Flexible Spatio-Temporal Energy-Efficient Runtime Management

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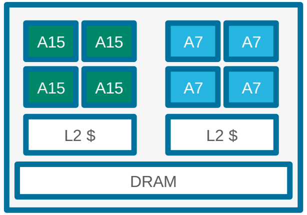
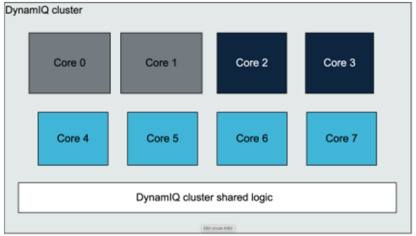
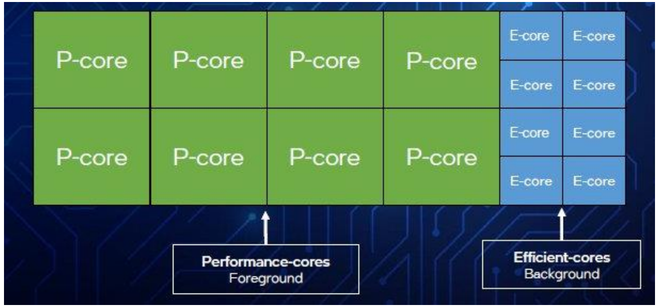
Trend towards heterogeneous multi-cores



ARM big.LITTLE (2013)



Arm DynamIQ (2017)

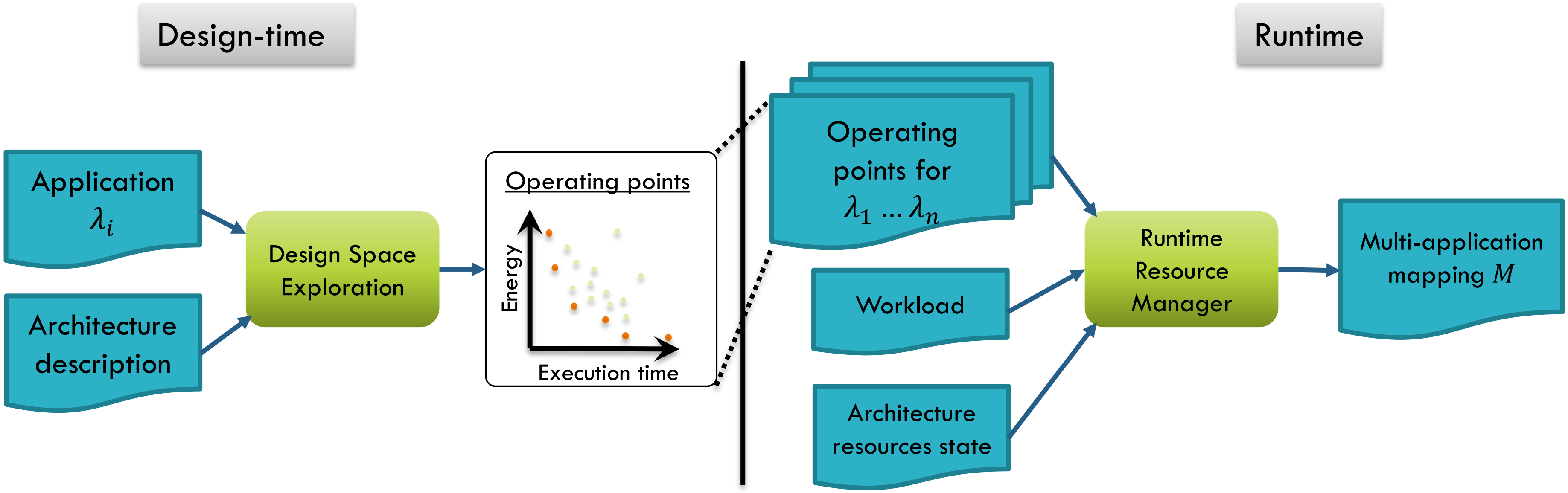


Intel Alder Lake (2022)

- Shared ISA, varying performance-energy characteristics
- Dynamic core selection & migration ➔ Adaptive energy-efficient execution
- **Question:** How should the system allocate the application to resources?

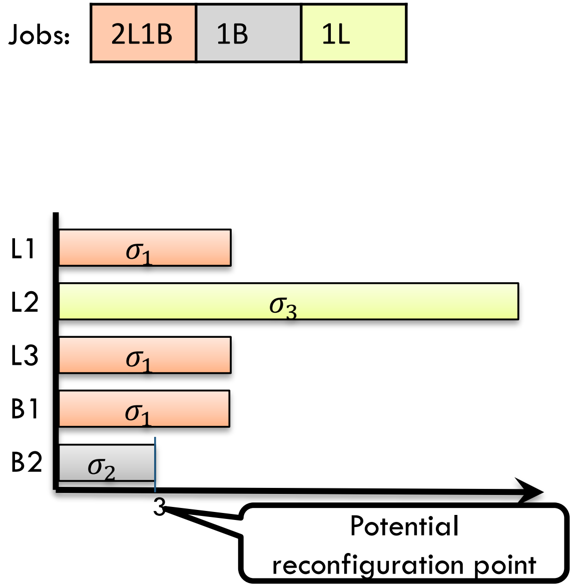
Sources: https://developer.arm.com/documentation/102547/0100/The-DynamIQ-Shared-Unit-120/Cluster-configurations
https://www.hardwarezone.com.sg/tech-news-intel-12th-gen-core-desktop-processors-k-sku-specs-features-price

Hybrid mapping methodology

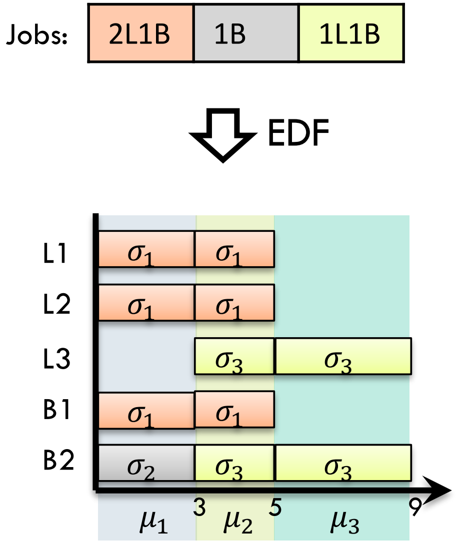


Mapping Decision Models

Spatial Mapping [1, 2]



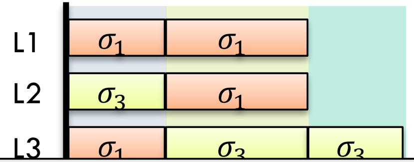
Fixed-Point Spatio-Temporal Mapping [3, 4]



Flexible Spatio-Temporal Mapping [**This work**]

Segments

Dur.	3	4	3
Jobs	2L1B	2L	⊥
	1B	⊥	⊥
	1L	1L1B	1L



Problems:
- ❑ The solution space is too large; hard to find optimal solutions
- ❑ No runtime algorithm

[1] C. Ykman-Couvreur et al., "Fast multi-dimension multi-choice knapsack heuristic for mp-soc run-time man
[2] S. Wildermann, M. Glaß, and J. Teich, "Multi-objective distributed run-time resource management for many-cores," DATE, 2014
[3] M. Niknafs et al, "Runtime resource management with workload prediction." DAC, 2019
[4] R. Khasanov, J. Castrillon, "Energy-efficient Runtime Resource Management for Adaptable Multi-application Mapping", DATE, 2020

