Carbon-Aware Scheduling on Multiple Edge Servers

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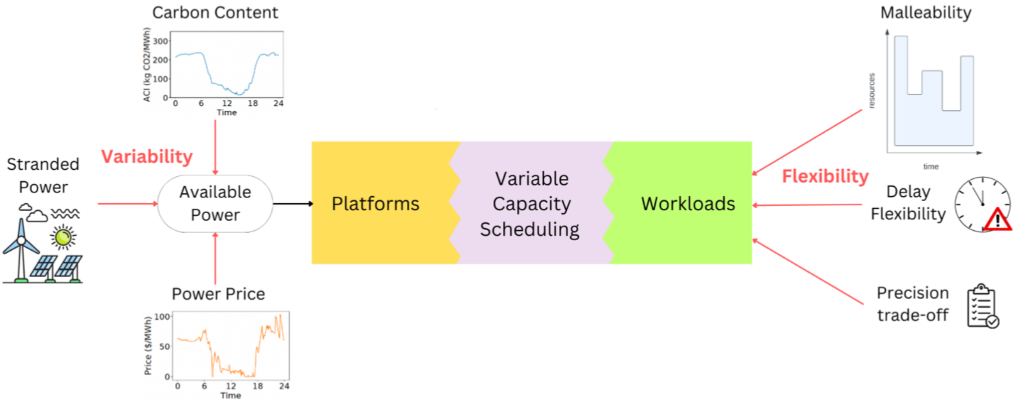
Where were we two years ago?

... Playing with variable capacity scheduling ☺



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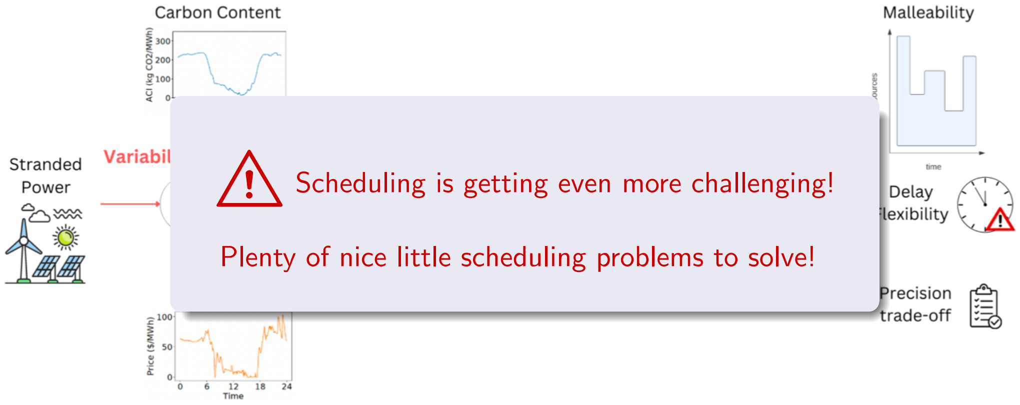
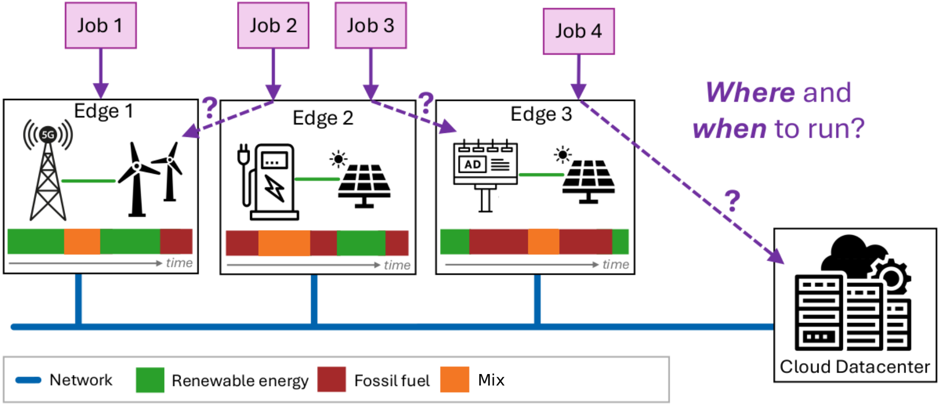


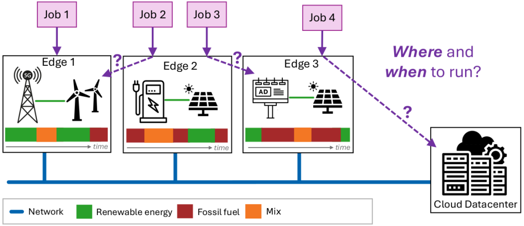
Scheduling is getting even more challenging!

