Scaling Exact Multi-Objective Combinatorial Optimization by Parallelization

Jianmei Guo, Edward Zulkoski,
Rafael Olaechea, Derek Rayside,
Krzysztof Czarnecki, Sven Apel,
Joanne M. Atlee

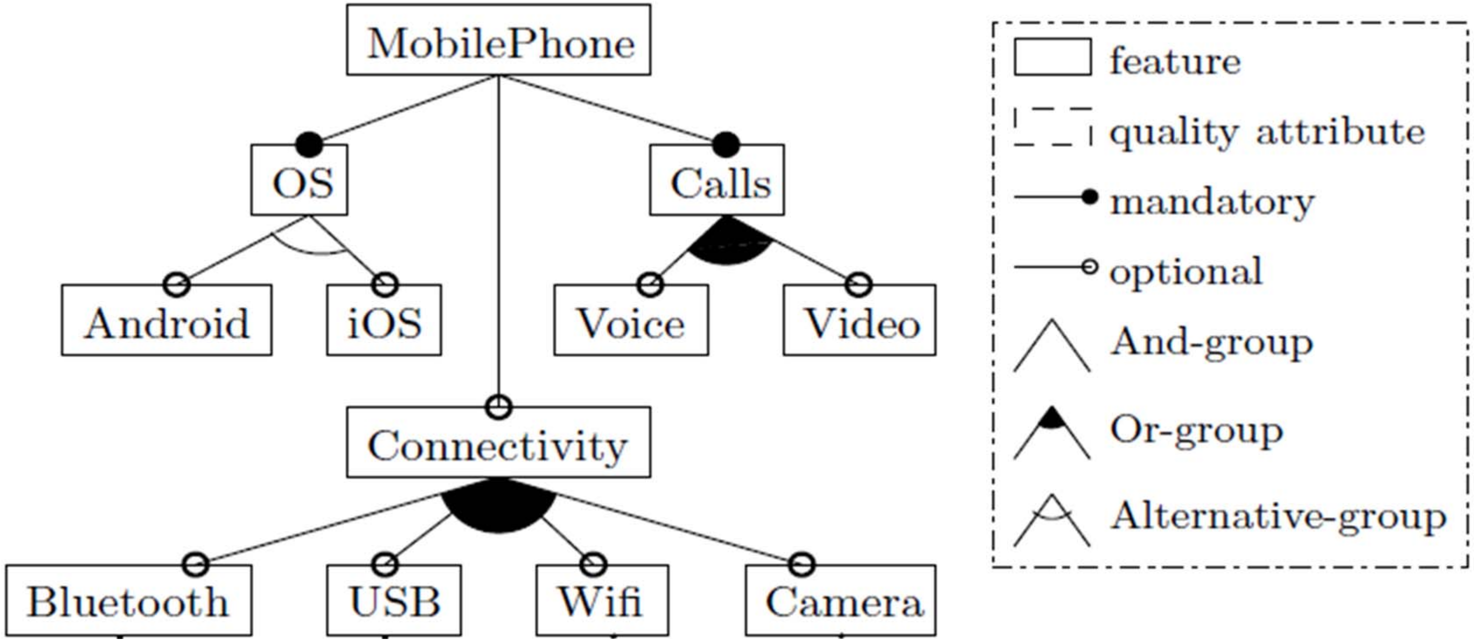
UNIVERSITY OF
WATERLOO

Multi-Objective Combinatorial Optimization (MOCO) Problems

Multi-Objective Combinatorial Optimization (MOCO) Problems

- In Software Engineering
  - Architecture design
  - Test data generation
  - Project planning
- In other domains
  - Hybrid vehicle powertrain design
  - Electric vehicle battery design
  - Civil infrastructure repair planning