Problem formulation

Workload Model

Job	Deadline (δ)	Rem. Ratio (ρ)
σ_1	80	45%
σ_2	60	67%
$\boldsymbol{\sigma_3}$	**70**	**100%**

σ_1, σ_2: Already running

σ_3: New

Operating Points for σ_1

OP	#L	#B	Time	Energy
φ_1	1	0	171	60
φ_2	1	1	95	72
φ_3	2	0	88	75
φ_4	2	2	78	80
φ_5	2	1	47	105
φ_6	1	2	35	120
φ_7	0	1	86	129
φ_8	0	2	46	142

Operating Points for σ_2

OP	#L	#B	Time	Energy
φ_1	1	1	45	60
φ_2	2	0	62	66
φ_3	2	1	35	70
φ_4	1	0	114	73
φ_5	2	2	32	75
φ_6	1	2	93	77
φ_7	0	2	42	110
φ_8	0	1	76	112

Operating Points for σ_3

OP	#L	#B	Time	Energy
φ_1	1	0	92	40
φ_2	2	0	53	45
φ_3	1	1	26	53
φ_4	2	2	23	54
φ_5	2	1	23	58
φ_6	1	2	17	64
φ_7	0	2	18	75
φ_8	0	1	34	81

Problem formulation

Schedule Plan Model (K)

Duration	13	17	29	15
σ_1 $\delta = 80$ $\rho = 0.45$	$\perp$	$\varphi_7^{(1)}$	$\varphi_1^{(1)}$	$\varphi_1^{(1)}$
σ_2 $\delta = 60$ $\rho = 0.67$	$\varphi_1^{(2)}$	$\varphi_1^{(2)}$	$\perp$	$\perp$
σ_3 $\delta = 70$ $\rho = 1.0$	$\varphi_3^{(3)}$	$\varphi_1^{(3)}$	$\varphi_1^{(3)}$	$\perp$

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Problem formulation

Schedule Plan Model (K)

Duration	13 [13]	17 [30]	29 [59]	15 [74]
σ_1 $\delta = 80$ $\rho = 0.45$	$\perp$	$\varphi_7^{(1)}$ $\xi = 25.5$	$\varphi_1^{(1)}$ $\xi \approx 10.2$	$\varphi_1^{(1)}$ $\xi \approx 5.3$
σ_2 $\delta = 60$ $\rho = 0.67$	$\varphi_1^{(2)}$ $\xi \approx 17.3$	$\varphi_1^{(2)}$ $\xi \approx 22.7$	$\perp$	$\perp$
σ_3 $\delta = 70$ $\rho = 1.0$	$\varphi_3^{(3)}$ $\xi = 26.5$	$\varphi_1^{(3)}$ $\xi \approx 7.4$	$\varphi_1^{(3)}$ $\xi \approx 12.6$	$\perp$

Main objective:

Minimize Overall Energy Consumption

Problem formulation

Schedule Plan Model (K)

Duration	13 [13]	17 [30]	29 [59]	15 [74]
σ_1 $\boldsymbol{\delta = 80}$ $\rho = 0.45$	$\perp$	$\varphi_7^{(1)}$ $\xi\ = 25.5$	$\varphi_1^{(1)}$ $\xi \approx 10.2$	$\varphi_1^{(1)}$ $\xi \approx 5.3$
σ_2 $\boldsymbol{\delta = 60}$ $\rho = 0.67$	$\varphi_1^{(2)}$ $\xi \approx 17.3$	$\varphi_1^{(2)}$ $\xi \approx 22.7$	$\perp$	$\perp$
σ_3 $\boldsymbol{\delta = 70}$ $\rho = 1.0$	$\varphi_3^{(3)}$ $\xi\ = 26.5$	$\varphi_1^{(3)}$ $\xi \approx 7.4$	$\varphi_1^{(3)}$ $\xi \approx 12.6$	$\perp$

Main objective:

Minimize Overall Energy Consumption

Constraints:

- ❑ Deadline

Problem formulation

Schedule Plan Model (K)

Duration	13 [13]	17 [30]	29 [59]	15 [74]
σ_1 $\delta = 80$ $\boldsymbol{\rho} = \mathbf{0.45}$	$\perp$	$\varphi_7^{(1)}$ $\xi = 25.5$ $\boldsymbol{\rho} \approx \mathbf{0.2}$	$\varphi_1^{(1)}$ $\xi \approx 10.2$ $\boldsymbol{\rho} \approx \mathbf{0.17}$	$\varphi_1^{(1)}$ $\xi \approx 5.3$ $\boldsymbol{\rho} \approx \mathbf{0.08}$
σ_2 $\delta = 60$ $\boldsymbol{\rho} = \mathbf{0.67}$	$\varphi_1^{(2)}$ $\xi \approx 17.3$ $\boldsymbol{\rho} \approx \mathbf{0.29}$	$\varphi_1^{(2)}$ $\xi \approx 22.7$ $\boldsymbol{\rho} \approx \mathbf{0.38}$	$\perp$	$\perp$
σ_3 $\delta = 70$ $\boldsymbol{\rho} = \mathbf{1.0}$	$\varphi_3^{(3)}$ $\xi = 26.5$ $\boldsymbol{\rho} = \mathbf{0.5}$	$\varphi_1^{(3)}$ $\xi \approx 7.4$ $\boldsymbol{\rho} \approx \mathbf{0.18}$	$\varphi_1^{(3)}$ $\xi \approx 12.6$ $\boldsymbol{\rho} \approx \mathbf{0.32}$	$\perp$

Main objective:

Minimize Overall Energy Consumption

Constraints:

- ❑ Deadline
- ❑ Completion

Problem formulation

Schedule Plan Model (K)

Duration	13 [13]	17 [30]	29 [59]	15 [74]
σ_1 $\delta = 80$ $\rho = 0.45$	$\perp$	$\varphi_7^{(1)}$ $\xi = 25.5$ $\rho \approx 0.2$ **1B**	$\varphi_1^{(1)}$ $\xi \approx 10.2$ $\rho \approx 0.17$ **1L**	$\varphi_1^{(1)}$ $\xi \approx 5.3$ $\rho \approx 0.08$ **1L**
σ_2 $\delta = 60$ $\rho = 0.67$	$\varphi_1^{(2)}$ $\xi \approx 17.3$ $\rho \approx 0.29$ **1L1B**	$\varphi_1^{(2)}$ $\xi \approx 22.7$ $\rho \approx 0.38$ **1L1B**	$\perp$	$\perp$
σ_3 $\delta = 70$ $\rho = 1.0$	$\varphi_3^{(3)}$ $\xi = 26.5$ $\rho = 0.5$ **1L1B**	$\varphi_1^{(3)}$ $\xi \approx 7.4$ $\rho \approx 0.18$ **1L**	$\varphi_1^{(3)}$ $\xi \approx 12.6$ $\rho \approx 0.32$ **1L**	$\perp$
	2L2B	2L2B	2L	1L

Main objective:

Minimize Overall Energy Consumption

Constraints:

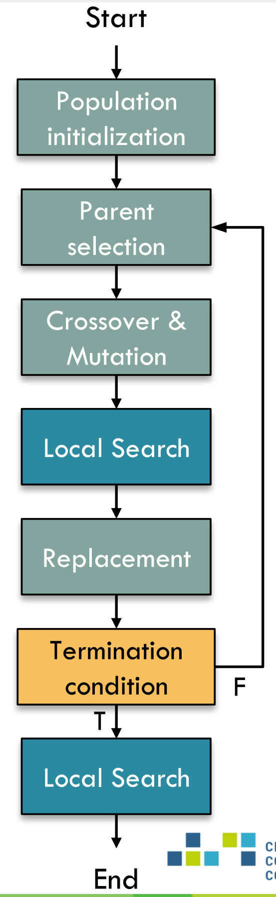
- ❑ Deadline
- ❑ Completion
- ❑ Resource