Plenty of nice little scheduling problems to solve!

A nice little scheduling problem

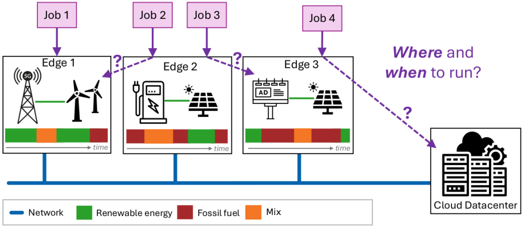


Platform



- Edge servers powered by renewable energy sources, with different levels of carbon intensity depending on time
- Migration possible between edge servers
- Powerful *cloud* server to avoid missed deadlines

Jobs



- Jobs arrive **online** with **deadlines** to respect
- Can be preempted and migrated during execution (cost for recovery/checkpoint)
- Possible execution on a big cloud server powered only by the grid
- Aim: complete all jobs before their deadlines while **minimizing the total carbon cost**

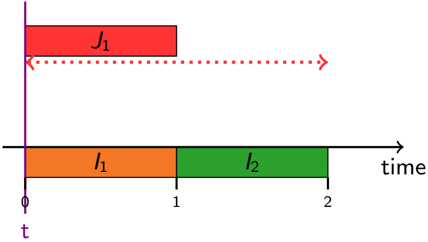
Contents

Online scheduling

Assumptions:

- **Online** (release dates and deadlines are unknown)
- One edge with total knowledge of energy intervals

Exemple with $k_1 > k_2$, respectively the carbon intensity of I_1 and I_2:



Two cases:

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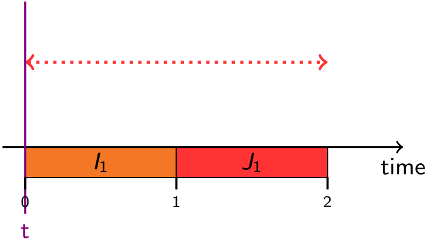

Two cases:

- k_2

Online scheduling

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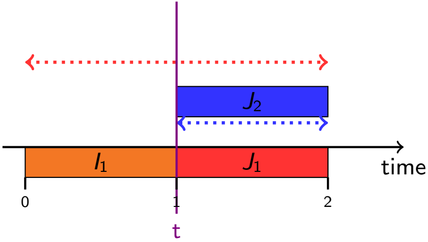

Two cases:

- $k_2 + K$

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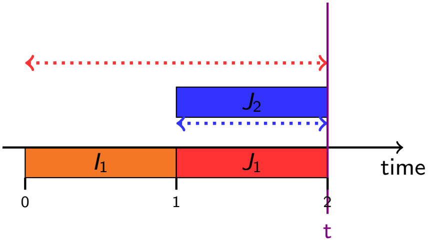

Two cases:

- $k_2 + K > k_1 + k_2$

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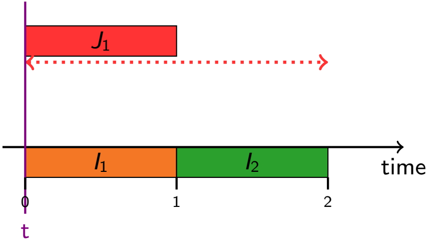

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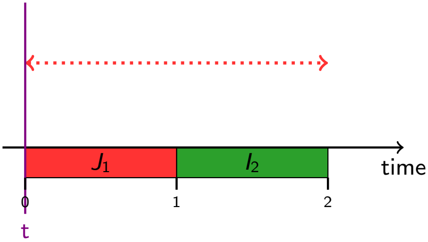

Two cases:

- $k_2 + K > k_1 + k_2$
- k_1

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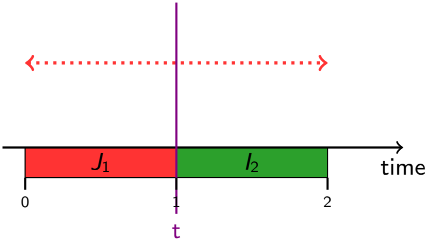

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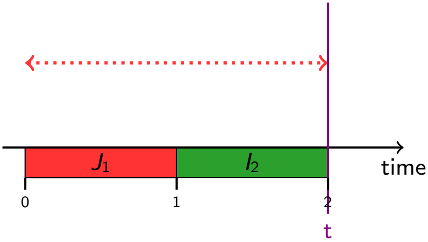