A Running Example

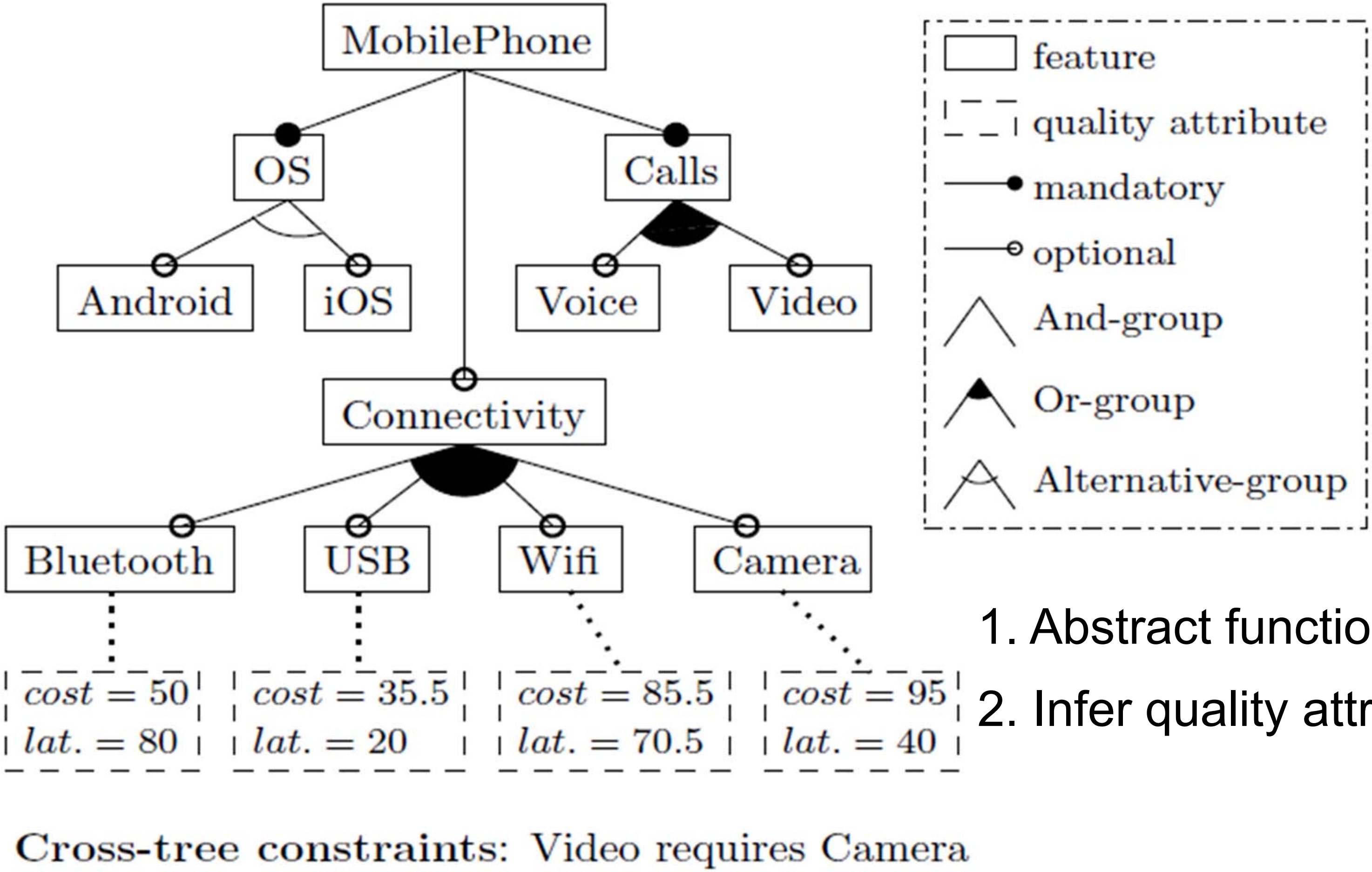


1. Abstract functions as features

Cross-tree constraints: Video requires Camera

[Kang et al., Feature-Oriented Domain Analysis (FODA) Feasibility Study. Technical report, CMU SEI, SEI-90-TR-21, 1990]

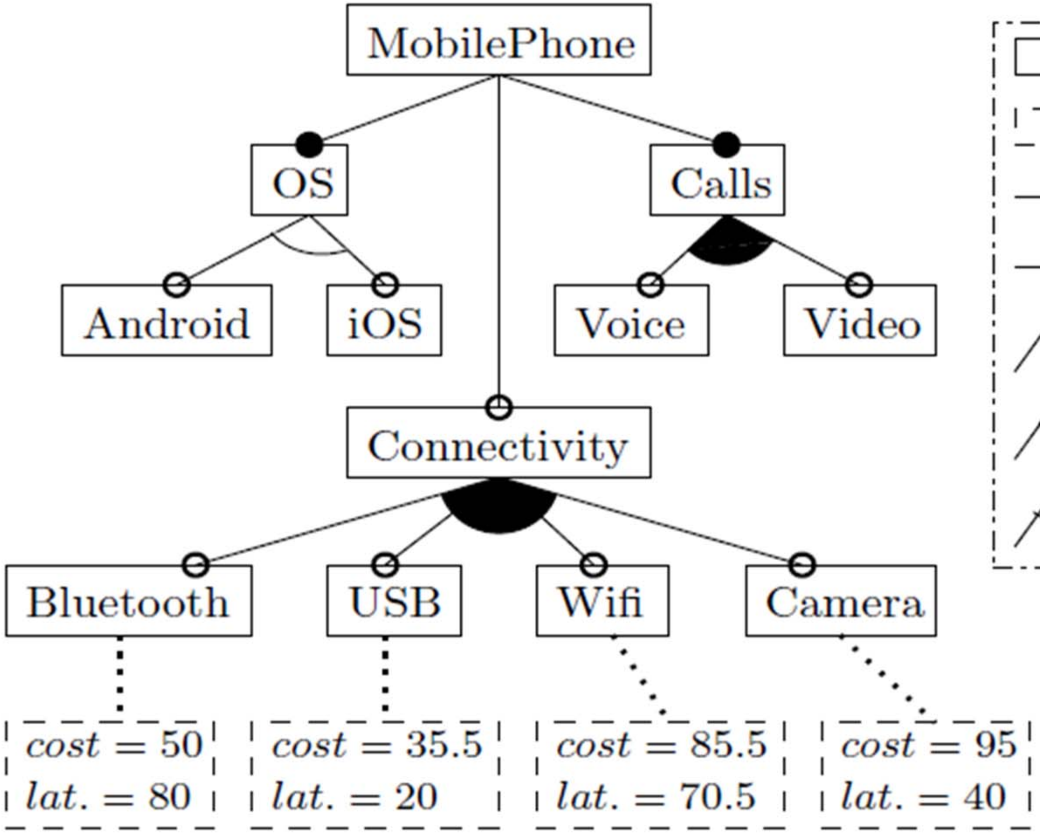
A Running Example

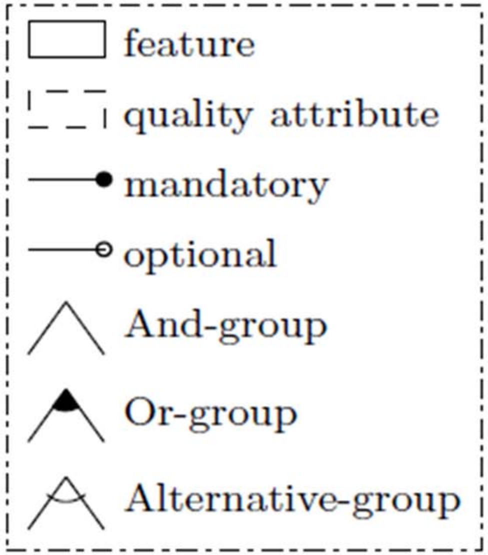


1. Abstract functions as features
2. Infer quality attributes

[Guo et al., Variability-Aware Performance Prediction: A Statistical Learning Approach, ASE 2013]