STEM – Spatio-Temporal Evolutionary Mapping

- STEM is based on Memetic Algorithms:
  - Genetic Algorithm
  - Knowledge-based heuristics
- Chromosome Representation

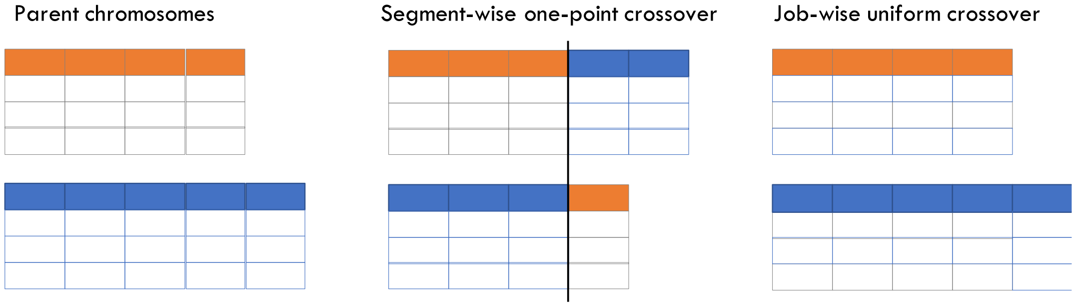
Dur.	10	25	20	13
σ_1	$\varphi_5^{(1)}$	$\varphi_5^{(1)}$	$\perp$	$\perp$
σ_2	$\varphi_2^{(2)}$	$\varphi_1^{(2)}$	$\varphi_{10}^{(2)}$	$\varphi_{10}^{(2)}$
σ_3	$\varphi_{15}^{(3)}$	$\perp$	$\varphi_2^{(3)}$	$\perp$

- Fitness is a tuple: (Group, Value)
  - Gr. 1: Valid chromosomes, value – energy
  - Gr. 2: Violates deadlines, value – avg. deadline violation
  - Gr. 3: Violates resource constr., value – avg. overuse of PEs

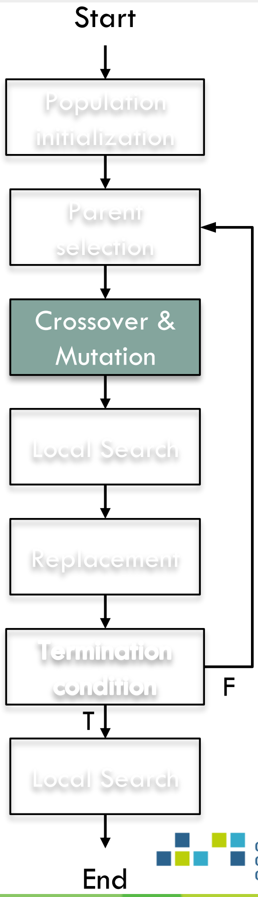


STEM Genetic Operators

- Crossover ($p_c = 0.7$)

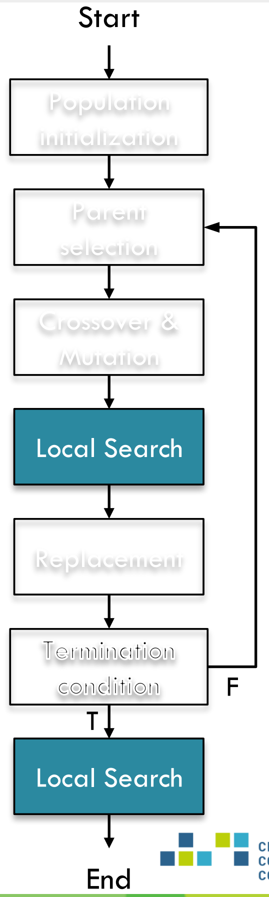


- Mutation operators ($p_m = 0.6$)
  - Swap two segments, insert or remove a segment
  - Alter the duration of a random segment
  - Alter a random operating point



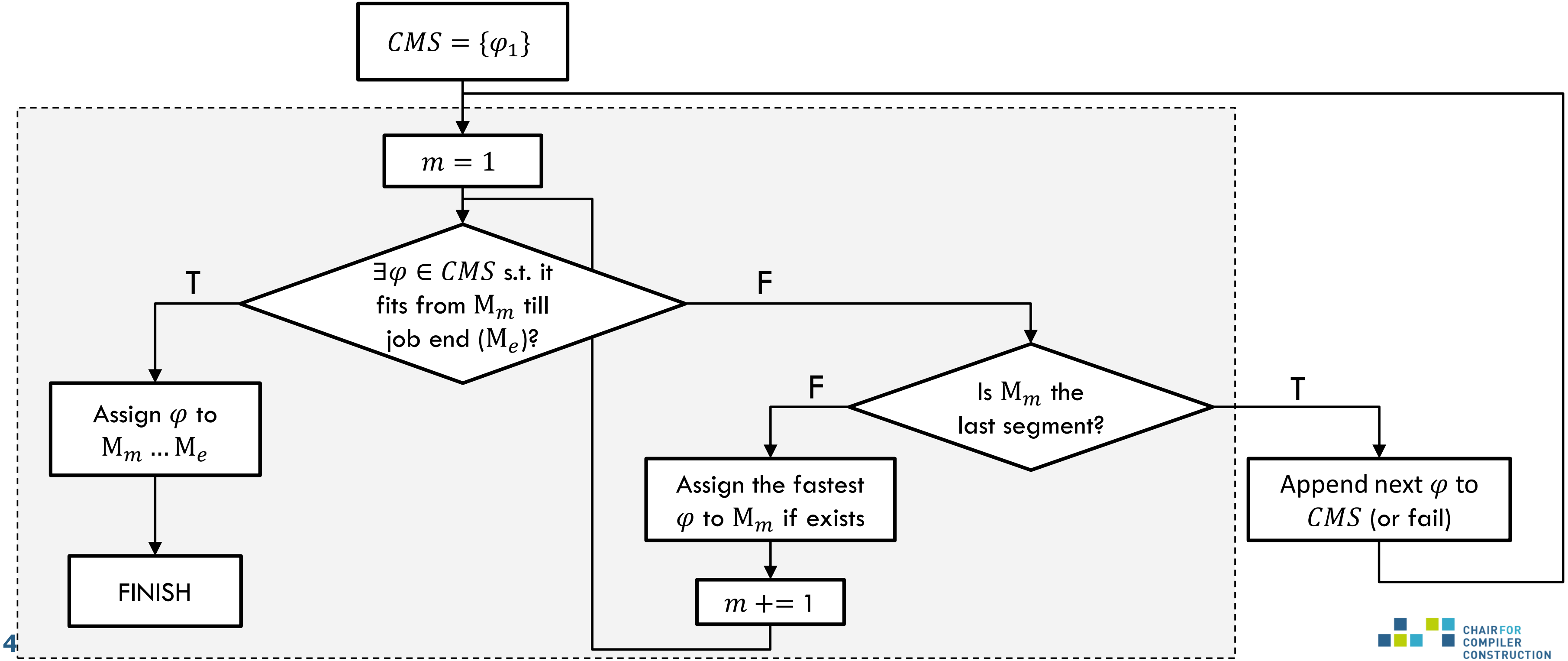
STEM Memetic Operators (Local Search)

- Idea: Find a better individual *close* to the current one
- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction
- Gr.1&2 ($p_{r_1} = p_{r_2} = 0.8$)
  - Chromosome Simplification
  - Segment Manipulations
  - Segment Duration Adjustment
  - Front Propagation of Operating Points