Two cases:

- $k_2 + K > k_1 + k_2$
- $k_1 > k_2$

Offline scheduling, one edge, $R + C > 0$

Assumptions:

- **Offline** (release dates and deadlines are known)
- One edge with total knowledge of energy intervals
- One job with $R + C > 0$

Complexity of the associated decision problem (carbon cost below K_{max}):

- **NP-hard** problem: proof by subset sum

Offline scheduling, one edge, $R + C = 0$

Assumptions:

- **Offline** (release dates and deadlines are known)
- One edge with total knowledge of energy intervals
- Multiple jobs with $R + C = 0$, which admit a valid schedule on the edge and available at time 0

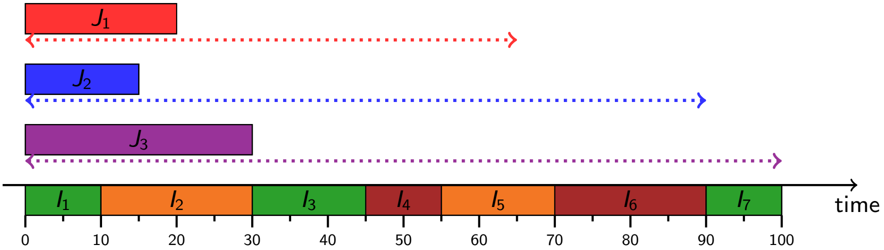
Optimal algorithm, OfflineGreenestPreemption, with **polynomial complexity** in: $O(u + mp + m\log(m))$

where u is the number of intervals in the edge server, m is the number of jobs and p the number of different carbon intensities

OfflineGreenestPreemption

One round per carbon type:

- Selection of the green intervals



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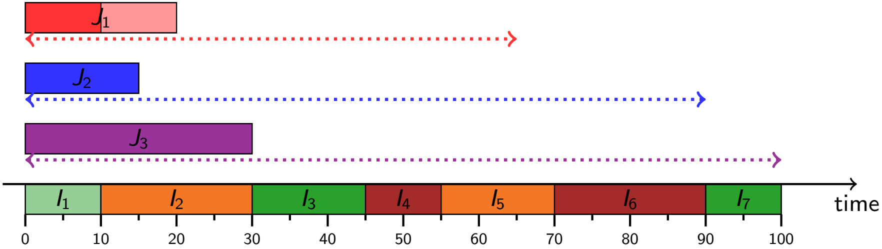

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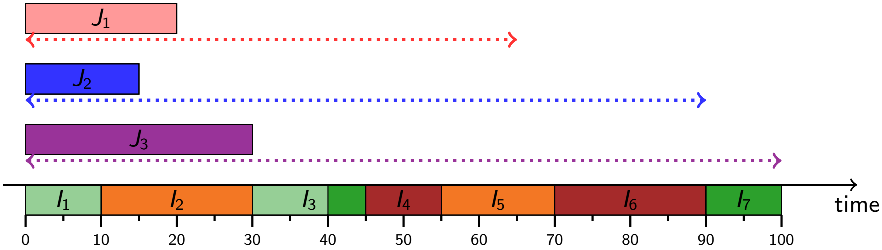

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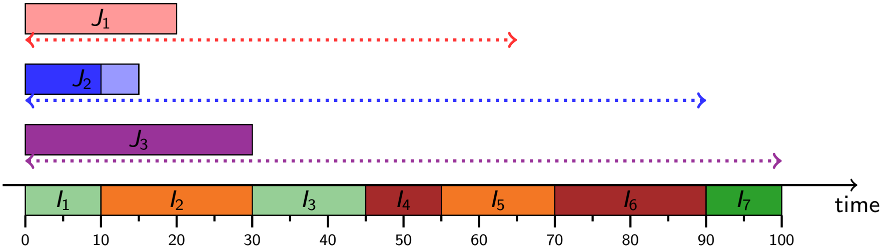

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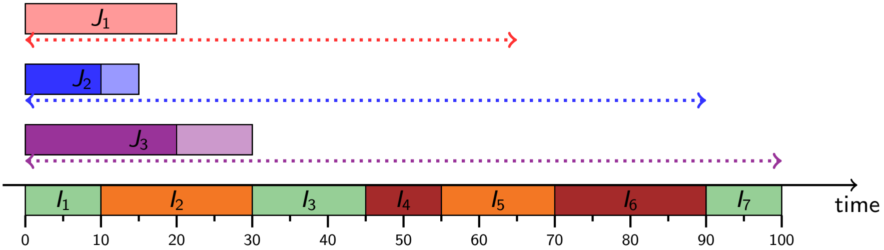