A Running Example



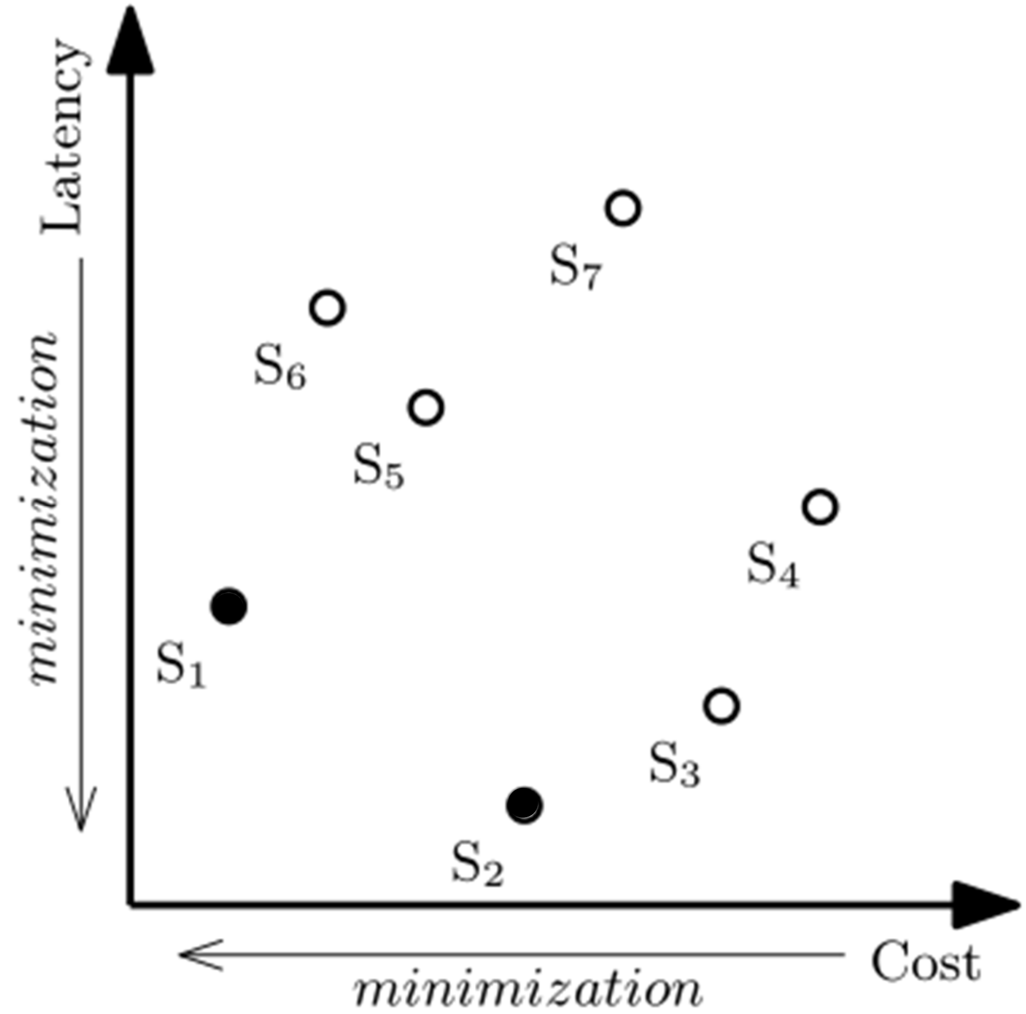


Cross-tree constraints: Video requires Camera

Objectives: minimizing cost, minimizing latency

1. Abstract functions as features
2. Infer quality attributes
3. Find the Pareto front

Search Space and Pareto Front



Challenges and Trade-offs

- Most MOCO problems are NP-hard.

