Incorporating flexibility in the long-term design of WDS using operational variables

Preliminary insights on Anytown

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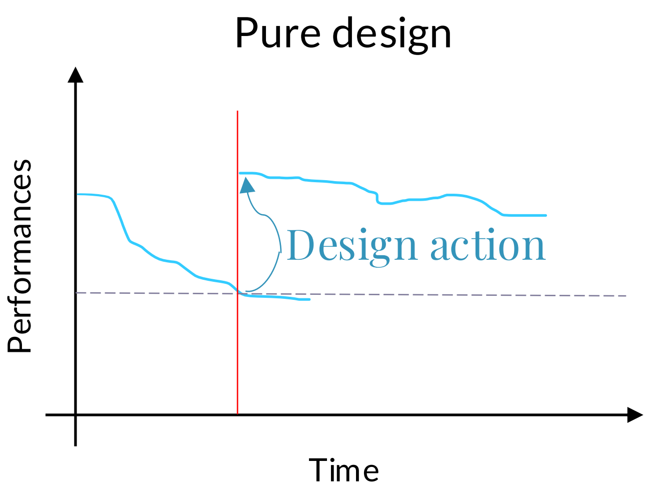
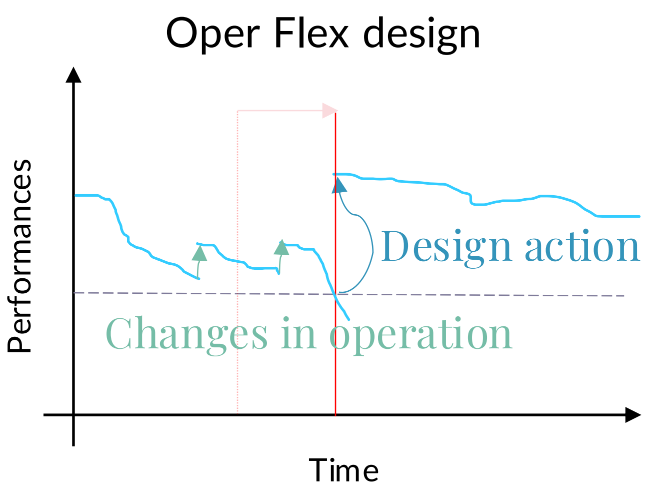
The operational flexibility of a WDS is

the ability of a system to **adjust its operations efficiently** to cope with a changing environment **without changes to the design.**



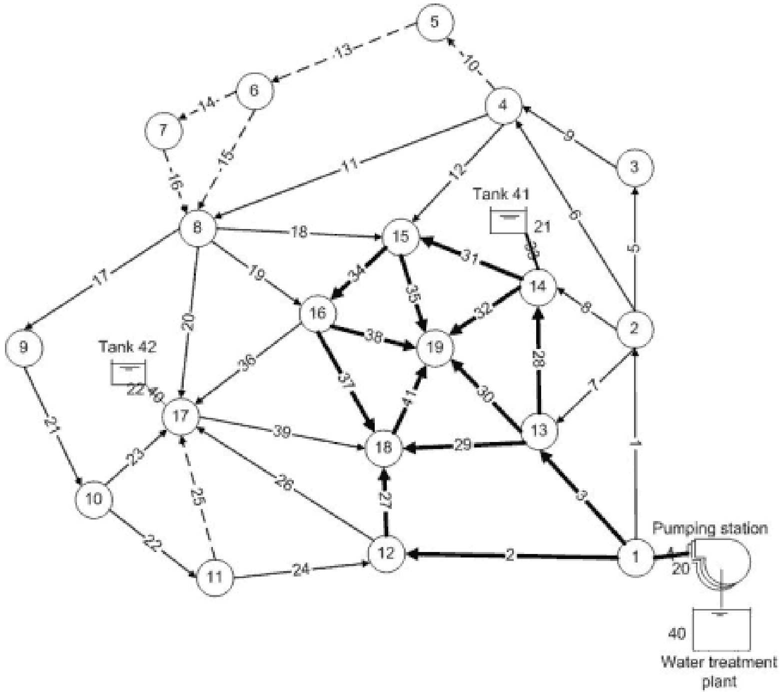


We want **to design operationally flexible** systems

because we believe

they are going **to provide more freedom and performance**

Case Study: Anytown*



Objectives

Net Present Value (Cost)

C_0 Immediate capital expenditure
C_t Yearly pumps' electricity cost

$$NPC = C_0 + \sum_{t=1}^{25} \frac{C_t}{(1+r)^t}$$

Todini's Reliability Index

A measure of energy surplus to meet required demand $q^*$and head h^*. Todini, 2000

$$I_r = \frac{\sum_{i=1}^{n_j} q_i^*(h_i - h_i^*)}{\sum_{k=1}^{n_s} Q_k H_k + \sum_{j=1}^{n_p} {P_j}/{\gamma} - \sum_{i=1}^{n_j} q_i^* h_i^*}$$