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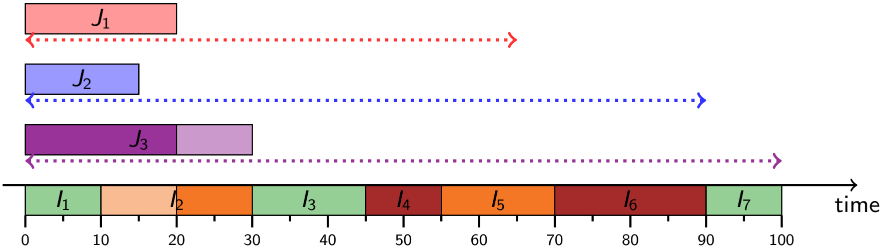

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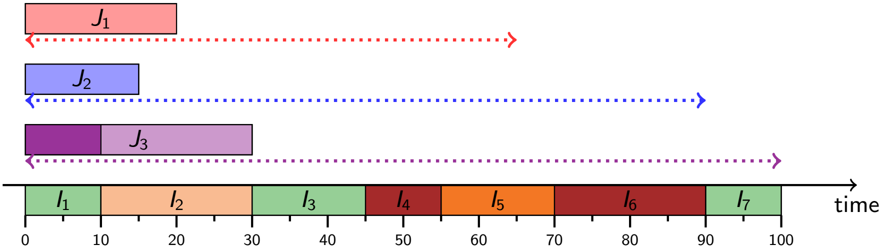

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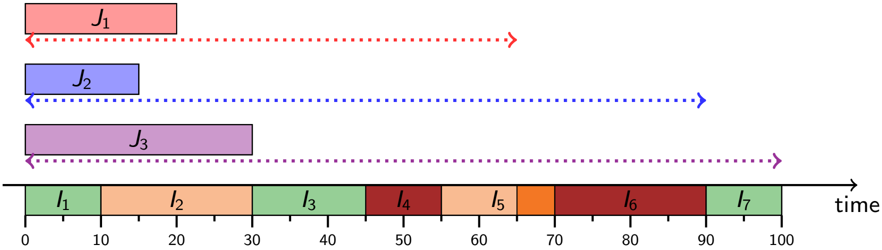

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One round per carbon type:

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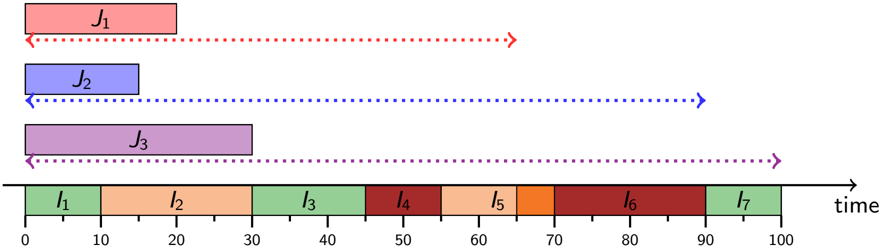

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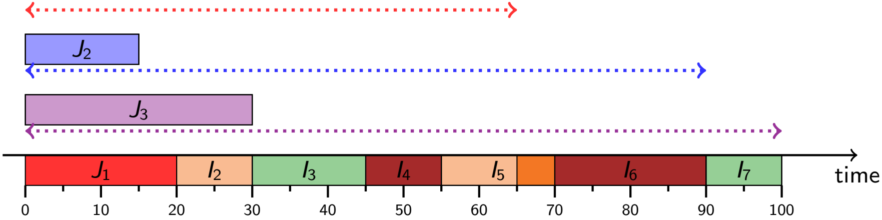

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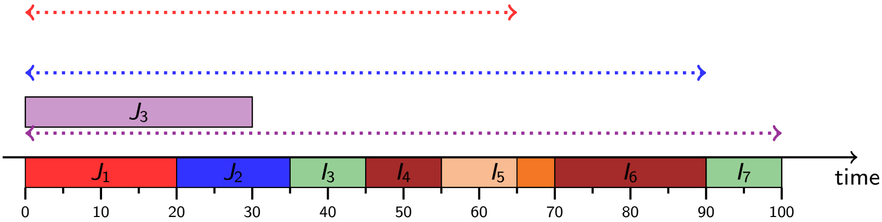