- Approximate methods

  + Mostly efficient

  - No guarantee for accuracy

  - Parameter sensitivity

- Exact methods

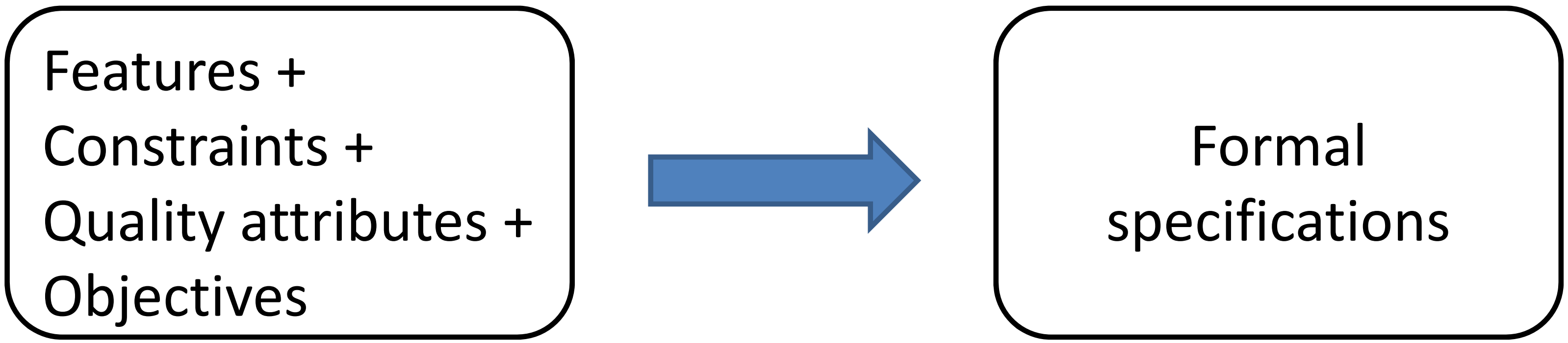
  + Never miss any optimal opportunity

  - Mostly time-consuming

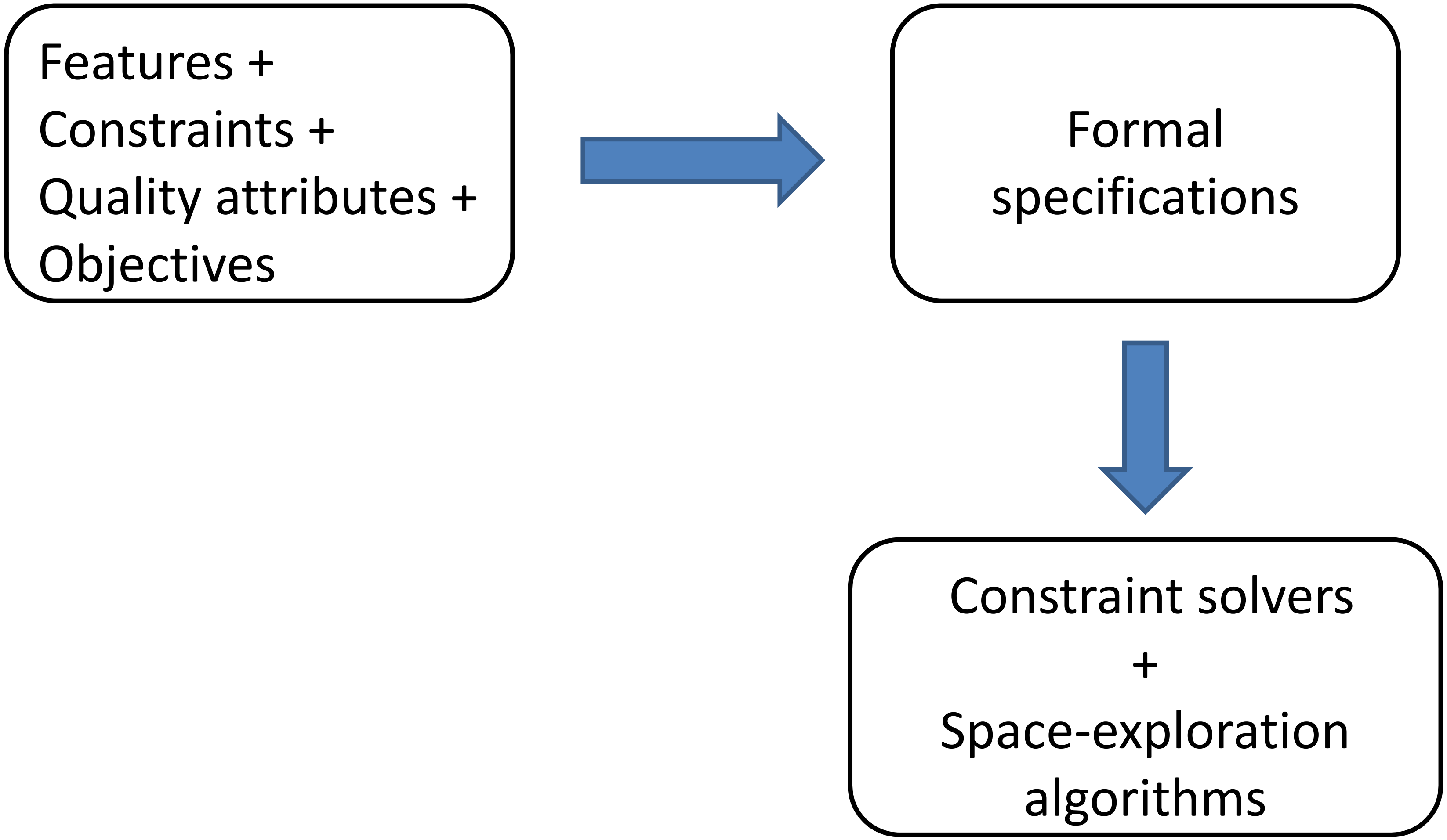
Workflow of Exact Methods using Solvers

Features +
Constraints +
Quality attributes +
Objectives

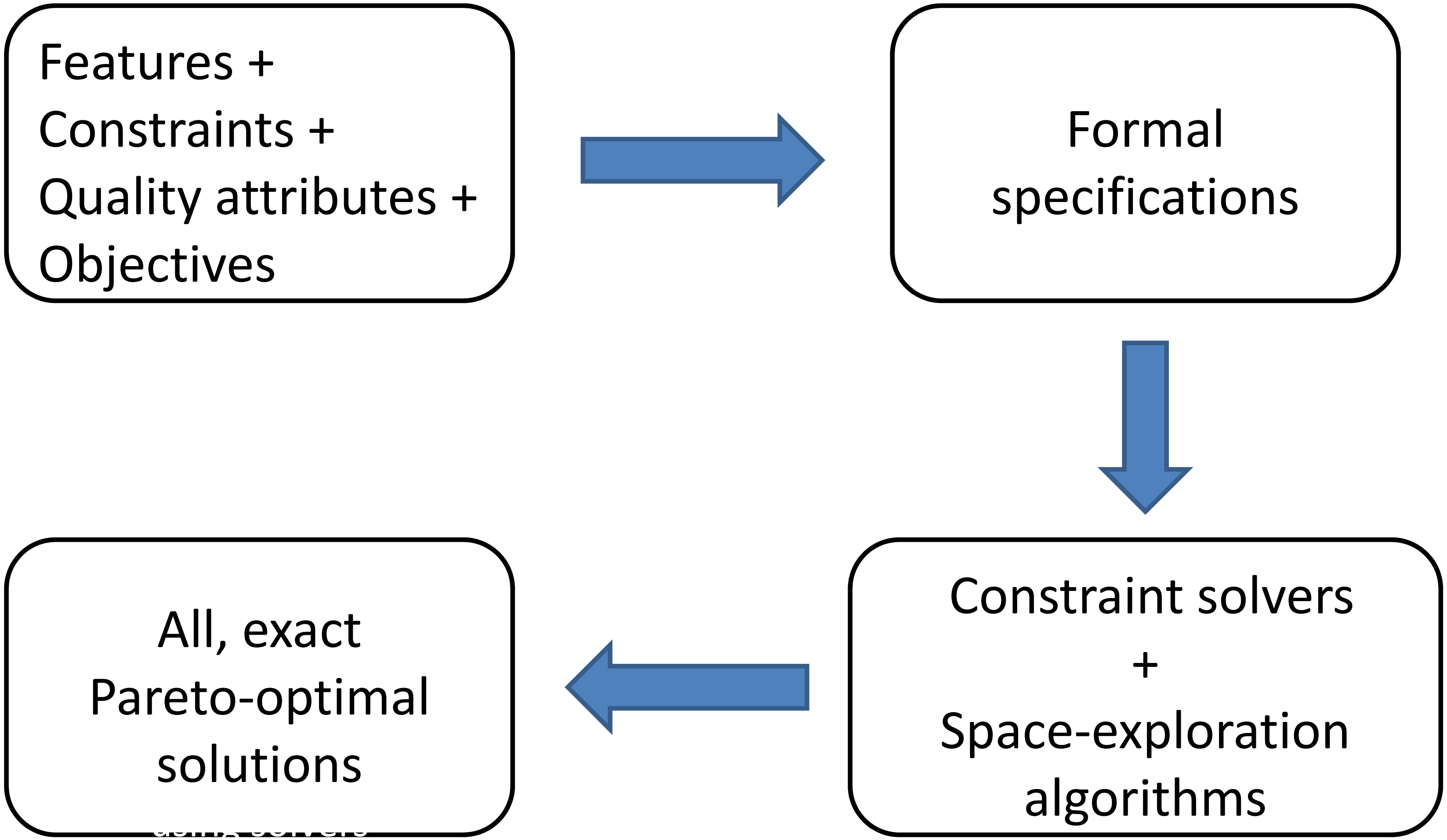
Workflow of Exact Methods using Solvers



Workflow of Exact Methods using Solvers

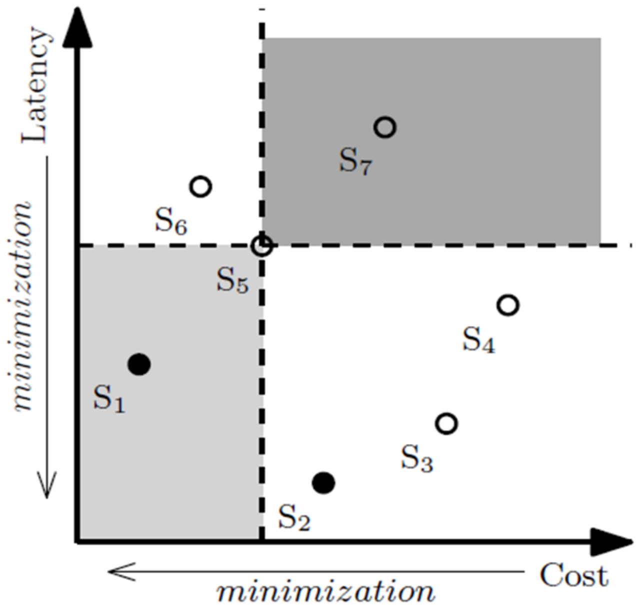


Workflow of Exact Methods using Solvers



Sequential Space Exploration

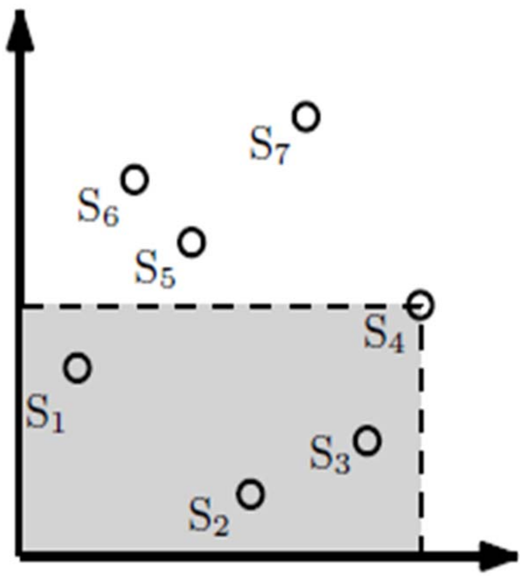
- Guided Improvement Algorithm (GIA)