FFEMS – Fast Flexible Energy-Minimizing Scheduler

- **Iterative Job Scheduling:** EDF order



FFEMS step-by-step

$\sigma_1\ [\delta = 120]$

#L	#B	Time	Energy
1	0	171	60
1	1	95	72
2	0	88	75
2	2	78	80
2	1	47	105
1	2	35	120
0	1	86	129
0	2	46	142

$\sigma_2\ [\delta = 80]$

#L	#B	Time	Energy
1	1	45	60
2	0	62	66
2	1	35	70
1	0	114	73
2	2	32	75
1	2	93	77
0	2	42	110
0	1	76	112

$\sigma_3\ [\delta = 100]$

#L	#B	Time	Energy
1	0	92	40
2	0	53	45
1	1	26	53
2	2	23	54
2	1	23	58
1	2	17	64
0	2	18	75
0	1	34	81

Dur.	45	47
σ_1		
σ_2	1L1B	$\perp$
σ_3	1L	1L

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FFEMS step-by-step

$\sigma_1\ [\delta = 120]$

#L	#B	Time	Energy
1	0	171	60
1	1	95	72
2	0	88	75
2	2	78	80
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$\sigma_2\ [\delta = 80]$

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#L	#B	Time	Energy
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1	1	26	53
2	2	23	54
2	1	23	58
1	2	17	64
0	2	18	75
0	1	34	81

Dur.	45	47
σ_1	$\perp$	
σ_2	1L1B	$\perp$
σ_3	1L	1L

FFEMS step-by-step

$\sigma_1\ [\delta = 120]$

#L	#B	Time	Energy
1	0	171	60
1	1	95	72
2	0	88	75
2	2	78	80
2	1	47	105
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$\sigma_3\ [\delta = 100]$

#L	#B	Time	Energy
1	0	92	40
2	0	53	45
1	1	26	53
2	2	23	54
2	1	23	58
1	2	17	64
0	2	18	75
0	1	34	81

Dur.	45	47
σ_1	$\perp$	1L1B
σ_2	1L1B	$\perp$
σ_3	1L	1L

FFEMS step-by-step

$\sigma_1\ [\delta = 120]$

#L	#B	Time	Energy
1	0	171 [86.4]	60
1	1	95 [48]	72
2	0	88 [44.5]	75
2	2	78 [39.4]	80
2	1	47 [23.7]	105
1	2	35	120
0	1	86	129
0	2	46	142

$\sigma_2\ [\delta = 80]$

#L	#B	Time	Energy
1	1	45	60
2	0	62	66
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0	2	42	110
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$\sigma_3\ [\delta = 100]$

#L	#B	Time	Energy
1	0	92	40
2	0	53	45
1	1	26	53
2	2	23	54
2	1	23	58
1	2	17	64
0	2	18	75
0	1	34	81

Dur.	45	47	
σ_1	$\perp$	1L1B	
σ_2	1L1B	$\perp$	$\perp$
σ_3	1L	1L	$\perp$

FFEMS step-by-step

$\sigma_1\ [\delta = 120]$

#L	#B	Time	Energy
1	0	171 [86.4]	60
1	1	95 [48]	72
2	0	88 [44.5]	75
2	2	78 [39.4]	80
2	1	47 [23.7]	105
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$\sigma_2\ [\delta = 80]$

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$\sigma_3\ [\delta = 100]$

#L	#B	Time	Energy
1	0	92	40
2	0	53	45
1	1	26	53
2	2	23	54
2	1	23	58
1	2	17	64
0	2	18	75
0	1	34	81

Dur.	45	47	23.7
σ_1	$\perp$	1L1B	2L1B
σ_2	1L1B	$\perp$	$\perp$
σ_3	1L	1L	$\perp$

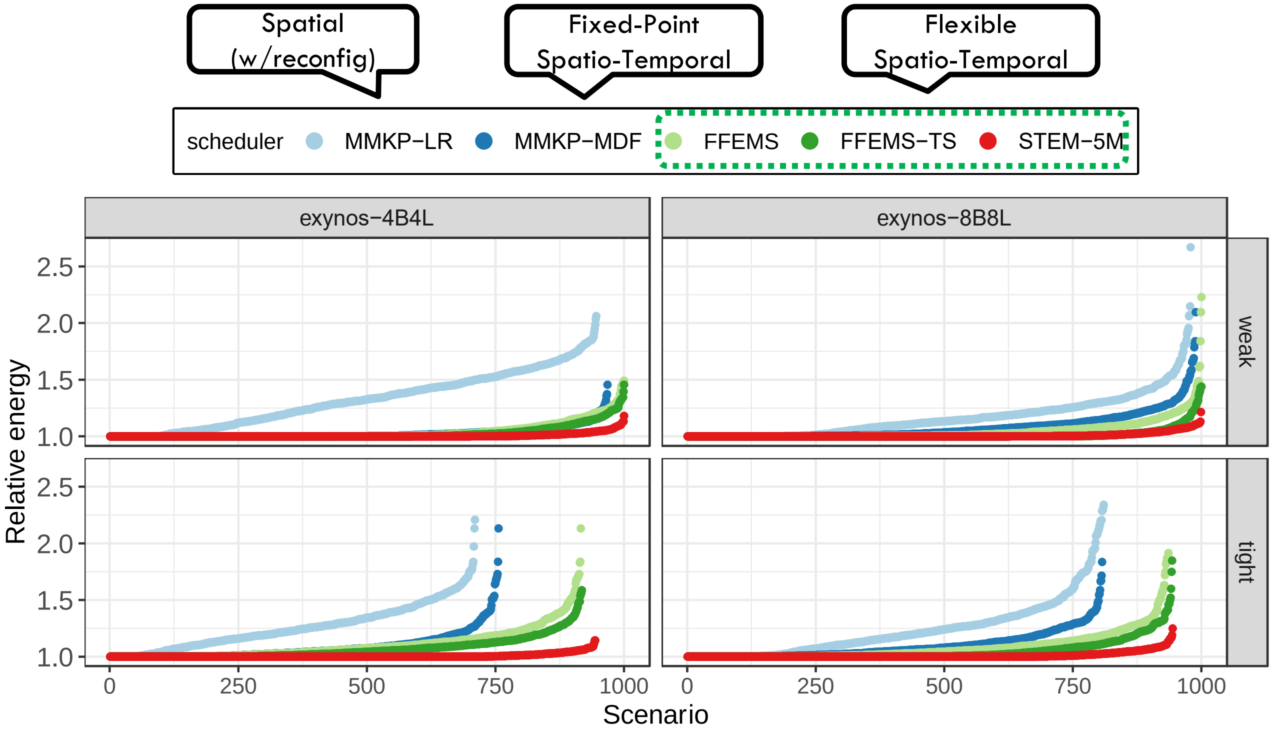
$E(\sigma_1) = 88.67J$

Tail-Switch

Dur.	45	47	17.7	10
σ_1	$\perp$	1L1B	2L1B	2L2B
σ_2	1L1B	$\perp$	$\perp$	$\perp$
σ_3	1L	1L	$\perp$	$\perp$