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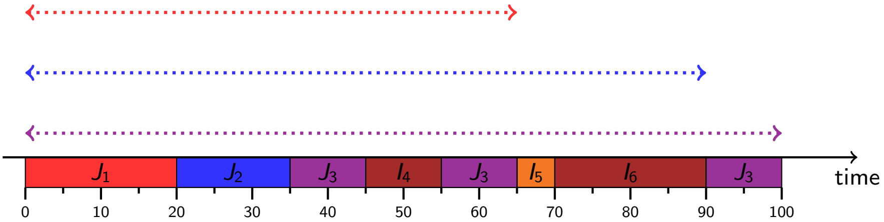

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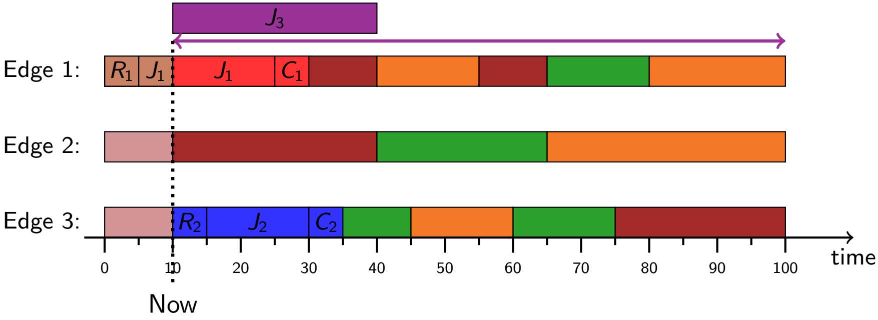
Baseline heuristics

Take decisions only when a new job is released, and only for this job:

- LOCAL: Schedules each job at the earliest on its edge
- ECT: Schedules each job at the earliest on any edge



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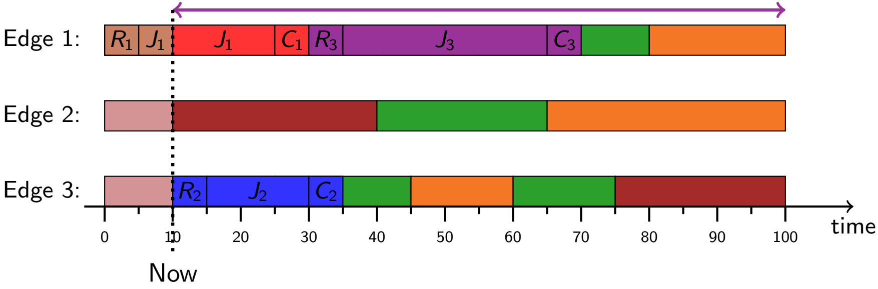

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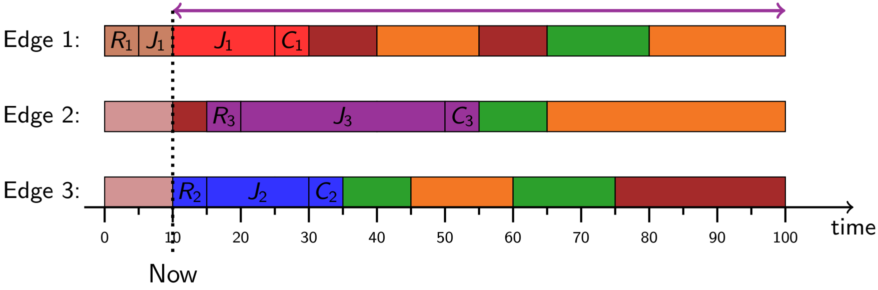
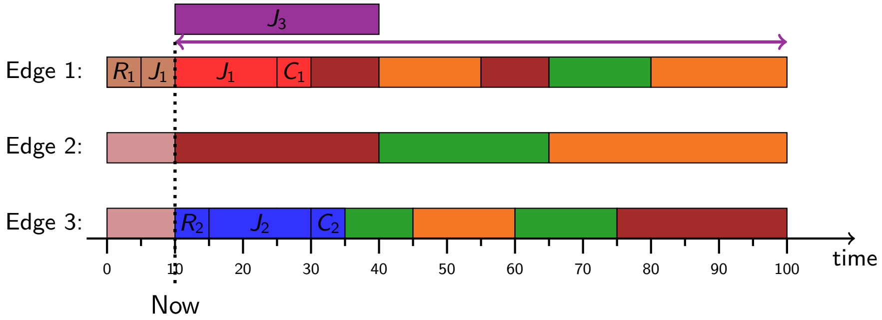


Green-aware heuristics

Take decisions only when a new job is released, and only for this job:

- LocalGreen: Schedules each job at the earliest on its edge but only using greenest energy interval
- EGT: Schedules each job at the earliest on any edge but only using greenest energy interval



How can we define green energy? Should depend on the system load!