[Rayside et al., A Guided Improvement Algorithm for Exact, General Purpose, Many-Objective Combinatorial Optimization. Technical report, MIT-CSAIL-TR-2009-033, 2009]

Sequential Space Exploration

- Guided Improvement Algorithm (GIA)

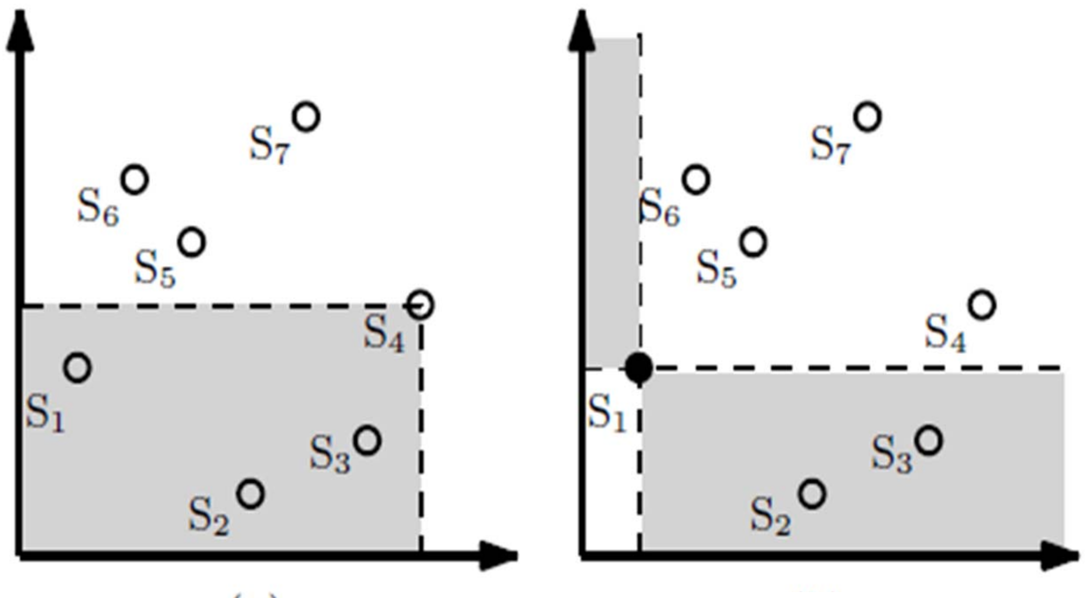


(a)

[Rayside et al., A Guided Improvement Algorithm for Exact, General Purpose, Many-Objective Combinatorial Optimization. Technical report, MIT-CSAIL-TR-2009-033, 2009]

Sequential Space Exploration

- Guided Improvement Algorithm (GIA)



(a)

[Rayside et al., A Guided Improvement Algorithm for Exact, General Purpose, Many-Objective Combinatorial Optimization. Technical report, MIT-CSAIL-TR-2009-033, 2009]

Our Research Question

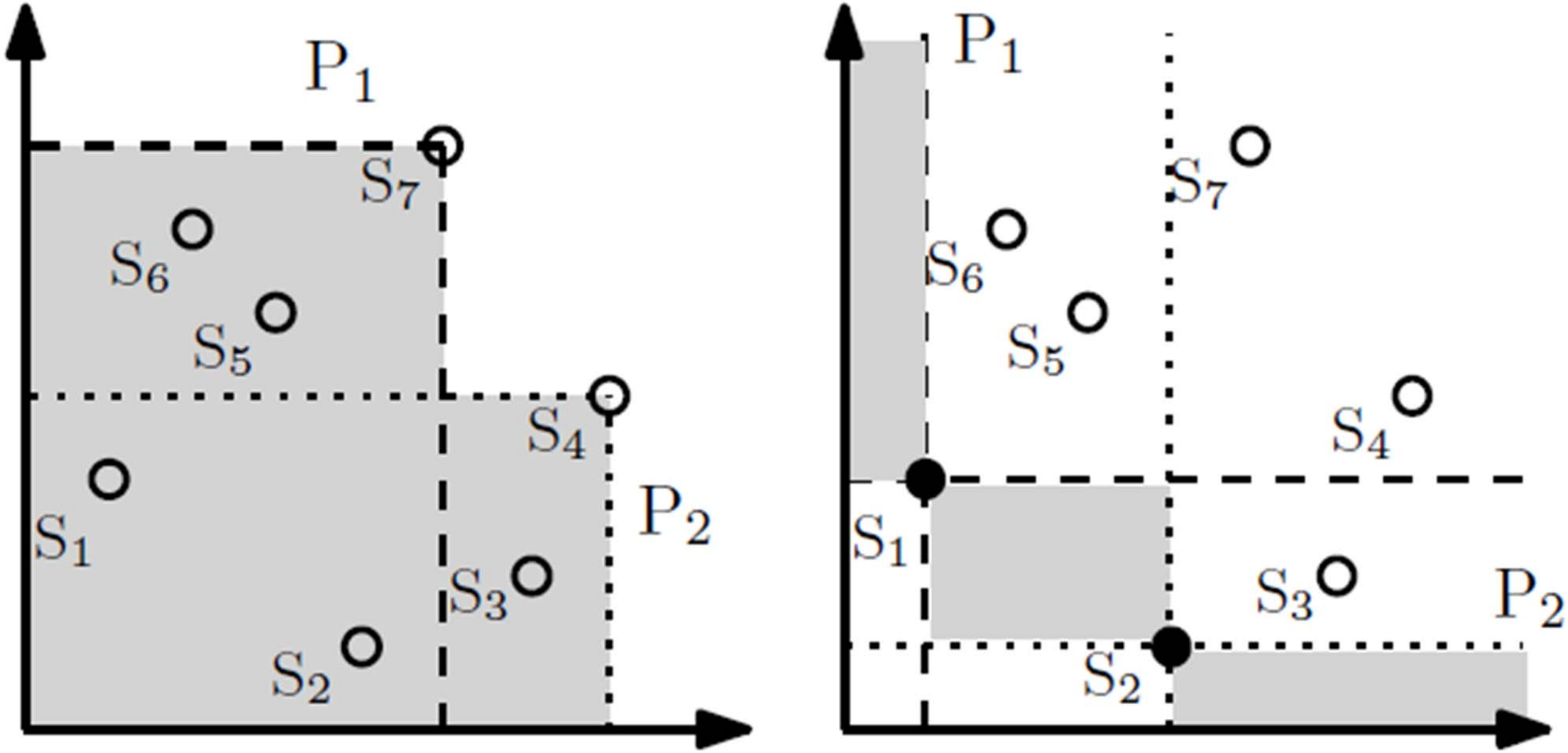
Can parallelization improve the efficiency of exact solving MOCO problems?