Constraints (Design requirements)

Meet demand and min. pressure at
- ~~instantaneous peak flow~~
- ~~fire flow conditions~~
- average daily pattern

Decision variables

Design

New pipes
- Diameter

Existing pipes
- Do nothing
- Clean
- Duplicate

New tanks
- Location
- Volume

Operations

Pumping station
- Schedule

*Full original formulation: Walski et al., 1987

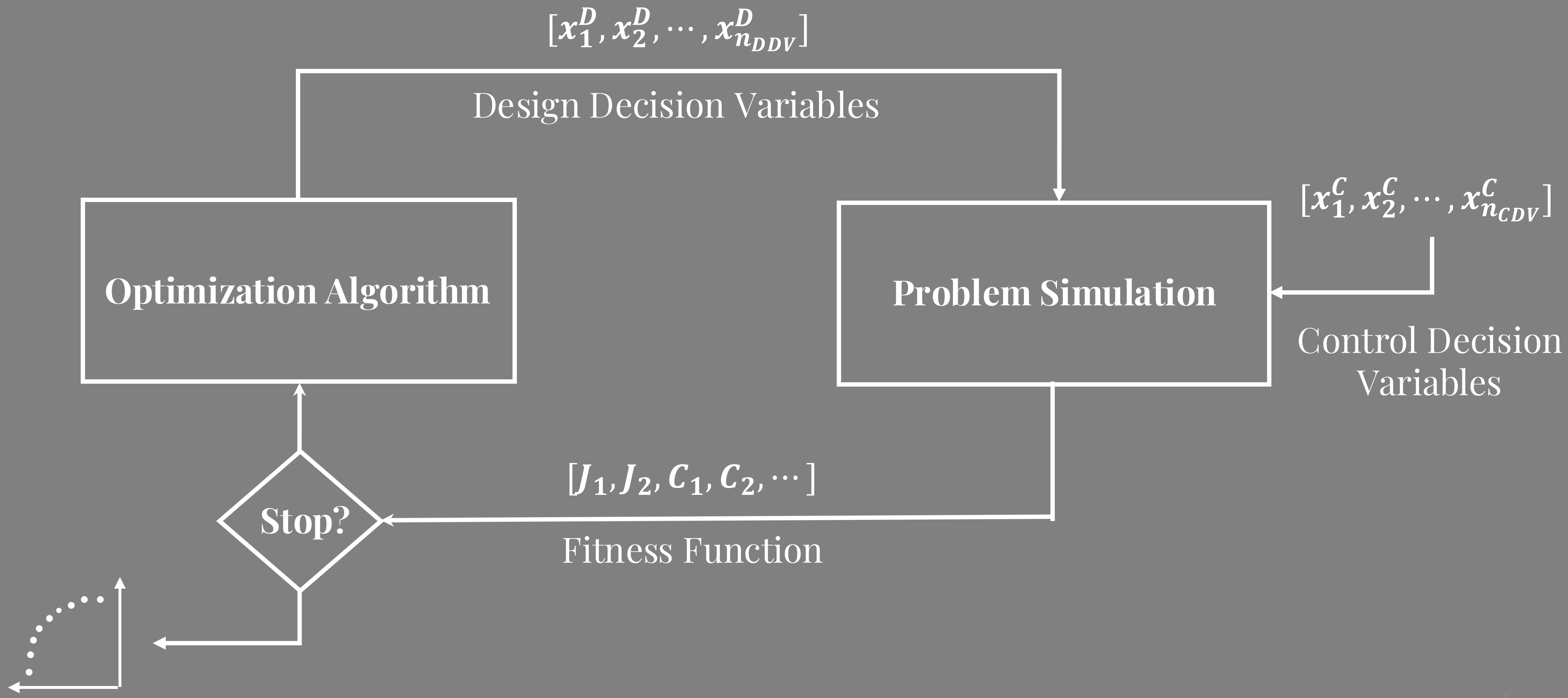
Methodology

Pure design

Integrated

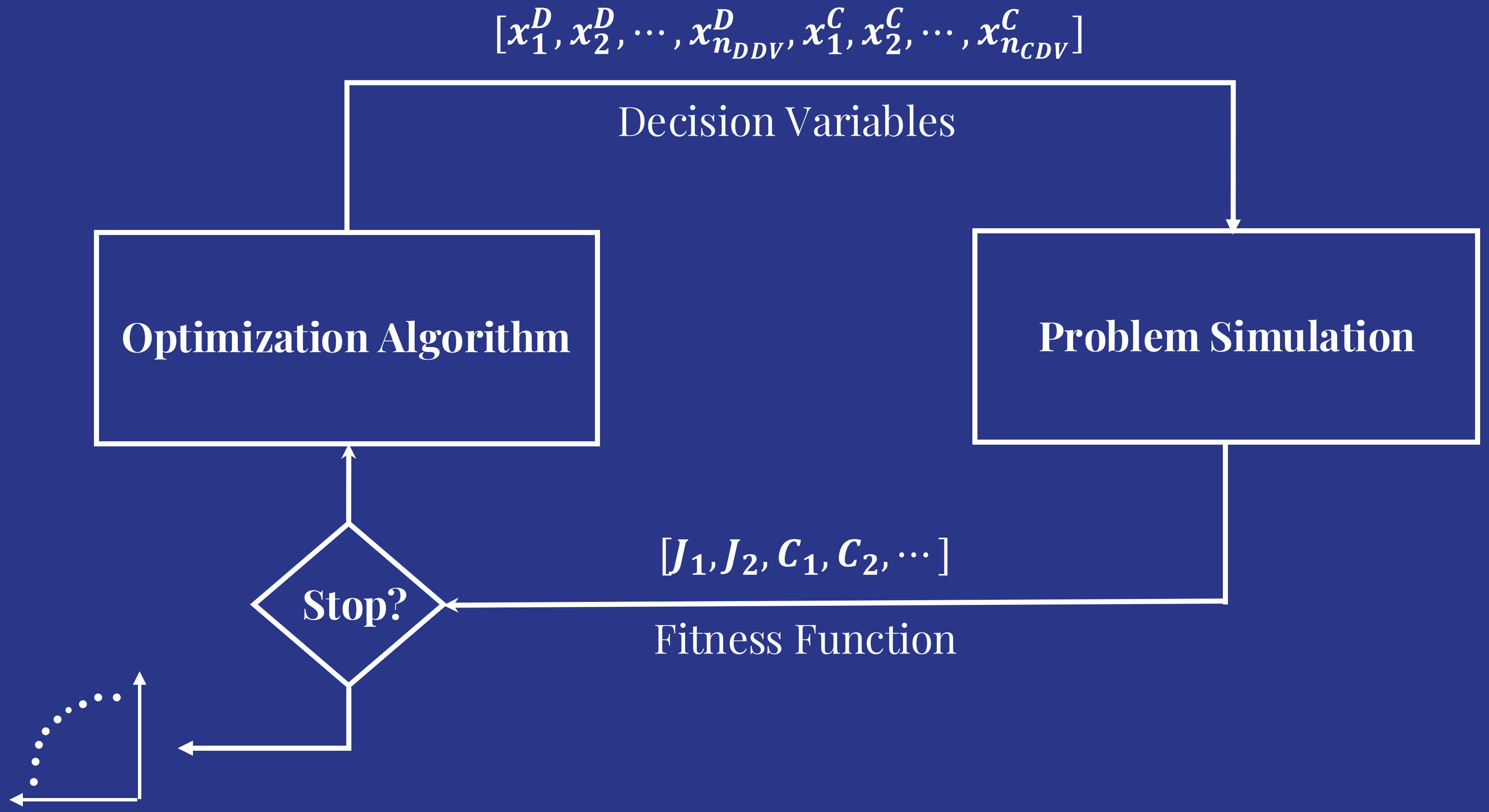
Two-phase looped

Pure design

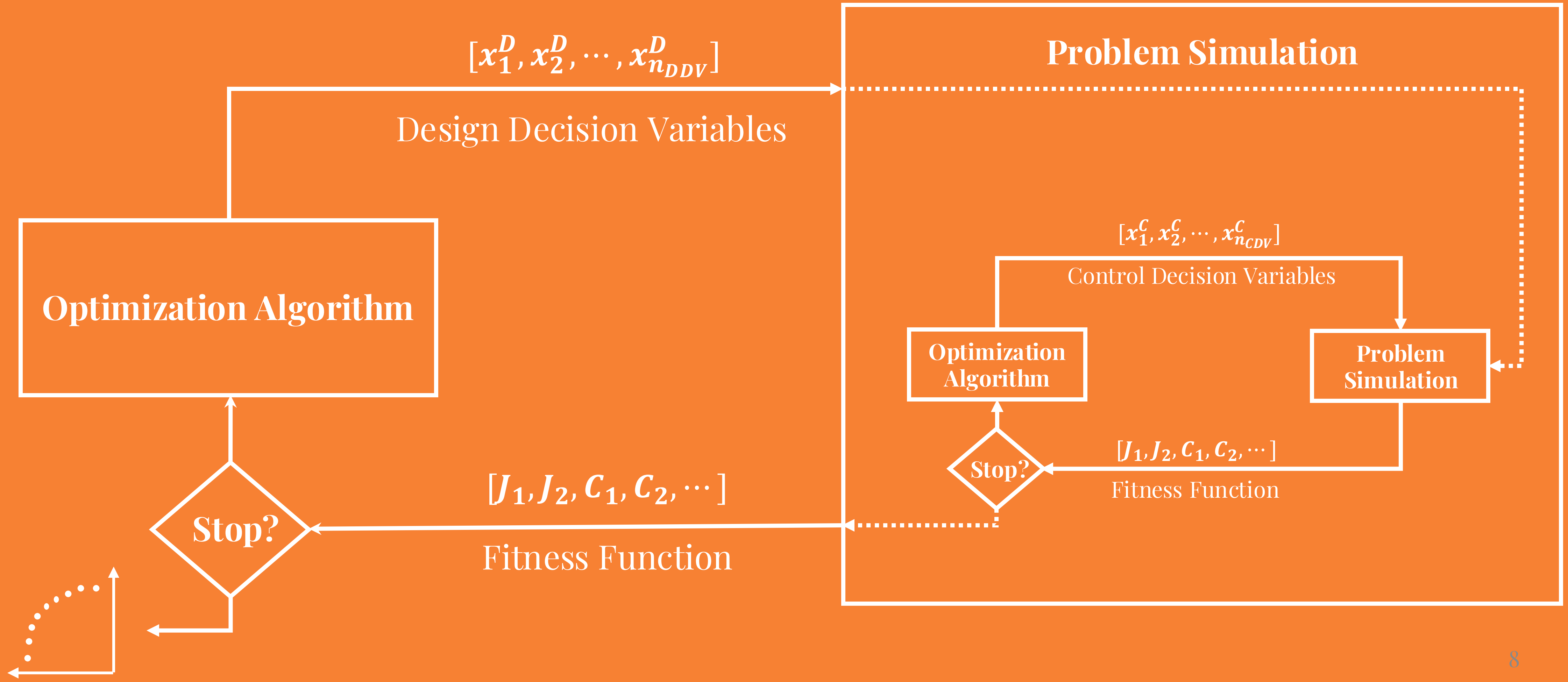


$[x_1^D, x_2^D, \cdots, x_{n_{DDV}}^D]$
Design Decision Variables
Optimization Algorithm
Problem Simulation
$[x_1^C, x_2^C, \cdots, x_{n_{CDV}}^C]$