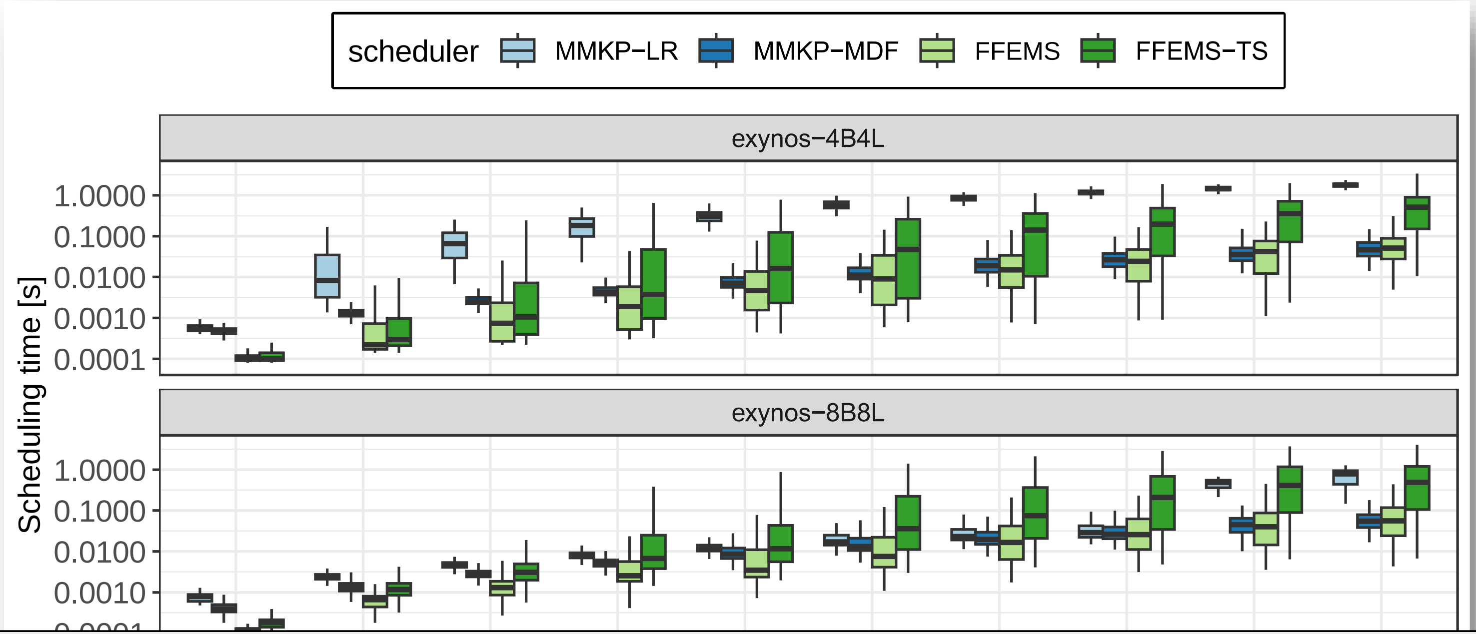
$E(\sigma_1) = 85.47J$

Evaluation – Success Rate and Energy-Efficiency



- **MMKP-LR** is the worst in energy efficiency and success rate
- **MMKP-MDF** selects more often the most efficient configs
  ➔ enhances energy efficiency
- **Flexible Mapping** allows fine-tuning of schedules
  ➔ enhances success rate (up to 19%)
- **FFEMS** deviates by a maximum of 3% in terms of success rate from optimal schedules
- **FFEMS-TS** improves energy efficiency (up to 6%)

Evaluation – Runtime Overhead



FFEMS runs as fast as MMKP-MDF but schedules more scenarios!

Conclusion

Spatial Mapping [1, 2] | Fixed-Point Spatio-Temporal Mapping [3, 4] | Flexible Spatio-Temporal Mapping [**This work**]

- Impact of Mapping Decision Models:
  - **Spatial Mapping** often misses energy-efficient configurations
  - **Fixed-Point Spatio-Temporal Mapping** enhances energy savings via job postponing
  - **Flexible Spatio-Temporal Mapping** increases the success rate thanks to fine tuning of schedules
- **FFEMS** demonstrates an outstanding balance between performance and overhead (16% more test cases, with the same overhead as MMKP-MDF)
- **FFEMS-TS** further improves energy efficiency (up to 6%), albeit with a slight increase in runtime overhead

[1] C. Ykman-Couvreur et al., "Fast multi-dimension multi-choice knapsack heuristic for mp-soc run-time management," SOC, 2006.
[2] S. Wildermann, M. Glaß, and J. Teich, "Multi-objective distributed run-time resource management for many-cores," DATE, 2014
[3] M. Niknafs et al, "Runtime resource management with workload prediction." DAC, 2019
[4] R. Khasanov, J. Castrillon, "Energy-efficient Runtime Resource Management for Adaptable Multi-application Mapping", DATE, 2020

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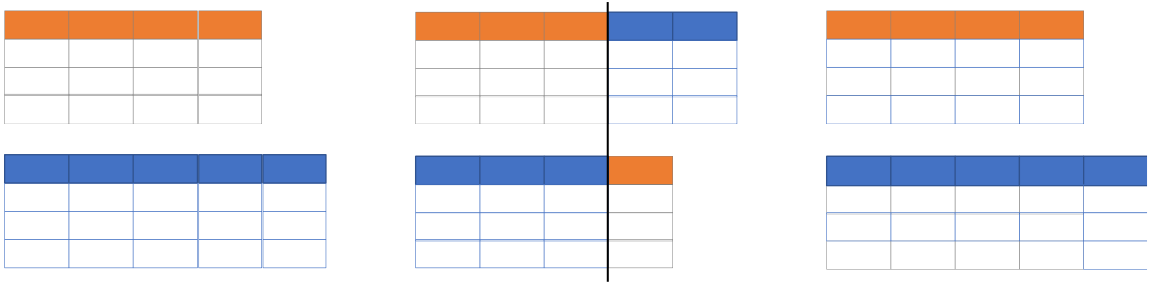
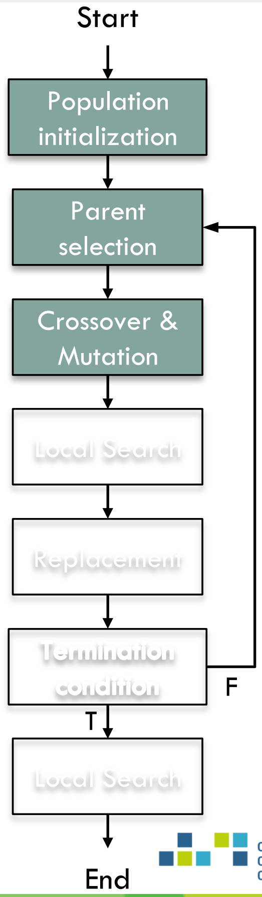
Backup

STEM steps

- Population Initialization (90 individuals)
  - Structured approach to minimize violations
- Parent Selection (one pair)
  - Exponential Ranking Selection with Stochastic Universal Sampling
- Crossover ($p_c = 0.7$)

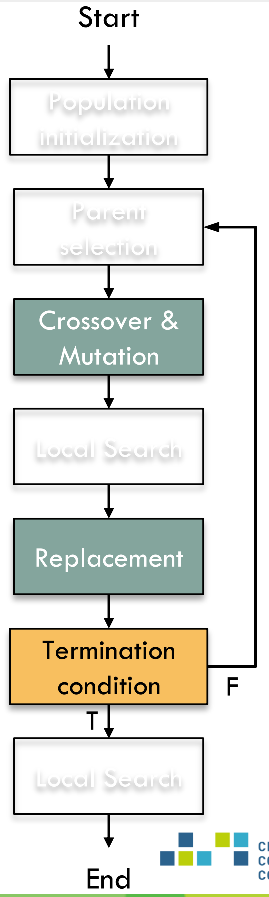
Parent chromosomes | Segment-wise one-point crossover | Job-wise uniform crossover