To what extent can it improve?

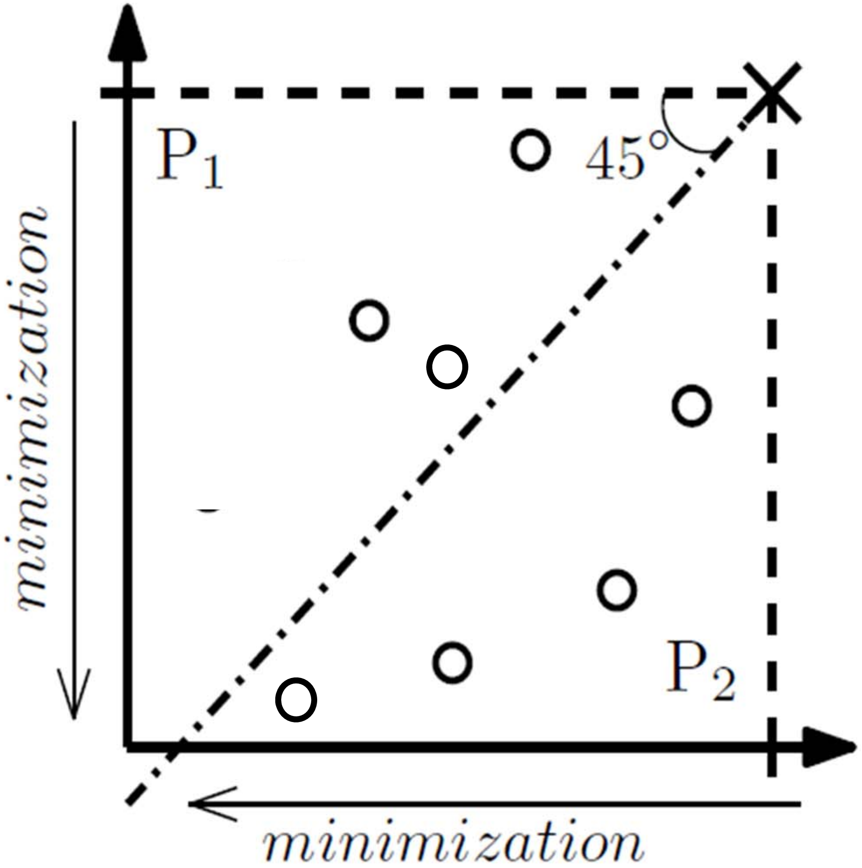
Parallel Space Exploration

- Partition GIA (ParGIA)
  - Collaborative communication
- Objective Split GIA (OS-GIA)
  - Geometric decomposition
- OS-ParGIA
  - A hybrid of OS-GIA and ParGIA
- Feature Split GIA (FS-GIA)
  - Problem division
- FS-ParGIA
  - A hybrid of FS-GIA and ParGIA

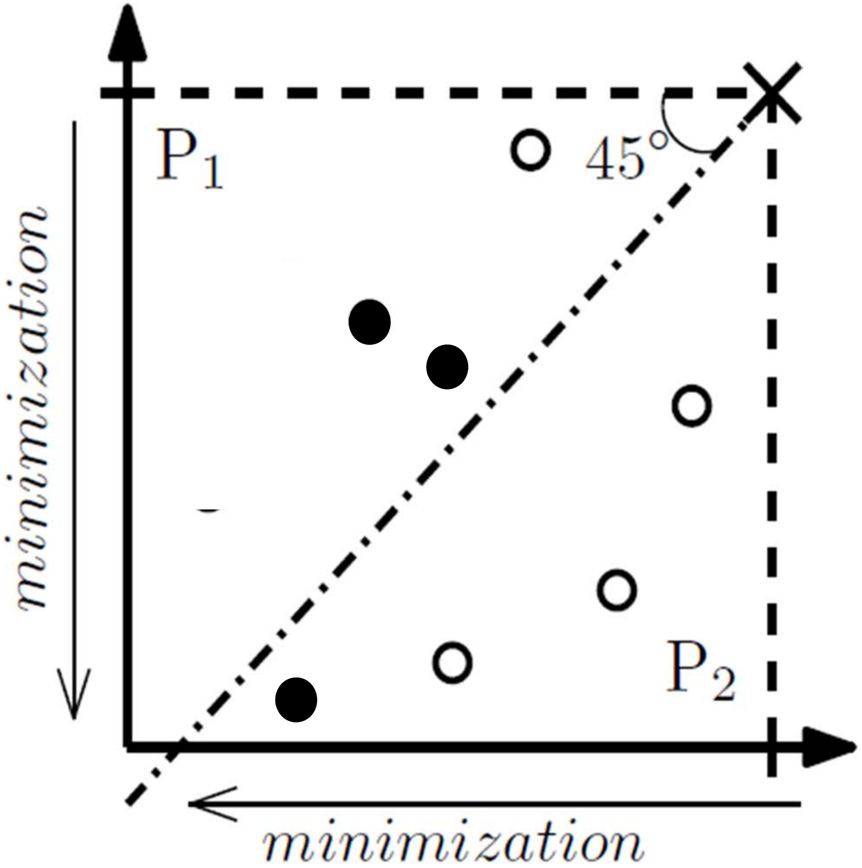
Partition GIA (ParGIA): collaborative communication



