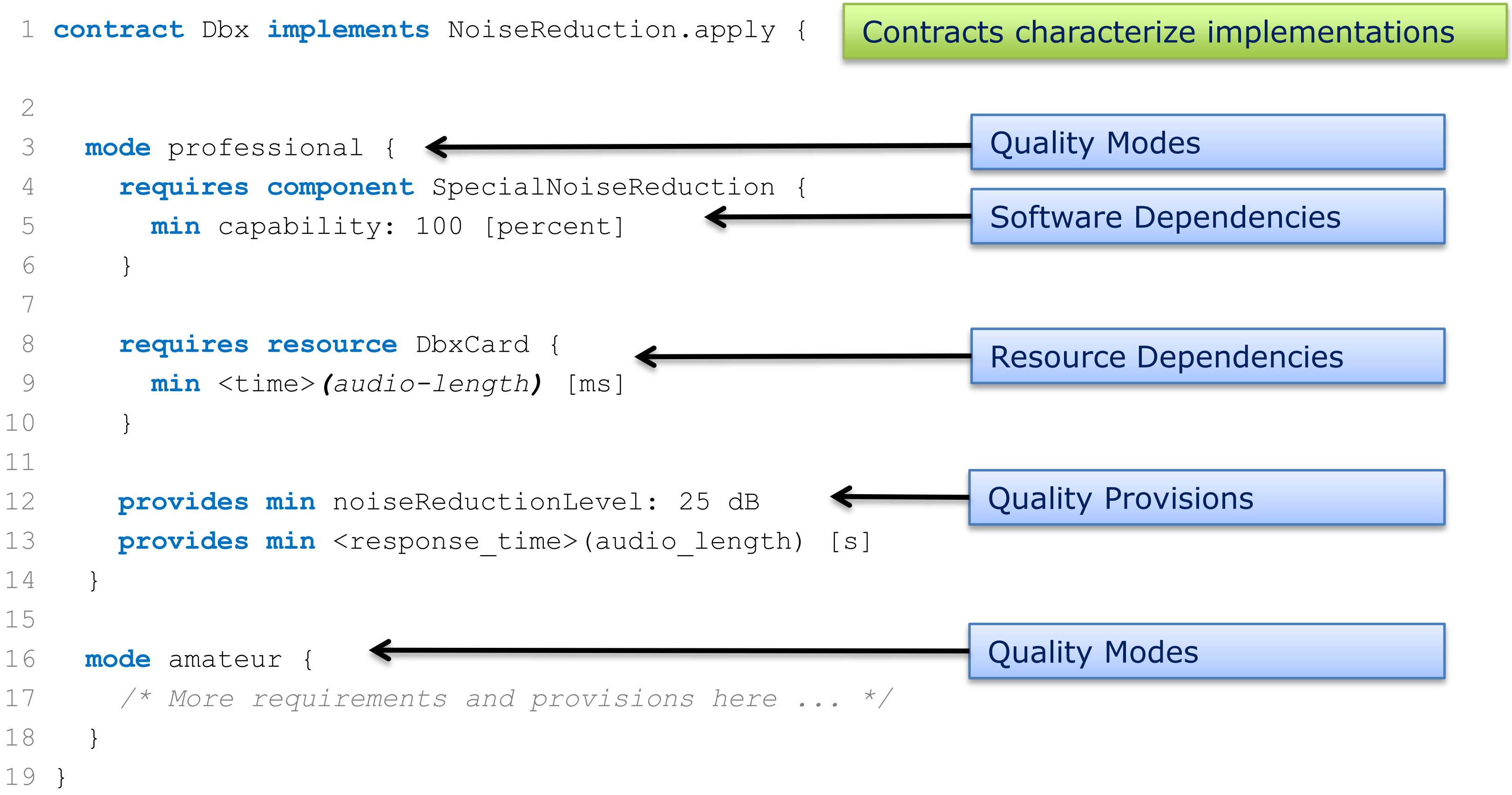
- Example CCM Structure Model for Sort:



apply

NoiseReduction
<meta> audio_length : Second
response_time : Second
noiseReductionLevel: dB

Quality Contract Language [GWC+12a]



```
contract Dbx implements NoiseReduction.apply {

  mode professional {
    requires component SpecialNoiseReduction {
      min capability: 100 [percent]
    }

    requires resource DbxCard {
      min <time>(audio-length) [ms]
    }

    provides min noiseReductionLevel: 25 dB
    provides min <response_time>(audio_length) [s]
  }

  mode amateur {
    /* More requirements and provisions here ... */
  }
}
```

Contracts characterize implementations

Quality Modes

Software Dependencies

Resource Dependencies

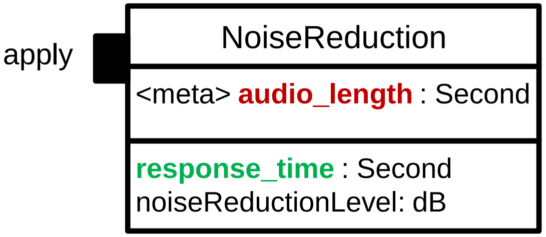
Quality Provisions

Quality Modes

Contract Refinement [GWC+12b]

- Target systems and user input are unknown to developer.
- Developer creates **contract templates**:

```
contract Dbx implements NoiseReduction.apply {
  mode professional {
     ...
     provides min response_time:
        <response_time>(audio_length)  [s];
  }
  ...
}
```



apply

NoiseReduction

<meta> **audio_length** : Second

response_time : Second
noiseReductionLevel: dB

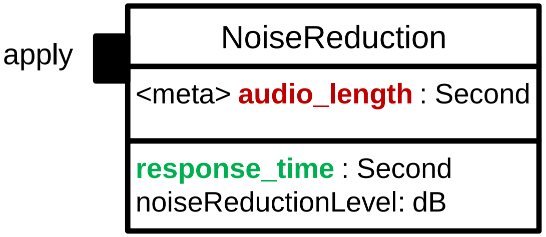
- Developer creates **Benchmark Suite** using **Profiler Framework** [WGR13]

```
for(i = 0; i <= N; i++) {
  Profiler.getProfiler(„response_time“).start();
  dbx.apply(sample_files[i]);
  Profiler.getProfiler(„response_time“).stop();
}
```

Contract Refinement [GWC+12b]

- Target systems and user input are unknown to developer.
- Developer creates **contract templates**:

```
contract Dbx implements NoiseReduction.apply {
  mode professional {
     ...
     provides min response_time:
       <response_time>(audio_length) [s];
  }
  ...
}
```