STEM steps

- Mutation operators ($p_m = 0.6$)
  - Swap two segments, insert or remove a segment
  - Alter the duration of a random segment
  - Alter a random operating point
- Local Search → see next slide
- Replacement
  - Round-Robin Tournament (q=8)
- Termination
  - Fixed number of generations
  - No significant improvement in the last N generations



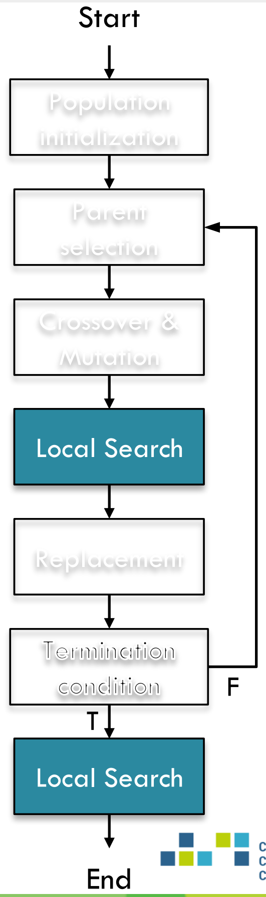
Memetic operators (Local Search)

- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction

Dur.	10	25	20	13
σ_1	5	5	⊥	⊥
σ_2	2	18	10	10
σ_3	15	2	2	⊥

⇨

Dur.	10	25	20	13
σ_1	5	5	⊥	⊥
σ_2	2	⊥	10	10
σ_3	15	2	2	⊥



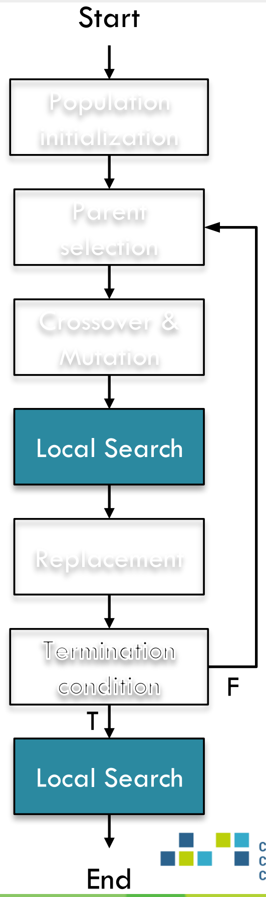
Memetic operators (Local Search)

- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction
- Gr.1&2 ($p_{r_1} = p_{r_2} = 0.8$)
  - Chromosome Simplification

Dur.	10	25	20	13
σ_1	5	5	$\perp$	$\perp$
σ_2	2	$\perp$	10	15
σ_3	15	23	$\perp$	$\perp$

$\Rightarrow$

Dur.	10	25	10
σ_1	5	5	$\perp$
σ_2	2	$\perp$	10
σ_3	15	23	$\perp$



Memetic operators (Local Search)

- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction
- Gr.1&2 ($p_{r_1} = p_{r_2} = 0.8$)
  - Chromosome Simplification
  - Segment Manipulations

Dur.	10	25	10
σ_1	5	5	$\perp$
σ_2	2	$\perp$	10
σ_3	15	23	$\perp$

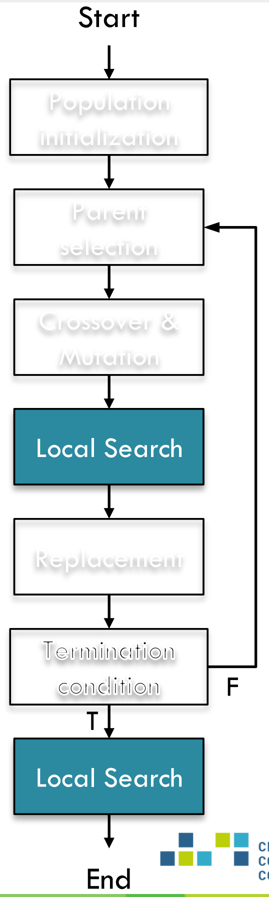
⇨

Dur.	10	10	15	10
σ_1	5	5	$\perp$	$\perp$
σ_2	2	$\perp$	$\perp$	10
σ_3	15	23	23	$\perp$

Dur.	10	25	5	13
σ_1	5	5	$\perp$	$\perp$
σ_2	2	$\perp$	10	10
σ_3	15	2	2	$\perp$

⇨

Dur.	15	25	13
σ_1	5	5	$\perp$
σ_2	2	$\perp$	10
σ_3	15	2	$\perp$



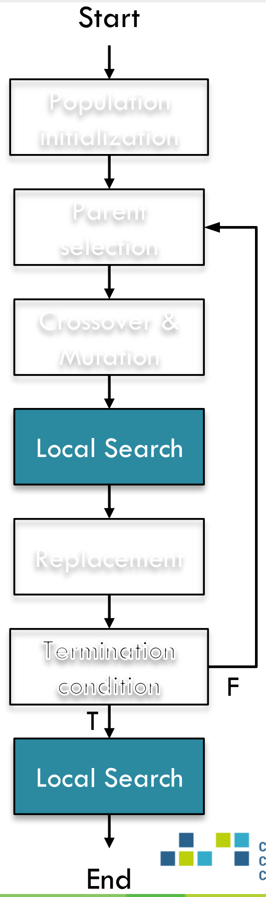
Memetic operators (Local Search)

- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction
- Gr.1&2 ($p_{r_1} = p_{r_2} = 0.8$)
  - Chromosome Simplification
  - Segment Manipulations
  - Segment Duration Adjustment

Dur.	15	25	13
σ_1	5	5	$\perp$
σ_2	2	$\perp$	10
σ_3	15	2	$\perp$

⇨

Dur.	18	25	13
σ_1	5	5	$\perp$
σ_2	2	$\perp$	10
σ_3	15	2	$\perp$

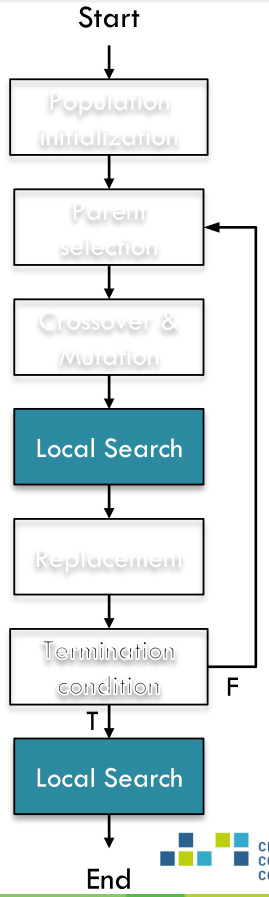


Memetic operators (Local Search)