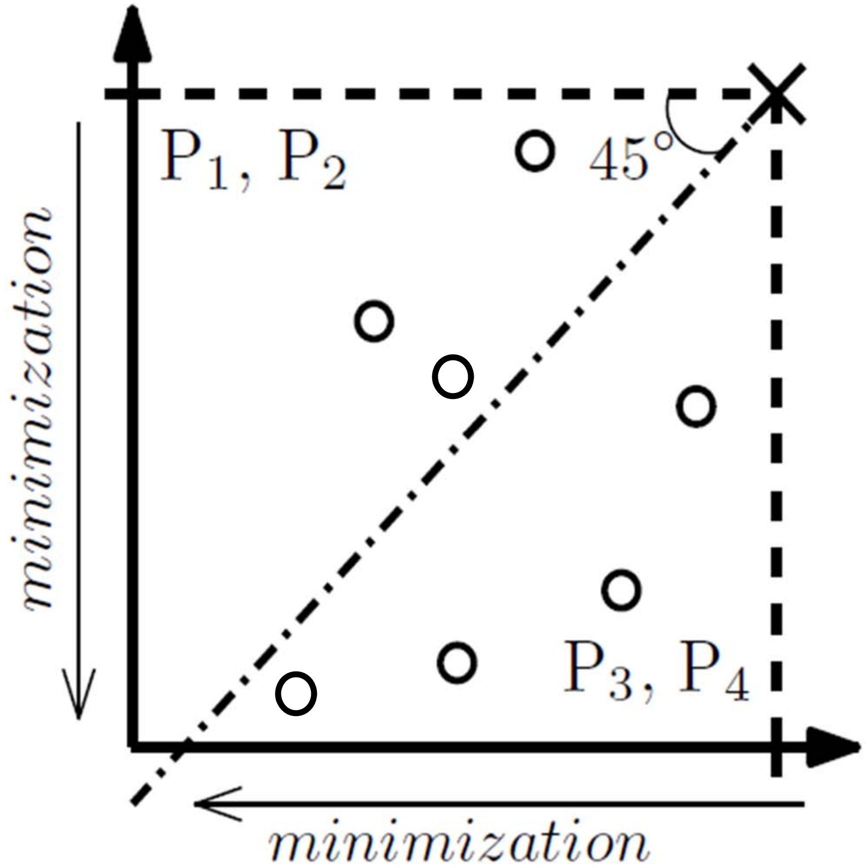
Objective Split GIA (OS-GIA): geometric decomposition



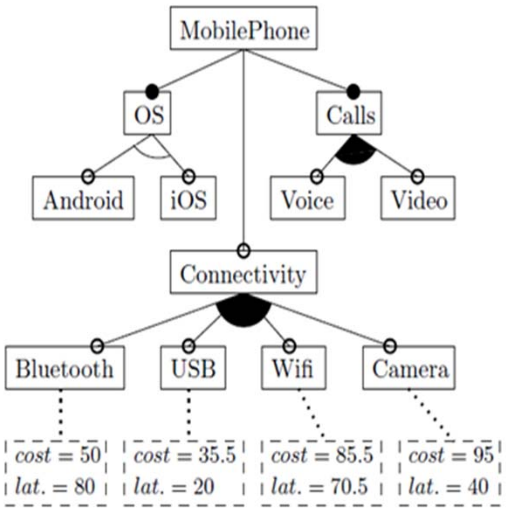
Objective Split GIA (OS-GIA): geometric decomposition



OS-ParGIA: geometric decomposition & collaborative communication



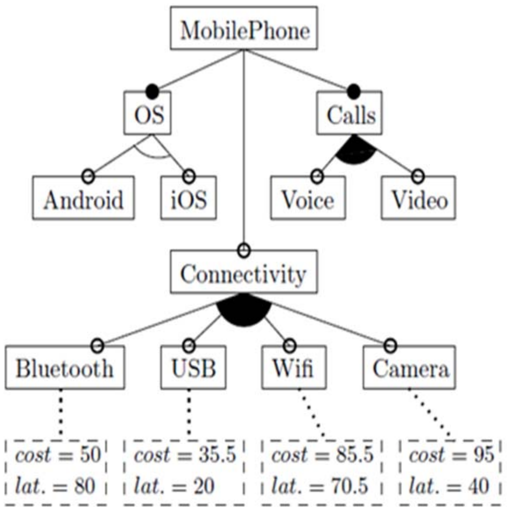
Feature Split GIA (FS-GIA): problem division



Cross-tree constraints: Video requires Camera

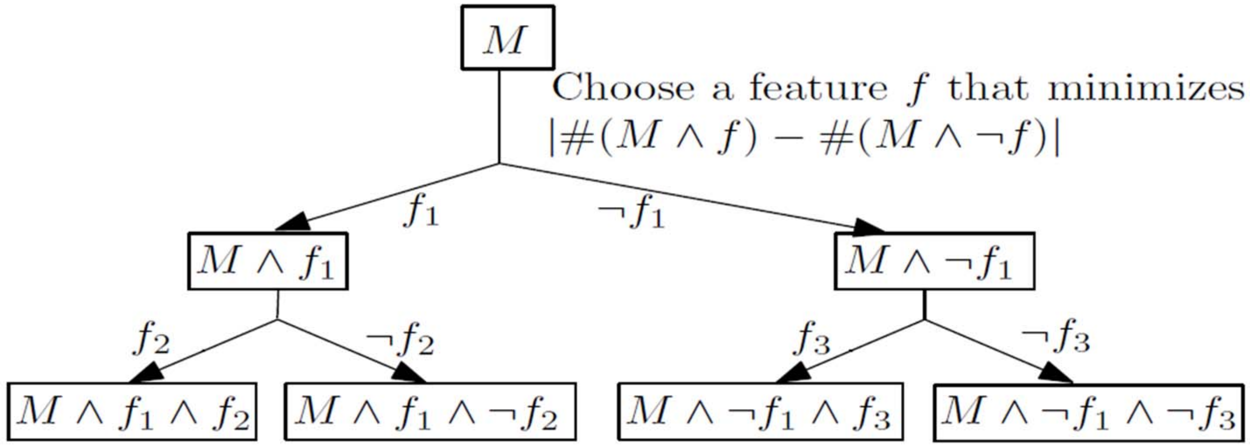
Objectives: minimizing cost, minimizing latency