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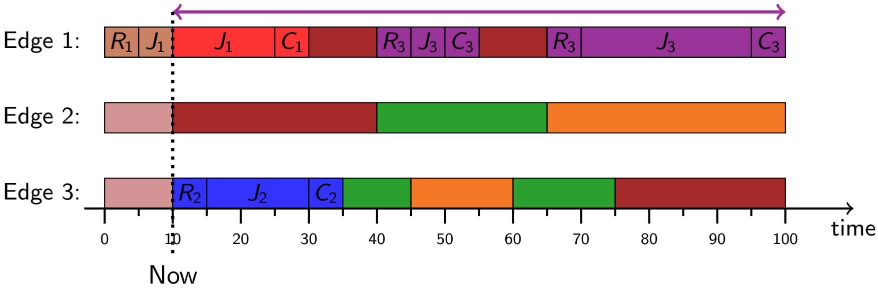
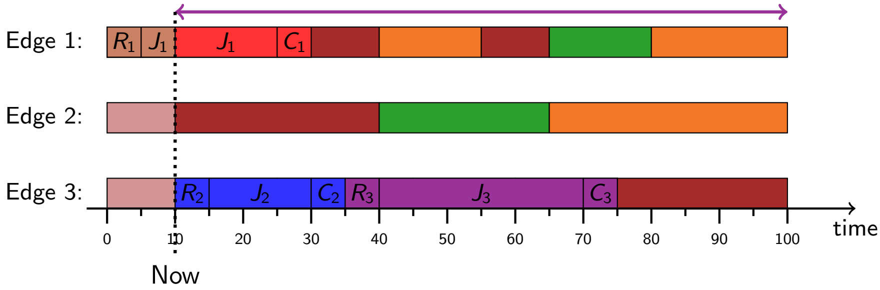


How can we define green energy? Should depend on the system load!

Green-aware heuristics

Take decisions only when a new job is released, and only for this job:

- LOCALGREEN: Schedules each job at the earliest on its edge but only using greenest energy interval
- EGT: **Schedules each job at the earliest on any edge but only using greenest energy intervals**



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Re-evaluation heuristics

General idea:

- Each time a new job is submitted, cancels the current schedule and computes a new one, job by job (in a specific order, such as EDF)

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Two strategies:

- ReallocMigration: Try to shedule the job on each edge server (using OfflineGreenestPreemption with the already placed jobs) and choose the server with the lowest variation in carbon cost
- ReallocInPlace: Same than ReallocMigration, but when a job starts its execution on an edge, it will do all of its execution on this edge

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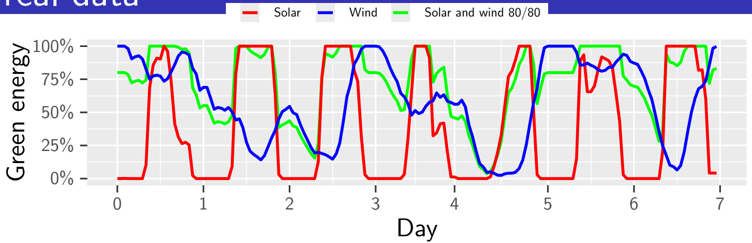
Predictions:

- Re-evaluation of the current schedule when there is an update to the predictions of edges' energy intervals

Contents

Traces from real data



- Simulation length: $T = 30$ days
- One year of ERCOT data (2024)
- 10 edge servers, with various on-site generation models and a **3-day forecast**:
  - Solar only, Wind only, Solar and wind, Mix: 3 solar, 3 wind, 4 solar and wind
- CLOUD carbon cost K ; carbon cost of transfer k^{trans}: depends on the month
- b^r: 2.15 Gbit/s ; 3.5 Gbit/s for Cloud
- b^w: 2.15 Gbit/s ; 7 Gbit/s for Cloud
- b^{trans}: 10 Gbit/s