- Benchmarks executed at **deployment** time on **each target machine**:

audio_length	response_time
1s	945ms
2s	1823ms
...	...
120s	110215ms

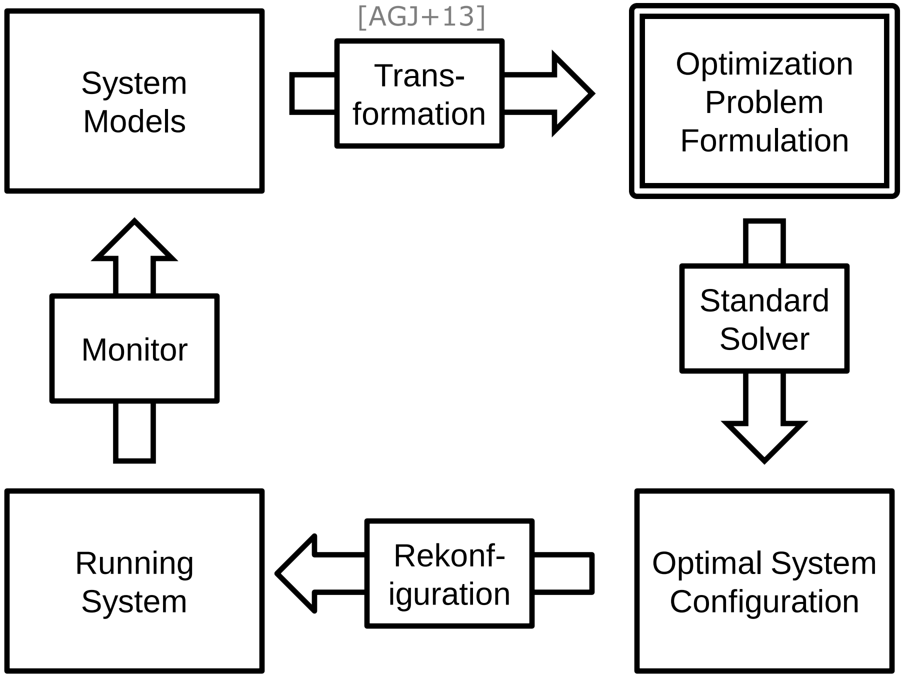
```
<response_time>(audio_length) [s]
⇩
1.147*10^(-6)*audio_length^2-1922 [s];
```

One contract per machine and implementation.

PART 2: RUNTIME

Contract Negotiation

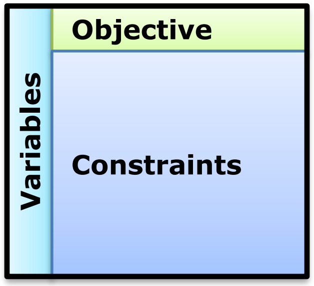
… denotes a **global optimization problem** of a system of **components**, which are **known and controllable** by **central coordinators** as known from the self-adaptive system‵s community.



		Objectives	
		Single	Multiple
Accuracy	Exact	ILP PBO	MOILP
	Approx.	ACO	

Contract Negotiation by ILP [GWC+11]

- Base: Integer Linear Programming (ILP)

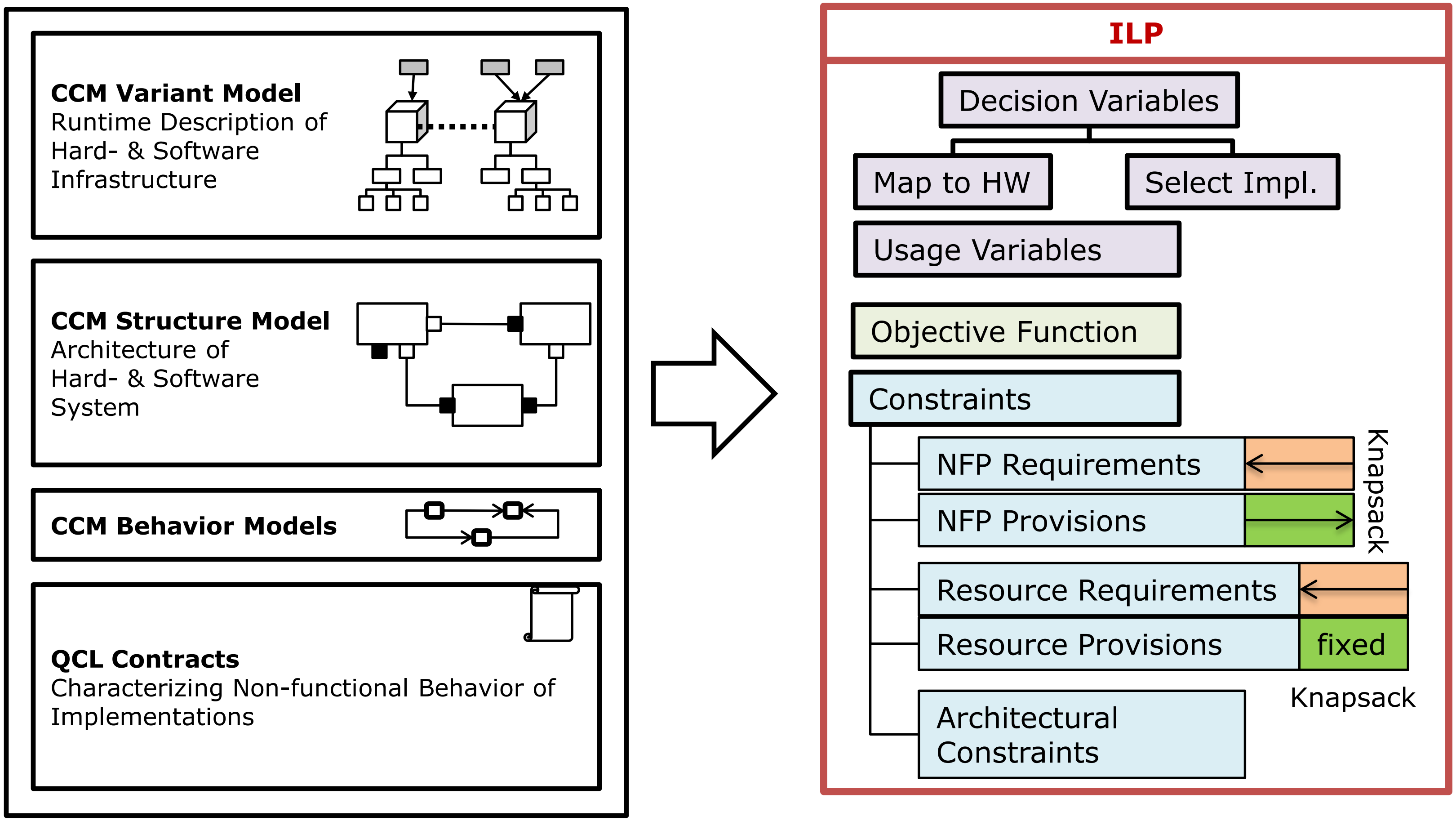


- **Goal**: determine the variable assignment, which
  - Maximizes objective function and
  - Adheres to the constraints.

- Avoids pruning of whole search space (worst case)

Contract Negotiation by ILP [GWC+11]

- Integer Linear Programming (ILP)



CCM Variant Model
Runtime Description of Hard- & Software Infrastructure

CCM Structure Model
Architecture of Hard- & Software System

CCM Behavior Models

QCL Contracts
Characterizing Non-functional Behavior of Implementations

ILP

Decision Variables

Map to HW

Select Impl.