Feature Split GIA (FS-GIA): problem division



Cross-tree constraints: Video requires Camera

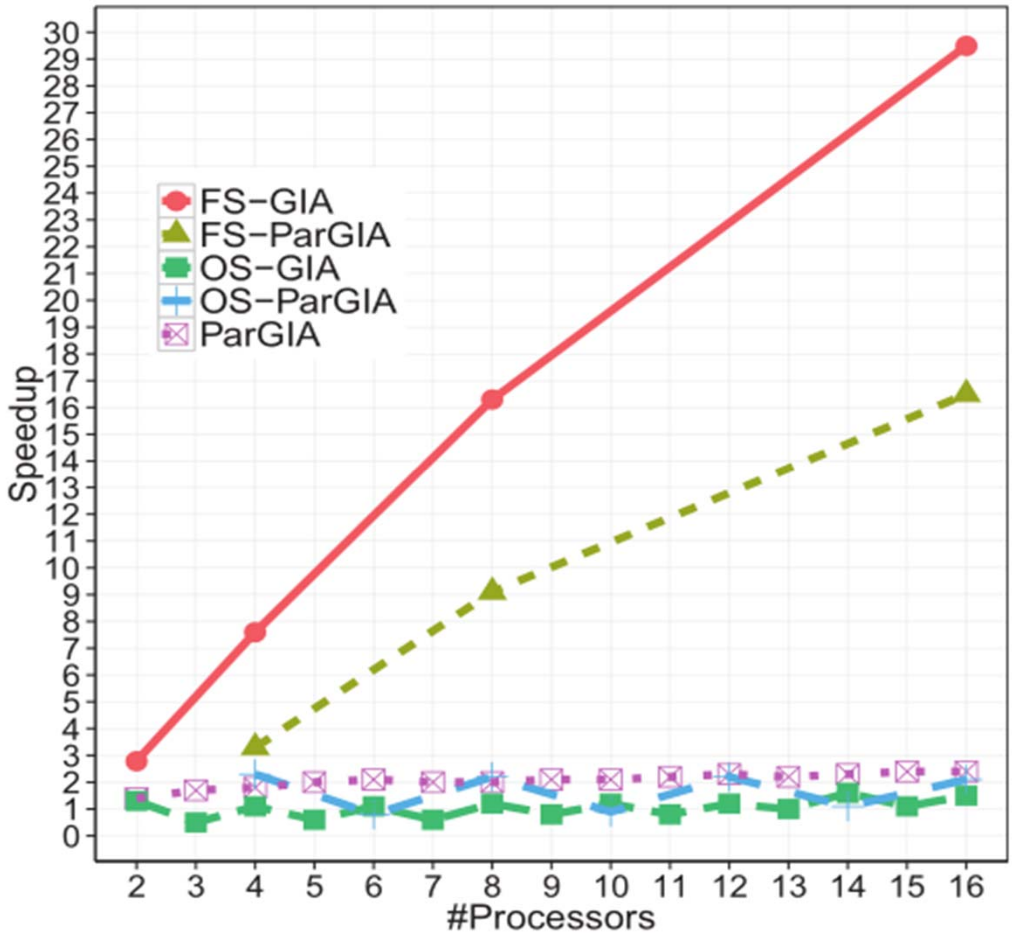
Objectives: minimizing cost, minimizing latency



- Recursive division
- Load balance
- #SAT solver

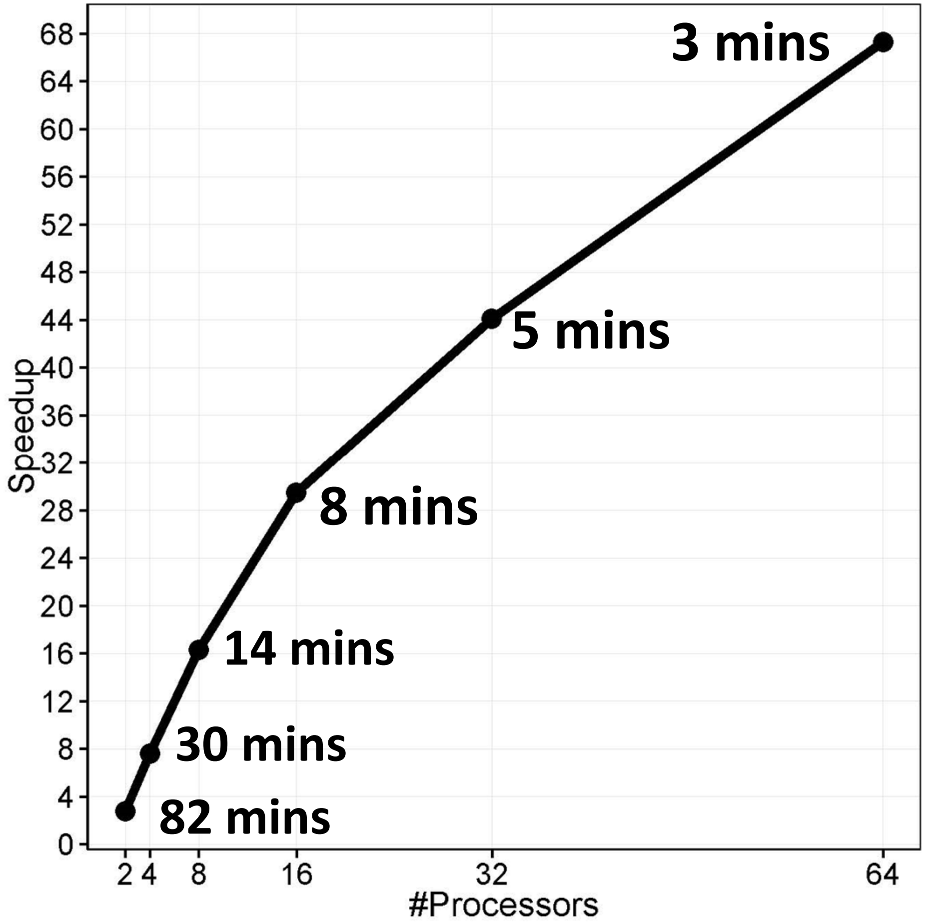
Evaluation

FS-GIA is identified as the fastest and the most scalable algorithm.



Evaluation

FS-GIA gains **super-linear** speedups that **scale** well up to **64 cores**.



A case study

- 44 features
- 2,000,000 variants
- 4 objectives

Time consumption

- 229 minutes using 1 core

-> 3 minutes using 64 cores!

Threats to Validity

- Generality to other MOCO problems, especially in industry

	#Features	#Solutions	#Objectives
SAS	35	5 184	7
Web Portal	44	2 120 800	4
E-Shop	290	5.02E+49	4

[Esfahani et al., GuideArch: Guiding the Exploration of Architectural Solution Space under Uncertainty. ICSE 2013.]

[Sayyad et al., On the Value of User Preferences in Search-Based Software Engineering: A Case Study in Software Product Lines. ICSE 2013.]

Related Work

- According to Talbi et al.'s recent survey, "Parallelization of exact optimization methods" … "is rarely tackled in the multiobjective context."
- K-PPM
  - Geometric decomposition into cubes
  - Not scalable

[Dhaenens et al., K-PPM: A New Exact Method to Solve Multi-Objective Combinatorial Optimization Problems. European Journal of Operational Research, 2010.]

Conclusion

- Five novel parallel MOCO algorithms
  - search for exact optimal solutions using off-the-shelf SAT/SMT/CSP solvers
  - parallelize the search via collaborative communication, divide-and-conquer, or both.
- FS-GIA outperforms all other proposed algorithms
  - Super-linear speedup that scales well up to 64 cores
- A new direction in scaling exact MOCO methods

Future Work

- Industry applications
  - Automotive wire harness optimization
- Hybrid optimization
  - Combine exact and approximate methods
- Theoretical guarantee
  - Performance bounds of exact MOCO algorithms

Thank you!

http://gsd.uwaterloo.ca/epoal