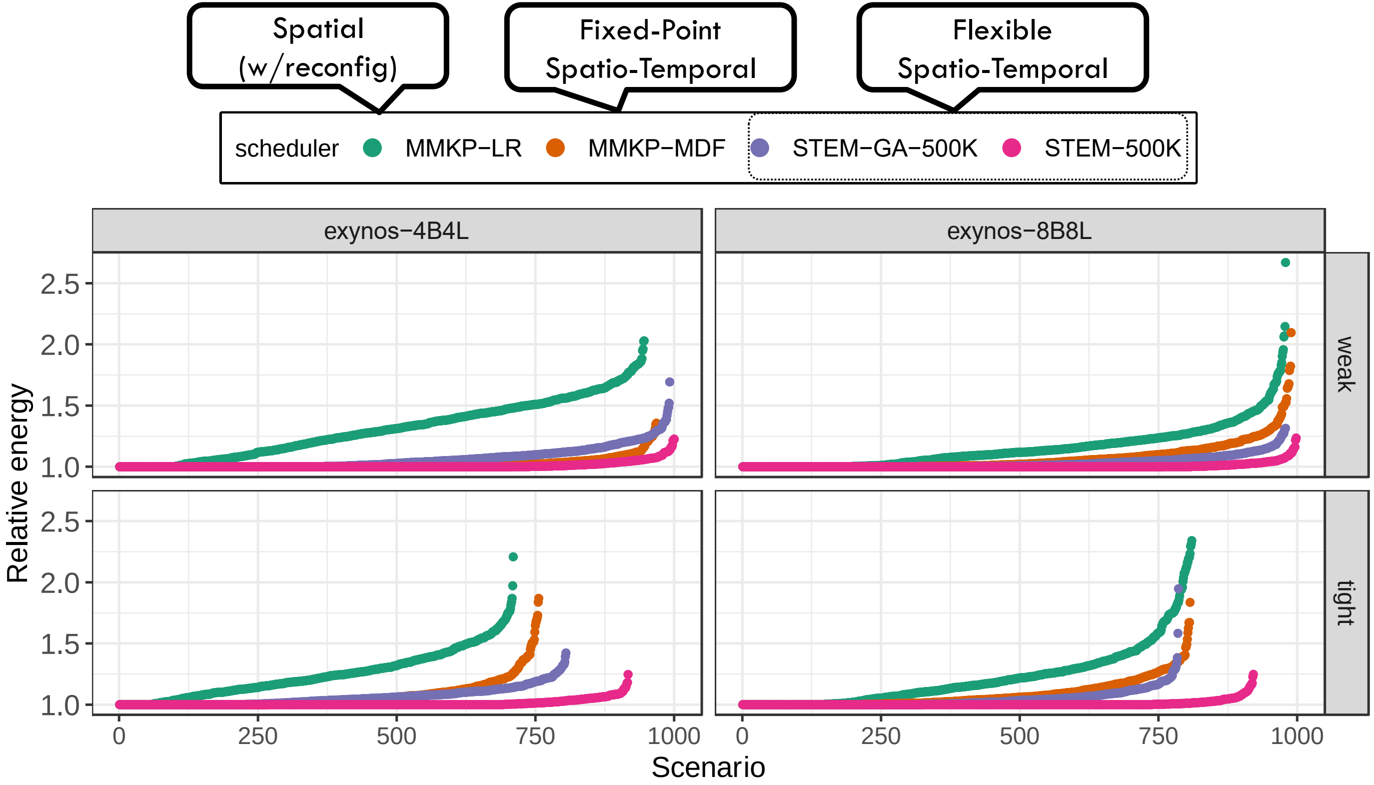
- Gr. 3 (Violating resource deadlines) ($p_{r_3} = 0.5$)
  - Resource Overuse Reduction
- Gr.1&2 ($p_{r_1} = p_{r_2} = 0.8$)
  - Chromosome Simplification
  - Segment Manipulations
  - Segment Duration Adjustment
  - Front Propagation of Operating Points

Dur.	10	10	15	10
σ_1	$\perp$	3	4	$\perp$
σ_2	2	$\perp$	$\perp$	10
σ_3	15	$\perp$	23	3

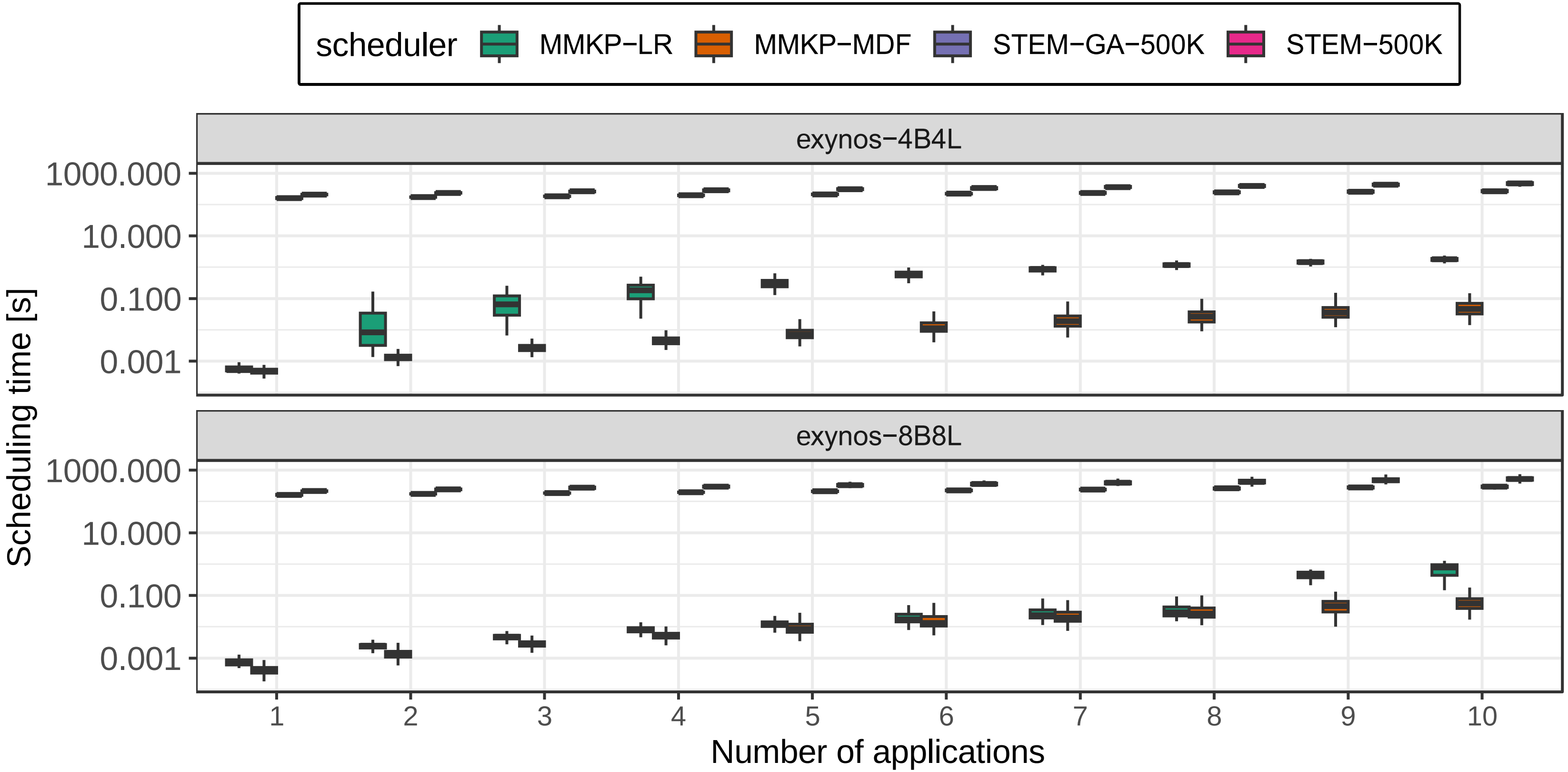
Dur.	10	10	15	10
σ_1	$\perp$	3	4	$\perp$
σ_2	2	$\perp$	$\perp$	10
σ_3	15	3	23	3