Usage Variables

Objective Function

Constraints

NFP Requirements

NFP Provisions

Knapsack

Resource Requirements

Resource Provisions

fixed

Knapsack

Architectural Constraints

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ILP by Example

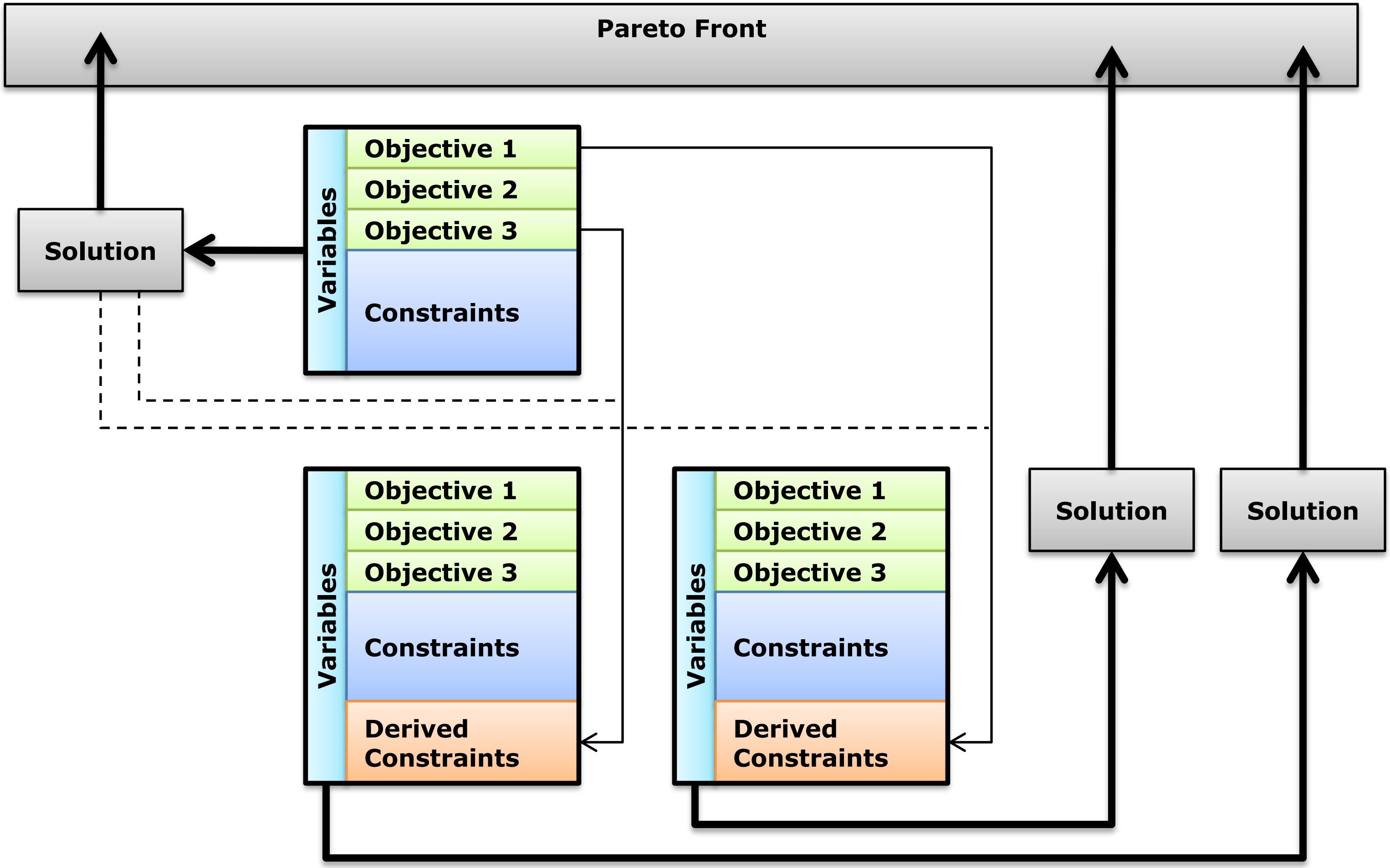
```
/* objective function: minimize energy consumption (based on cpu_time) */
min: 5700.0 b#Quicksort#delayed#R1 + 495.0 b#UnsortedFilter#slow#R1
+ 10285.0 b#Quicksort#immediate#R1 + 6160.0 b#Javasort#immediate#R1
+ 385.0 b#UnsortedFilter#fast#R1 + 2250.0 b#Random#slow#R1
+ 5940.0 b#Javasort#delayed#R1 + 2695.0 b#Random#fast#R1;

/* architectural constraints */
b#Random#fast#R1 + b#Random#slow#R1 = b#Quicksort#delayed#R1 + b#Quicksort#immediate#R1
                                      + b#Javasort#immediate#R1 + b#Javasort#delayed#R1;
b#UnsortedFilter#fast#R1 + b#UnsortedFilter#slow#R1 = 1;
b#Quicksort#immediate#R1 + b#Quicksort#delayed#R1
+ b#Javasort#immediate#R1 + b#Javasort#delayed#R1 = b#UnsortedFilter#slow#R1
                                                  + b#UnsortedFilter#fast#R1;

/* resource negotiation */
usage#R1#Core[TM]_i7_CPU_Q_720_@_1.60GHz#frequency <= 1596.0;
usage#R1#Core[TM]_i7_CPU_Q_720_@_1.60GHz#frequency >= 0;
usage#R1#Core[TM]_i7_CPU_Q_720_@_1.60GHz#frequency =
  100 b#Javasort#delayed#R1 + 100 b#UnsortedFilter#slow#R1 + 100 b#Quicksort#delayed#R1
+ 300 b#Random#fast#R1 + 300 b#Quicksort#immediate#R1 + 100 b#Random#slow#R1
+ 300 b#Javasort#immediate#R1 + 300 b#UnsortedFilter#fast#R1;

...
```