Synthetics simulation parameters

- Job duration: between 1 hour and 24 hours, with various mean, depends on job skew
- Job skew: $[1.1, 1.15, 1.18, 1.2, 1.4, 1.6]$
- Job data volume:
  - proportional to the data volume of the job, in $[17, 409]$ Gbit
  - fixed at $[1, 10, 50, 100, 200, 400]$ Gbit
  - uniformly distributed in $[[1, 50], [1, 100], [1, 200], [1, 400], [50, 200], [200, 400]]$ Gbit
- Load $\in \{0.1, 0.2, \ldots, 1\}$
- Looseness $= \frac{d_j - s_j}{\ell_j}$: $\{1.15, 1.5, 2, 4, 6, 10, 20\} \pm 10\%$
- Job arrival models:
  - Uniform: the workload is distributed uniformly across all 10 edges
  - Clustered: 30% of the edges receive 90% of the workload
  - Event/Mall: one edge receives 80% of the workload

Run experiments by selecting default or outsider value for each parameter (at most one outsider value by experiment)

First results

Metrics:

- Ratio full knowledge: comparison of the total carbon cost with partial / total knowledge of the energy interval costs

Heuristics	*GeoMean ratio full knowledge*		
AllCloud	1.00		
Local	1.00		
LocalGreen	1.01		
ECT	1.00		
EGT	1.00		
ReallocMigration	1.09		
ReallocInPlace	1.07		

Table 1: Statistics on default instances. Sorted by ratio ECT values.

- Prediction does not degrade performance too much

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- Ratio ECT: comparison of the total carbon cost of a heuristic for an instance with the total carbon cost of the ECT heuristic

Heuristics	*GeoMean ratio full knowledge*	*GeoMean ratio ECT*	
AllCloud	1.00	2.02	
Local	1.00	1.23	
LocalGreen	1.01	1.18	
ECT	1.00	1.00	
EGT	1.00	0.88	
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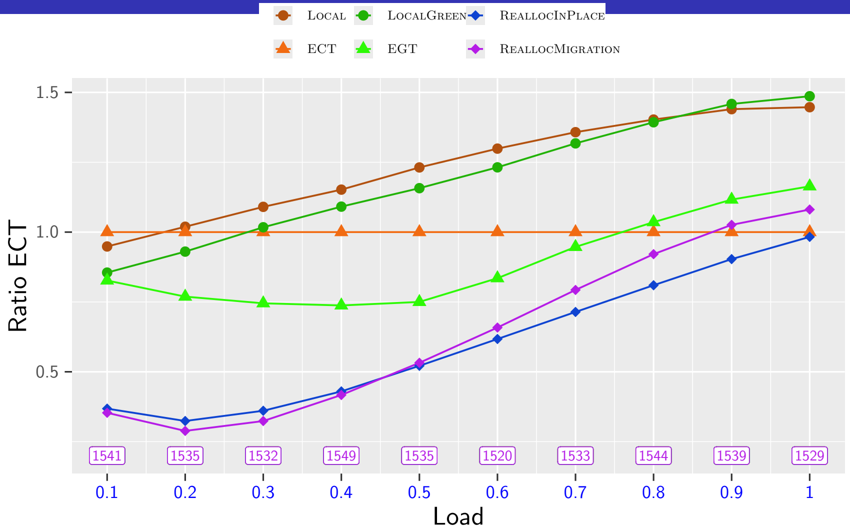
- Ratio ECT: comparison of the total carbon cost of a heuristic for an instance with the total carbon cost of the ECT heuristic
- Stretch: ratio between execution time and duration of jobs on edge servers

Heuristics	*GeoMean ratio full knowledge*	*GeoMean ratio ECT*	*GeoMean stretch*
AllCloud	1.00	2.02	1.00
Local	1.00	1.23	1.47
LocalGreen	1.01	1.18	1.99
ECT	1.00	1.00	1.07
EGT	1.00	0.88	2.21
ReallocMigration	1.09	0.61	2.57
ReallocInPlace	1.07	0.59	2.46

Table 1: Statistics on default instances. Sorted by ratio ECT values.