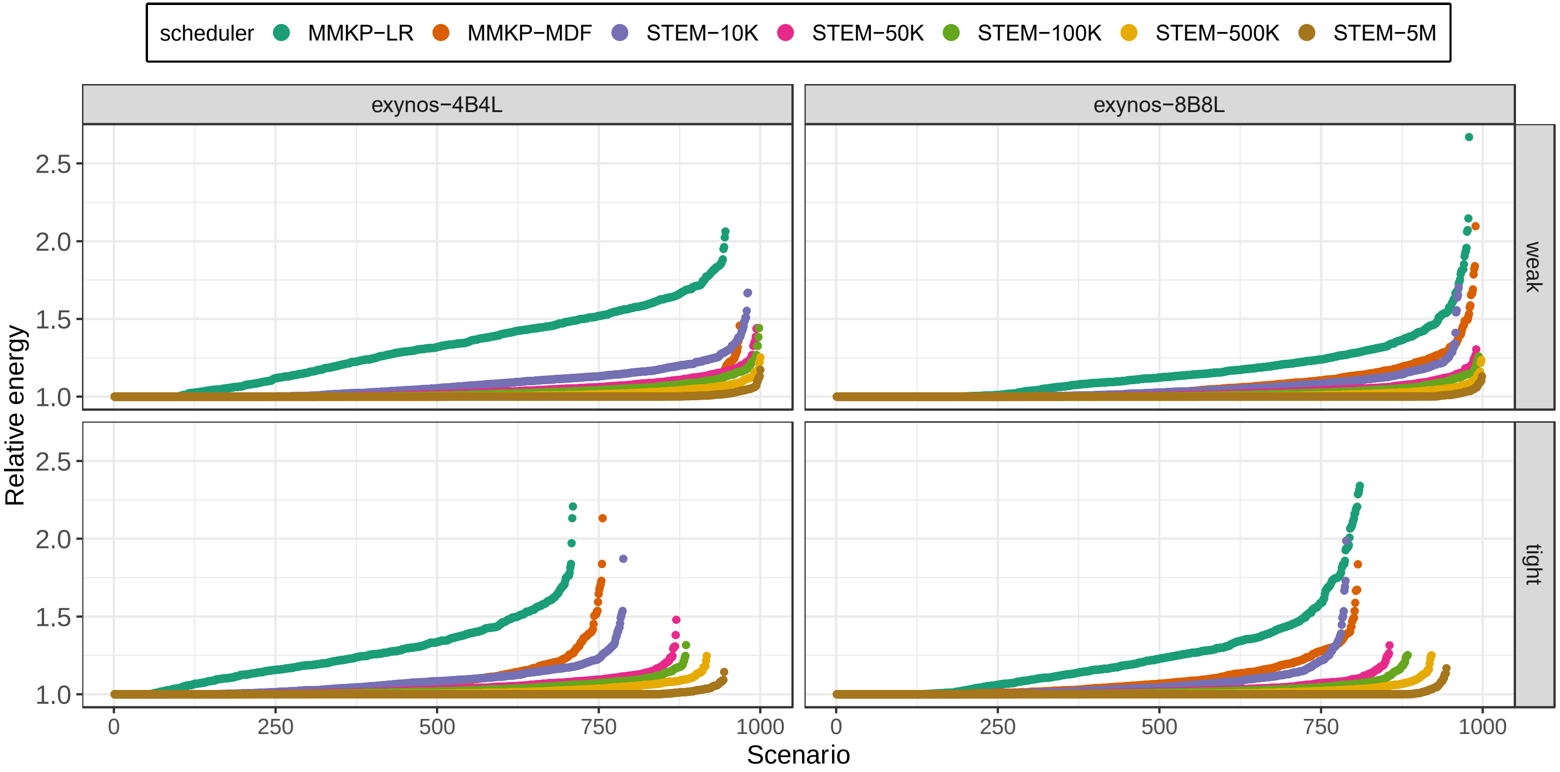
STEM - Evaluation (GA vs MA)



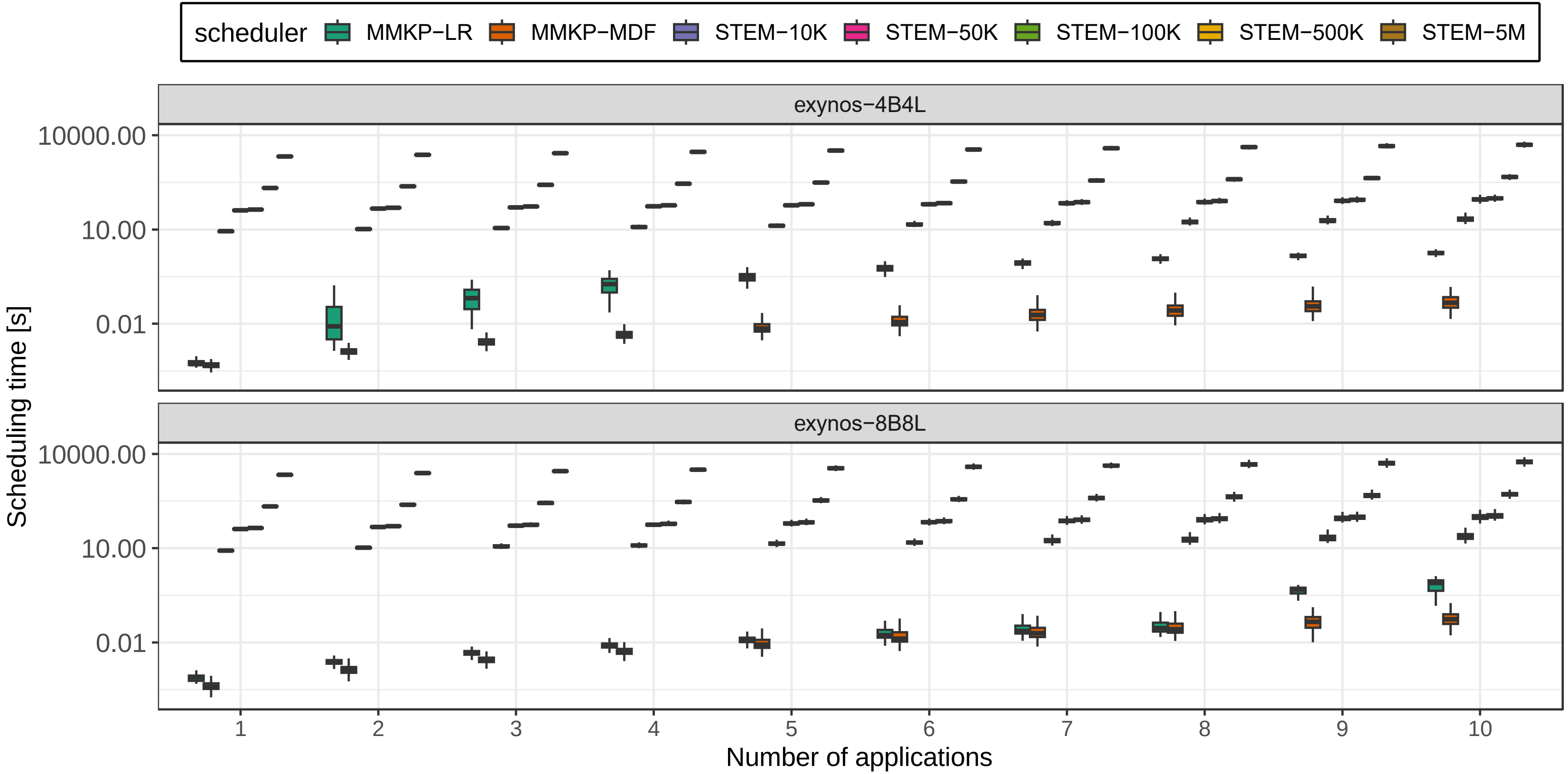
STEM - Evaluation (GA vs MA)



STEM - Evaluation (#Generations)



STEM - Evaluation (#Generations)



Evaluation – Success Rate and Energy-Efficiency