ILP by Example

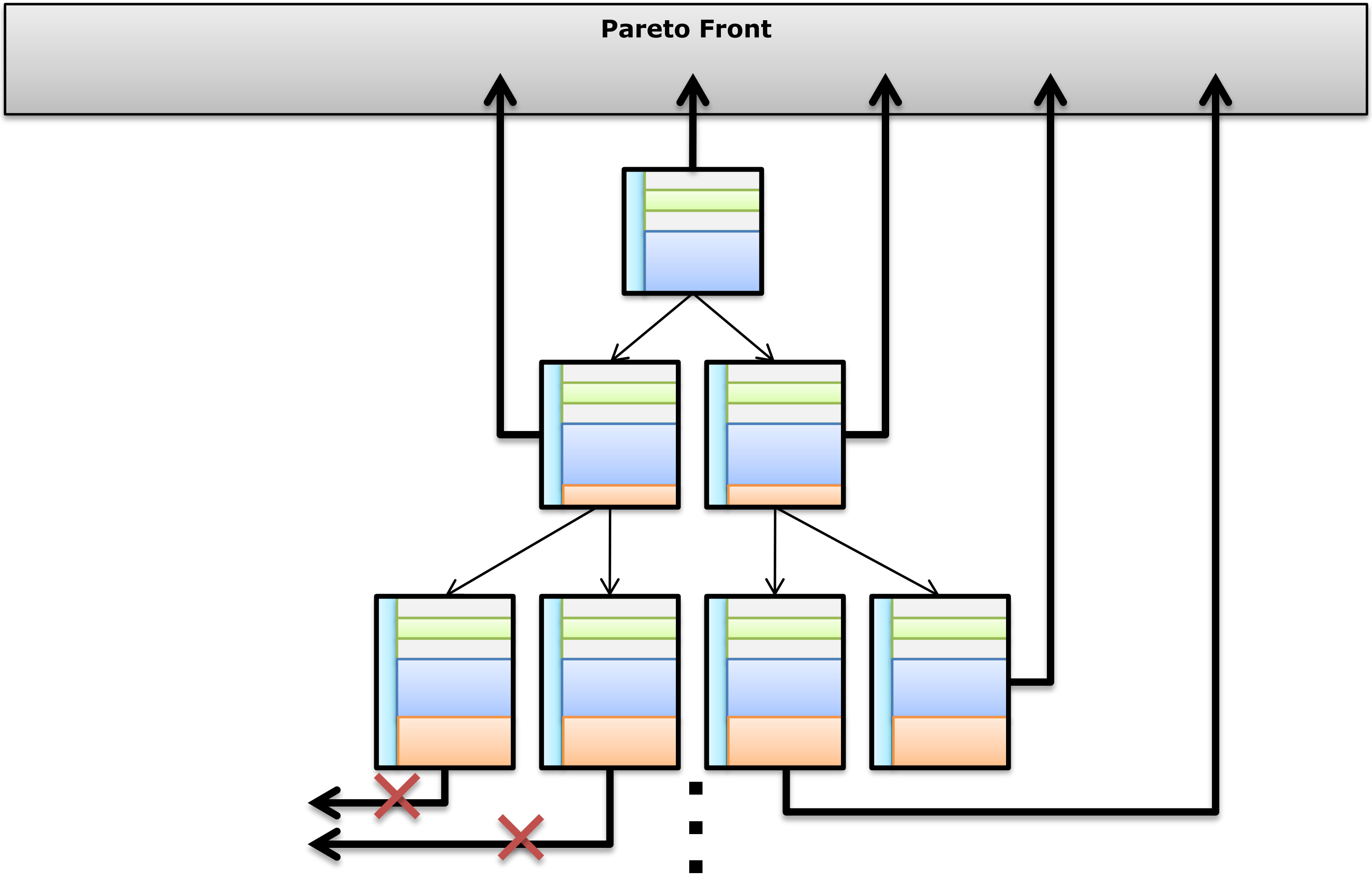
```
...

/* software NFP negotiation */
Sort#response_time = 382.05714282441 b#Quicksort#delayed#R1
                   + 377.31428570997804 b#Quicksort#immediate#R1
                   + 399.771428570494 b#Javasort#immediate#R1
                   + 416.34285718949195 b#Javasort#delayed#R1;
Filter#response_time = 23.921216866850248 b#UnsortedFilter#slow#R1
                     + 28.407017552658598 b#UnsortedFilter#fast#R1;
ListGen#response_time = 107.6078431285458 b#Random#slow#R1
                      + 106.7843137012918 b#Random#fast#R1;
Sort#response_time >= 50 b#UnsortedFilter#fast#R1;
ListGen#response_time >= 50 b#Quicksort#delayed#R1 + 50 b#Javasort#immediate#R1
                                                   + 50 b#Javasort#delayed#R1;
/* user request */
Filter#response_time <= 200.0;

/* boolean restriction */
binary b#Quicksort#delayed#R1, b#UnsortedFilter#slow#R1, b#Quicksort#immediate#R1,
b#Javasort#immediate#R1, b#UnsortedFilter#fast#R1, b#Random#slow#R1,
b#Javasort#delayed#R1, b#Random#fast#R1;
```

Contract Negotiation by MOILP

Klein und Hannan ´82



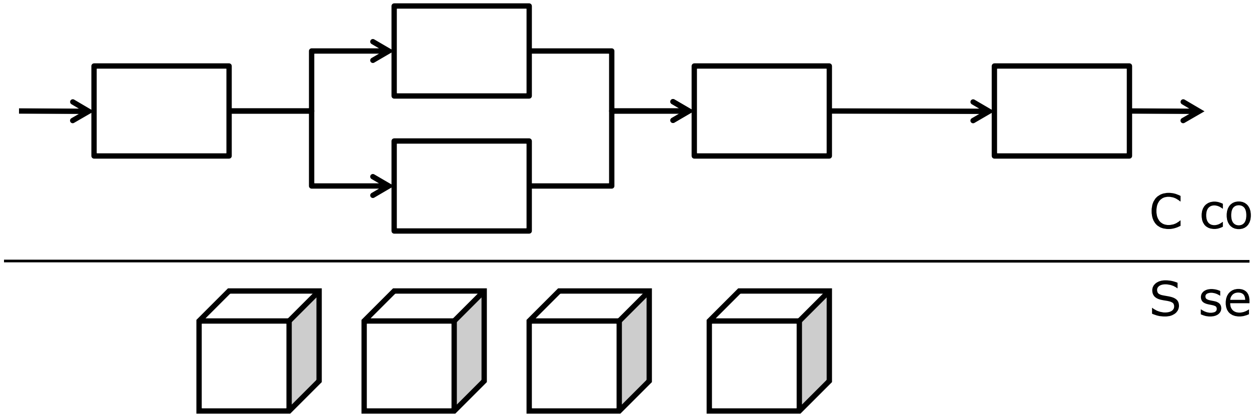
Contract Negotiation by MOILP



Quadradic Growth until Termination

Scalability Analysis [GWR+13]