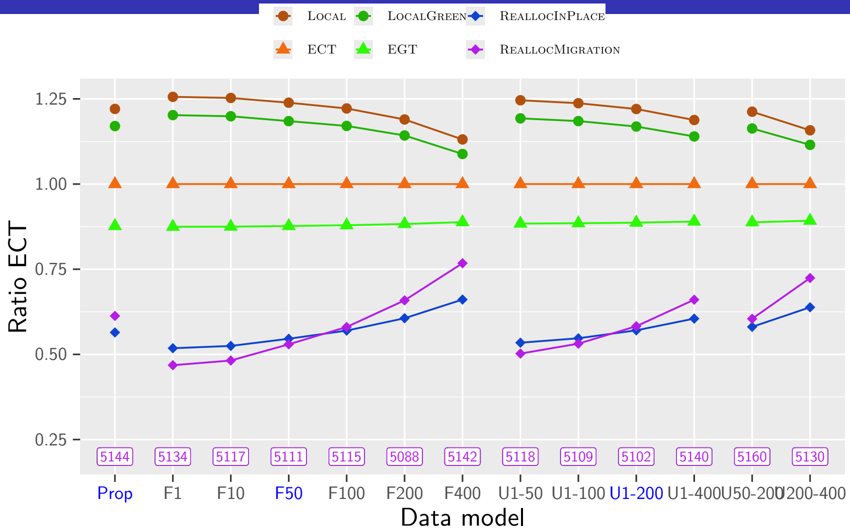
- Prediction does not degrade performance too much
- Good performance for re-evaluation algorithm at the expense of the stretch

Impact of the load on ratio ECT



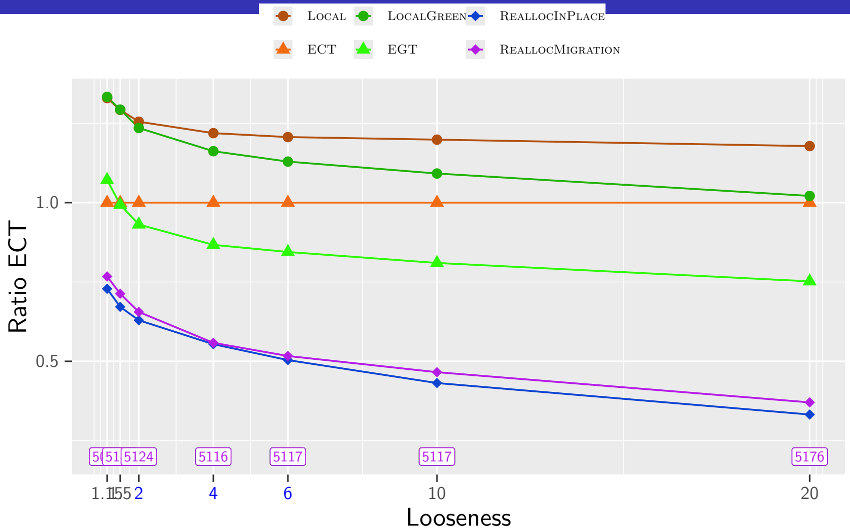
- Re-evaluation algorithms have very good gains at around 1/4 load

Impact of the data volume on ratio ECT



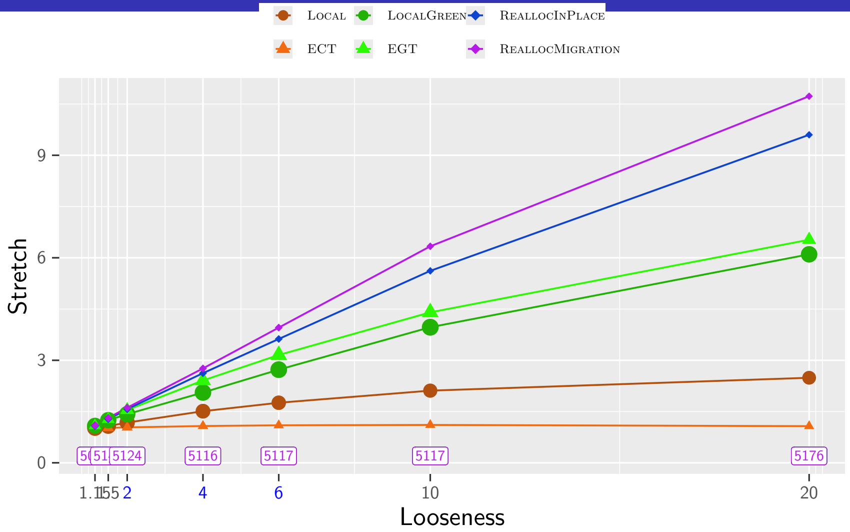
- Local-oriented algorithms are better when data volume is high

Impact of the looseness on ratio ECT



- Higher looseness implies better performance...

Impact of the looseness on stretch



- … but at the cost of the stretch

Conclusion

- Model of a complex edge scheduling problem
- Complexity results for the general problem and its subproblems
- Optimal polynomial algorithm to schedule jobs with free preemption
- 3-day prediction is enough to avoid significantly degrading performance
- Reevaluation heuristics offer robust performance