- Performed on **data-flow graphs (pipe-and-filter style)**

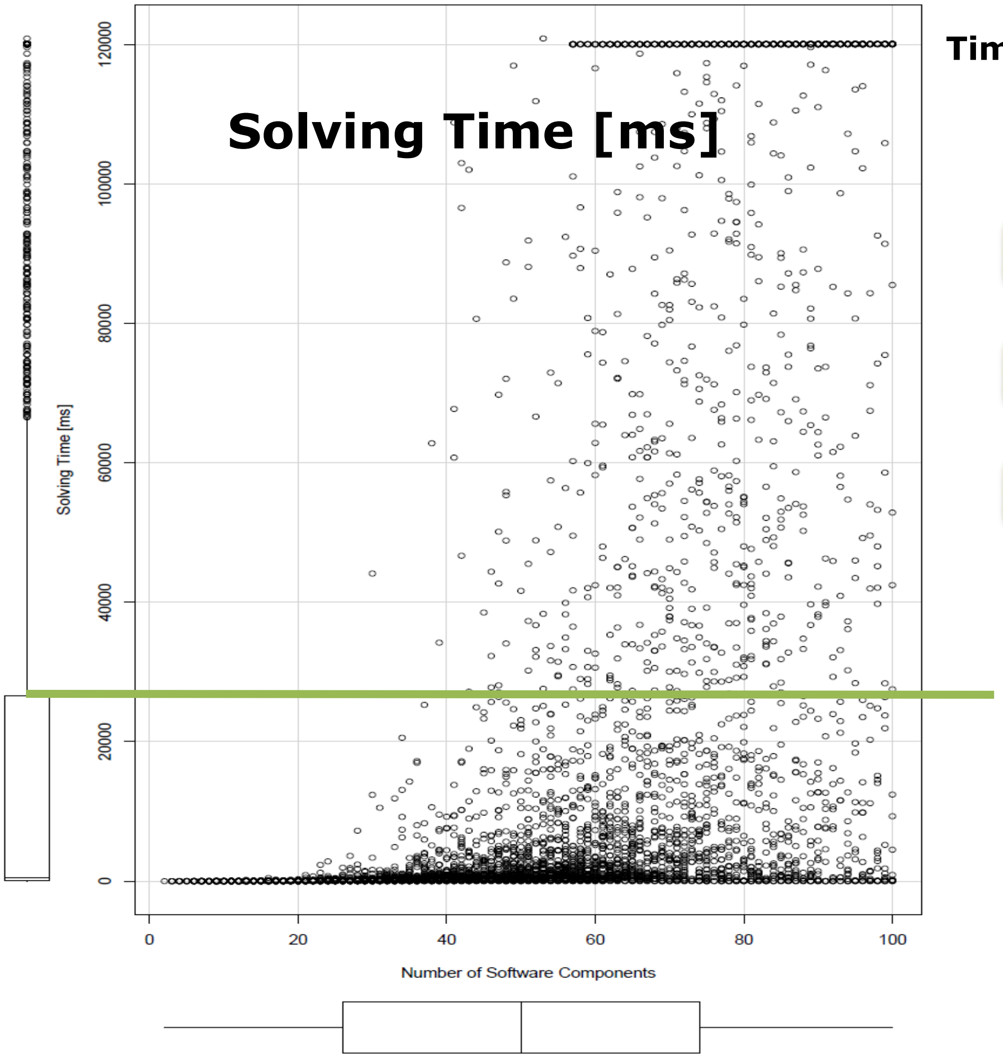


C components

S servers

- Measurements taken for C x S systems from **C = [2..100] and S = [2..100]**
- **All measurements made on Alienware X51** (Win7 64bit, SSD HDD, 8GB DDR1600 RAM, Intel Core i7-2600 with 4 physical cores at 3.4GHz)
- Concrete numbers will differ on other machines, solvers, etc.
- Focus on **principle findings**.

Scalability Analysis: ILP [GWR+13]



Timeout: 2min

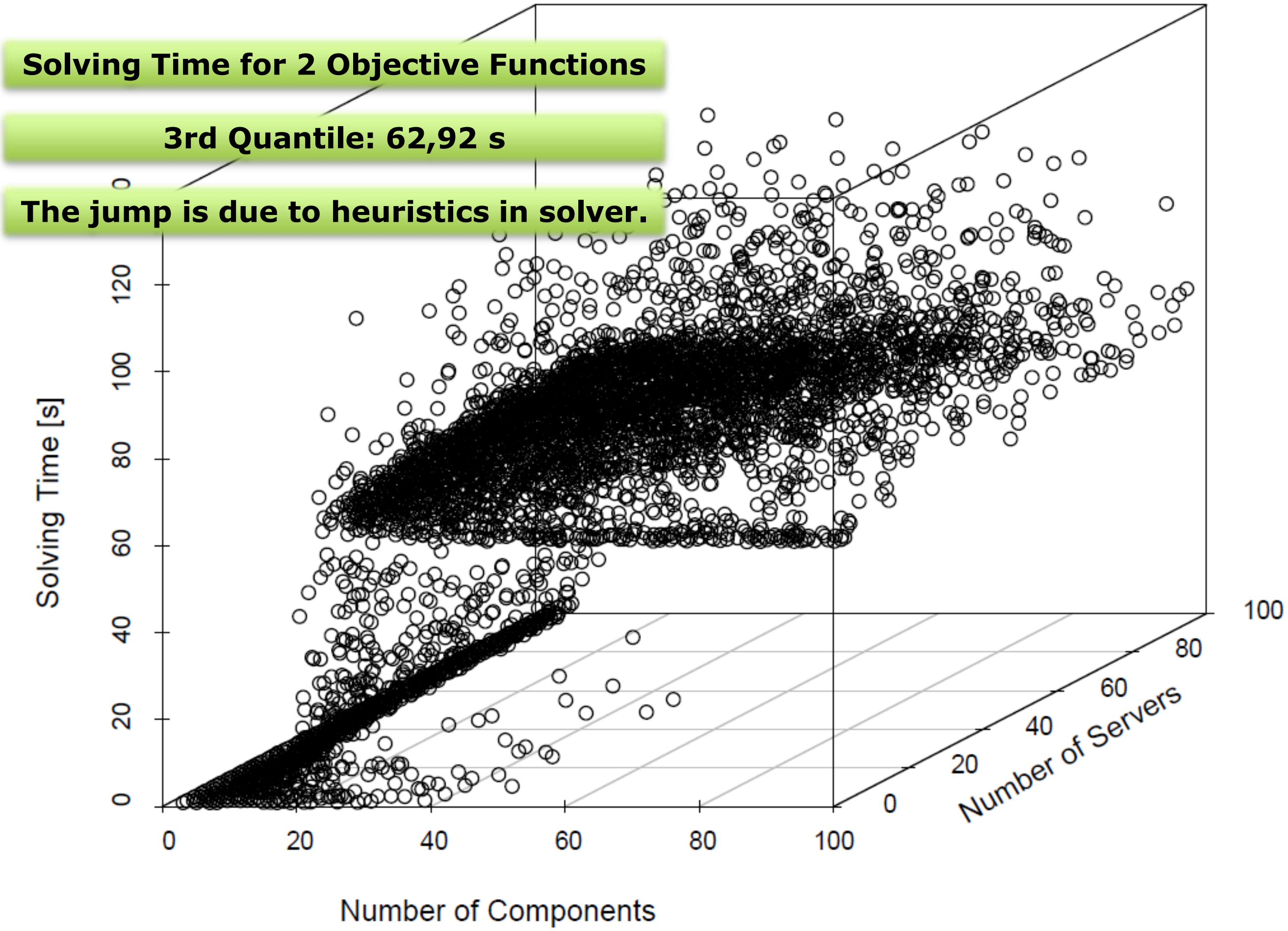
Feasible up to 100x100

Predictable up to 25 Components

Reason: Worst-case situations

3rd Quartile: 26,58s

Scalability Analysis: MOILP

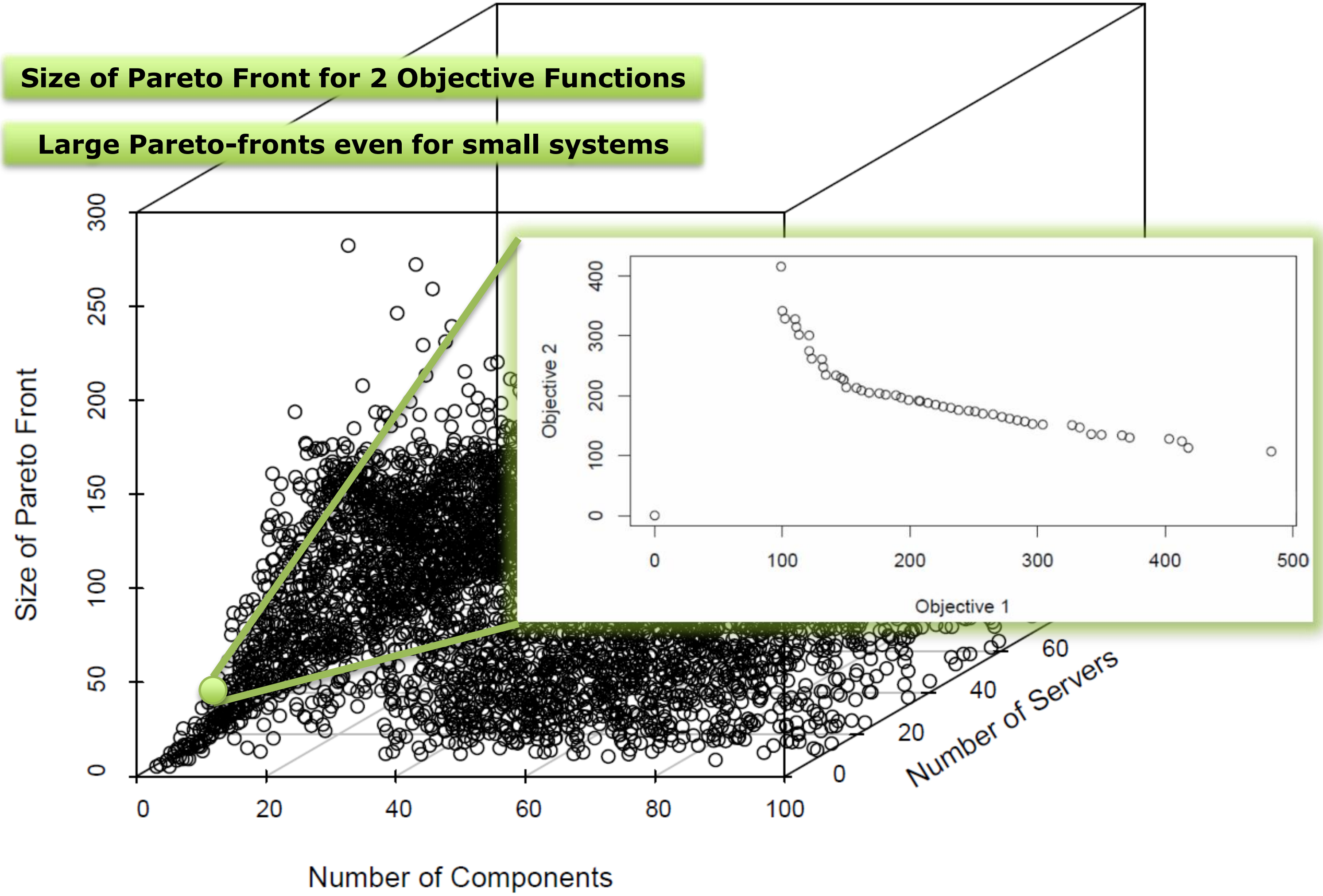


Solving Time for 2 Objective Functions

3rd Quantile: 62,92 s

The jump is due to heuristics in solver.

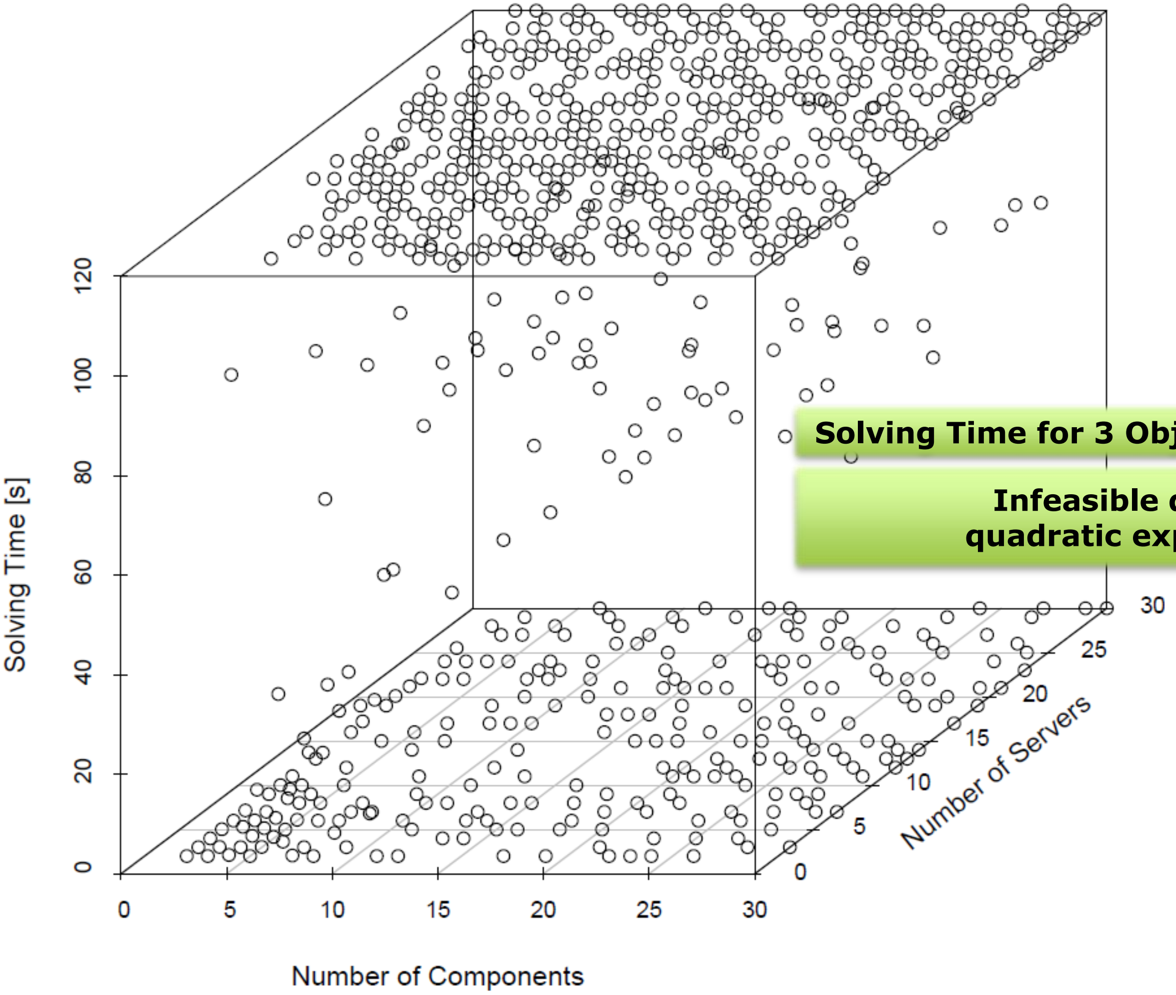
Scalability Analysis: MOILP



Size of Pareto Front for 2 Objective Functions

Large Pareto-fronts even for small systems

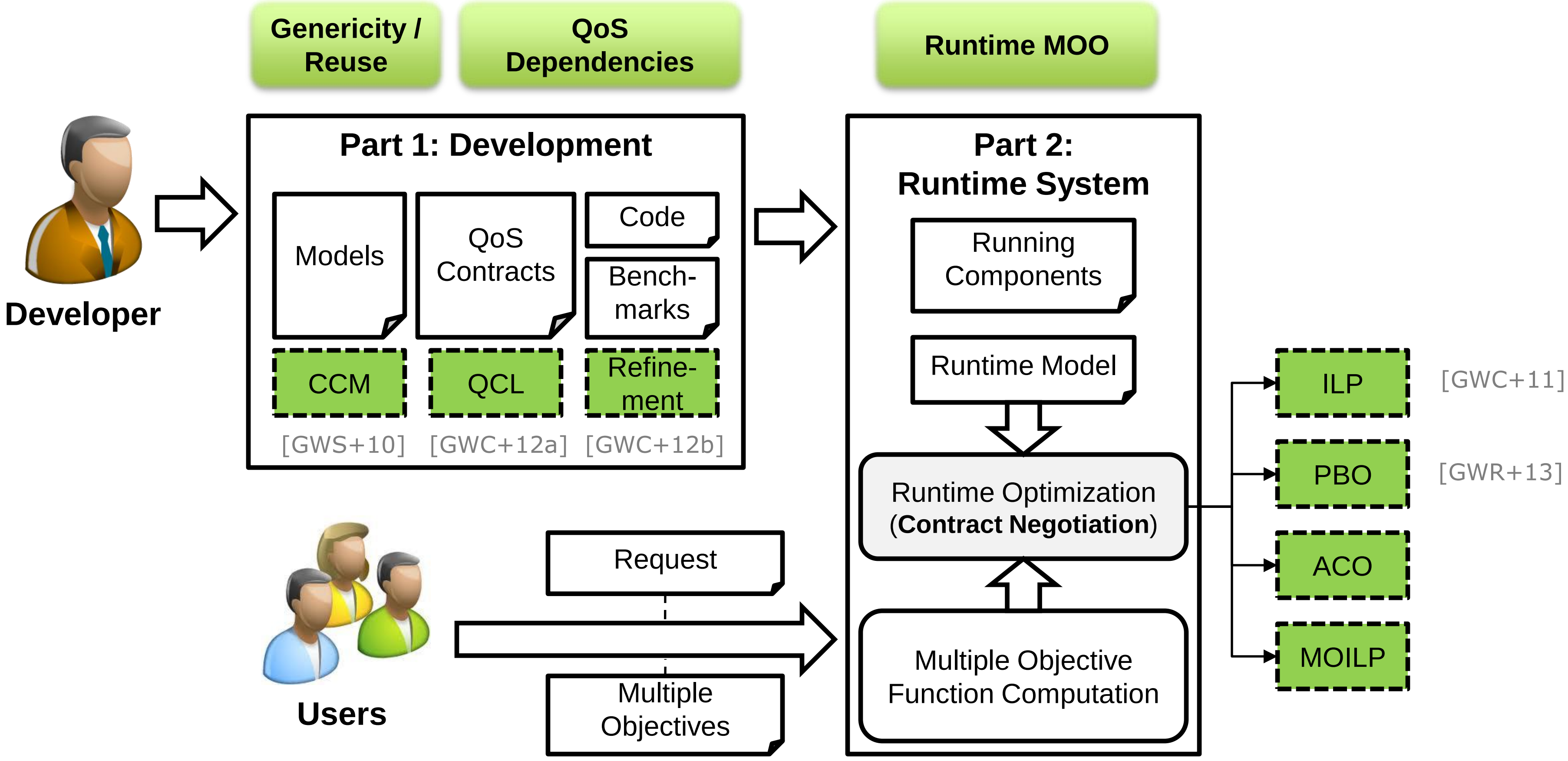
Scalability Analysis: MOILP



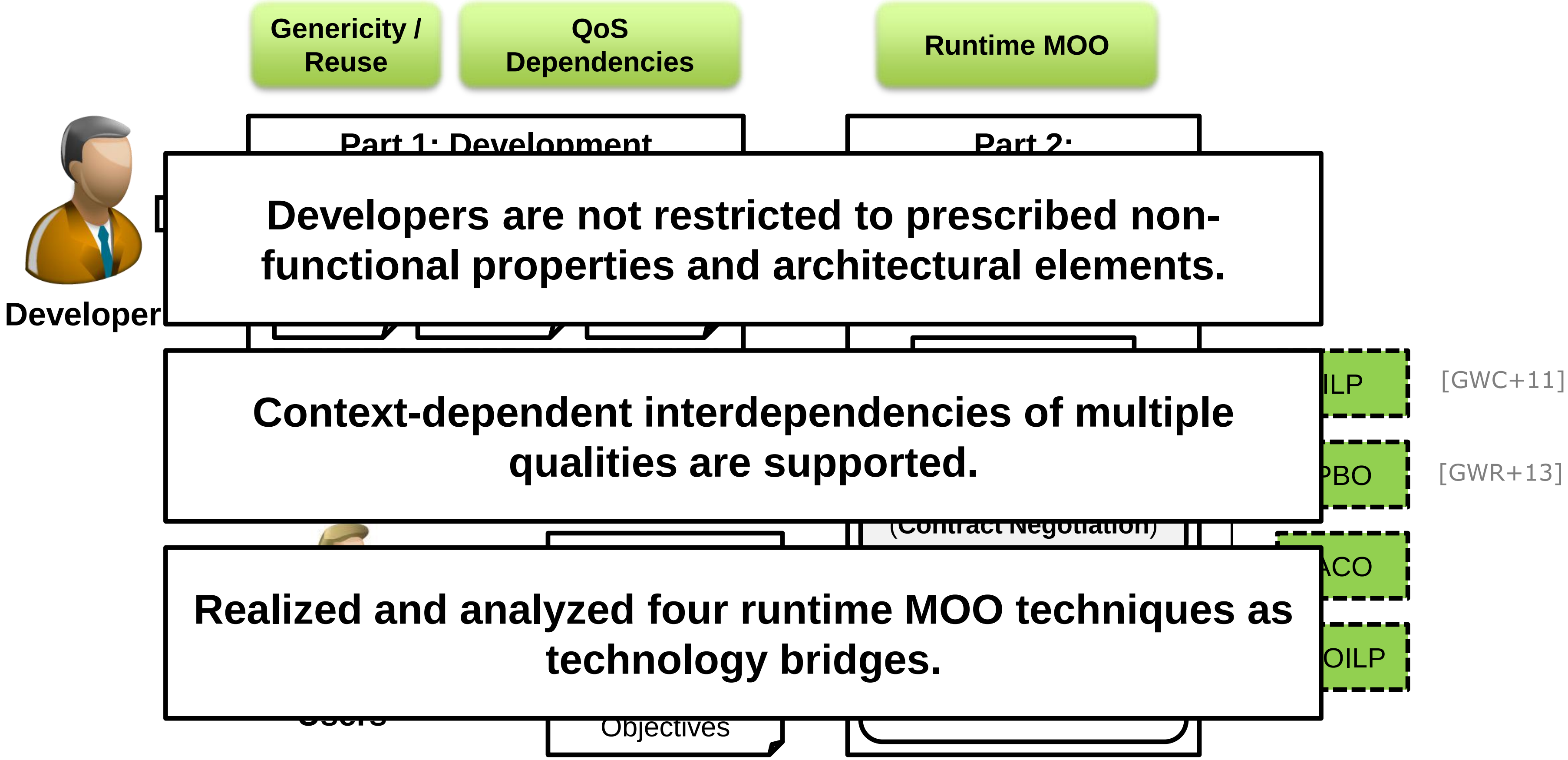
Solving Time for 3 Objective Functions

Infeasible due to quadratic explosion.

Contributions



Contributions



Developers are not restricted to prescribed non-functional properties and architectural elements.

Context-dependent interdependencies of multiple qualities are supported.

Realized and analyzed four runtime MOO techniques as technology bridges.

Future Work

- **Bootstrapping:** MQuAT for Monitoring, Optimization and Reconfiguration
  - Both are components with different implementations, too.
  - Scalability analysis is a first step for the optimization component
  - Collaboration planned with Prof. Fischer (Numerical Optimization Group)

- **Green Software Engineering** (CRC 912: HAEC, NFG ZESSY)
  [WGR+11, WRP+12, WRP+13, WGR13, GMT+13, WRG+13a, WRG+13b]
  - *Open Challenges*: Sustainability, Negotiation of Energy-Sources (Solar, Battery, Provider, etc.)

- Software Engineering for **Robotic** and **Cyber-Physical Systems**
  [GLR+11, GLP+12, PRG+12]
  - *Open Challenge*: Optimization across discrete and continuous system parts

Own Related Publications

[GWS+10] **S. Götz**, C. Wilke, M. Schmidt, S. Cech and U. Assmann. *Towards Energy Auto Tuning.* In: Proceedings of First Annual International Conference on Green Information Technology, GREEN IT 2010, GSTF (2010) p. 122-129.

[GWC+11] **S. Götz**, C. Wilke, S. Cech and U. Assmann. *Runtime Variability Management for Energy-efficient Software by Contract Negotiation.* In Proceedings of the 6th International Workshop on Models@run.time, ACM/IEEE (2011) p. 61-72.

[GWC+12a] **S. Götz**, C. Wilke, S. Cech and U. Assmann. *Architecture and Mechanisms of Energy Auto Tuning.* In Sustainable ICTs and Management Systems for Green Computing. IGI Global (2012) p. 45-73.

[GWC+12b] **S. Götz**, C. Wilke, S. Richly and U. Assmann. *Approximating Quality Contracts for Energy Auto-Tuning Software.* In Proceedings of First International Workshop on Green and Sustainable Software (GREENS'12), IEEE (2012) p. 8-14.

[GWR+13] **S. Götz**, C. Wilke, S. Richly and U. Aßmann. *Model-driven Self-Optimization using Integer Linear Programming and Pseudo-Boolean Optimization.* In Proceedings of the Fifth International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE), XPS Press (2013) p. 55-64.

[AGJ+13] U. Assmann, **S. Götz**, J.-M. Jezequel, B. Morin and M. Trapp. *Uses and Purposes of M@RT Systems.* To appear in State-of-the-Art Survey Volume on Models@run.time. Springer LNCS, 2013.

Own Future Work Publications

[WRG+13b] C. Wilke, S. Richly, **S. Götz**, C. Piechnick and U. Aßmann. *Energy Consumption and Efficiency in Mobile Applications: A User Feedback Study.* To appear in Proceedings of the IEEE International Conference on Green Computing and Communications (GreenCom), 2013.

[WRG+13a] C. Wilke, S. Richly, **S. Götz**, and U. Aßmann. *Energy Profiling as a Service.* To appear in GI Proceedings of Workshop "Umweltinformatik zwischen Nachhaltigkeit und Wandel" (UINW), 2013.

[GMT+13] **S. Götz**, J. Mendez, V. Thost and A.-Y. Turhan. *OWL 2 Reasoning To Detect Energy-Efficient Software Variants From Context.* To appear in Proceedings of the 10th OWL: Experiences and Directions Workshop (OWLED), 2013.

[PRG+13] G. Püschel, **S. Götz**, C. Wilke and U. Aßmann. *Towards Systematic Model-based Testing of Self-adaptive Systems.* In Proceedings of The Fifth International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE), XPS Press (2013), p. 65-70.

[WGR13] C. Wilke, **S. Götz** and S. Richly. *JouleUnit – A Generic Framework for Software Energy Profiling and Testing.* In Proceedings of the 1st Workshop "Green In Software Engineering Green By Software Engineering" (GIBSE), ACM/IEEE (2013) p. 9-13.

[WRP+13] C. Wilke, S. Richly, C. Piechnick, **S. Götz**, G. Püschel and U. Aßmann. *Comparing Mobile Applications' Energy Consumption.* In Proceedings of The 28th Annual ACM Symposium on Applied Computing (SAC 2013), ACM (2013) p. 1177-1179.

Own Future Work Publications

[WRP+12] C. Wilke, S. Richly, G. Püschel, C. Piechnick, **S. Götz** and Uwe Assmann. *Energy Labels for Mobile Applications.* To appear in Proceedings of 1. Workshop zur Entwicklung energiebewusster Software / First Workshop for the Development of Energy-aware Software (EEbS 2012), 2012.

[WGR+11] C. Wilke, **S. Götz**, J. Reimann and U. Assmann. *Vision Paper: Towards Model-Based Energy Testing.* In Proceedings of 14th International Conference on Model Driven Engineering Languages and Systems (MODELS 2011), Springer (2011) p. 480-489

[PRG+12] C. Piechnick, S. Richly, **S. Götz**, C. Wilke and U. Aßmann. *Using Role-Based Composition to Support Unanticipated, Dynamic Adaptation - Smart Application Grids.* **(Best Paper Award)** In Proceedings of The Fourth International Conference on Adaptive and Self-Adaptive Systems and Applications (ADAPTIVE), XPS Press (2012) pp. 93-102

[GLP+12] **S. Götz**, M. Leuthäuser, C. Piechnick, J. Reimann, S. Richly, J. Schroeter, C. Wilke und U. Aßmann. Entwicklung cyber-physikalischer Systeme am Beispiel des NAO Roboters. In Proceedings of Chemnitz Linux-Days, Universitätsverlag Chemnitz (2012) p. 42-52

[GLR+11] **S. Götz**, M. Leuthäuser, J. Reimann, J. Schroeter, C. Wende, C. Wilke and U. Assmann. *A Role-based Language for Collaborative Robot Applications.* In Proceedings of 1st International ISoLA Workshop on Software Aspects of Robotic Systems (ISOLA SARS 2011), Springer (2011) p. 1-15

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Literature

[KC03] J. O. Kephart and D. M. Chess. *The vision of autonomic computing*. In: IEEE Computer, 36:41-50, January 2003.

[L97] R. Laddaga. *DARPA self adaptive software broad agency announcement (baa) 98-12 proposer information pamphlet - excerpt*. http://people.csail.mit.edu/rladdaga/BAA98-12excerpt.html, December 1998.

[NW99] G. L. Nemhauser and L. A. Wolsey. *Integer and Combinatorial Optimization*. Wiley Interscience, 1999.

[RZ03] S. Röttger and S. Zschaler. *CQML+: Enhancements to CQML*. In Proceedings of the 1st International Workshop on Quality of Service in Component-Based Software Engineering, pages 43-56. Cepadues-Editions, 2003.

[ST09] M. Salehie and L. Tahvildari. *Self-adaptive software: Landscape and research challenges*. ACM Trans. Auton. Adapt. Syst., 4:14:1-14:42, May 2009.

[S10] Josef Spillner: *Methodik und Referenzarchitektur zur inkrementellen Verbesserung der Metaqualität einer vertragsgebundenen, heterogenen und verteilten Dienstausführung*. Dissertation. TU Dresden. 2010.

[ZM03] S. Zschaler and M. Meyerhöfer. *Explicit Modelling of QoS-Dependencies*. In Proceedings of the 1st International Workshop on Quality of Service in Component-Based Software Engineering, p. 57-66. Cepadues-Editions, 2003.