Control Decision Variables
$[J_1, J_2, C_1, C_2, \cdots]$
Fitness Function
Stop?

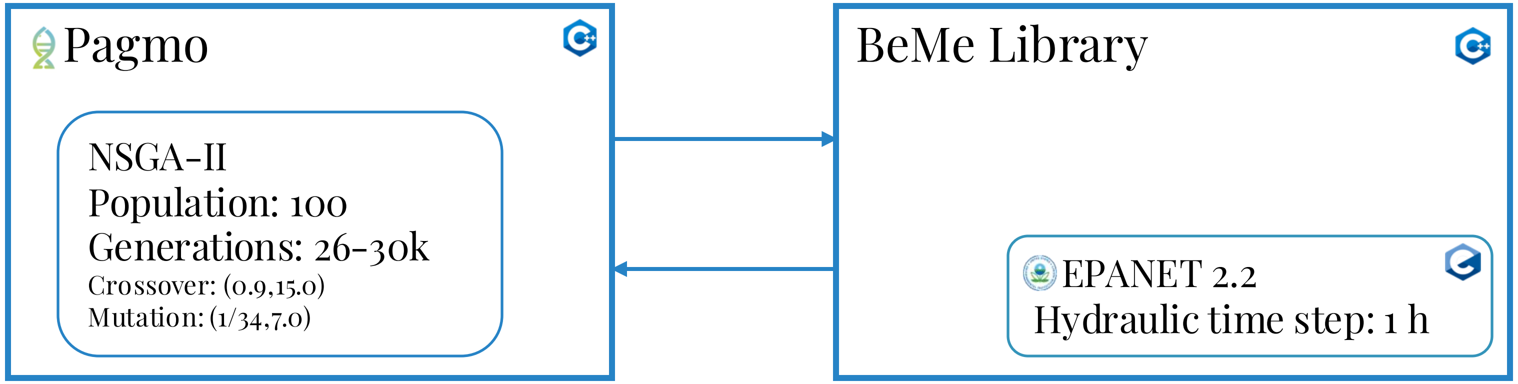
Integrated


$[x_1^D, x_2^D, \cdots, x_{n_{DDV}}^D, x_1^C, x_2^C, \cdots, x_{n_{CDV}}^C]$
Decision Variables
Optimization Algorithm
Problem Simulation
$[J_1, J_2, C_1, C_2, \cdots]$
Stop?
Fitness Function

Two-phase looped



Experimental Settings



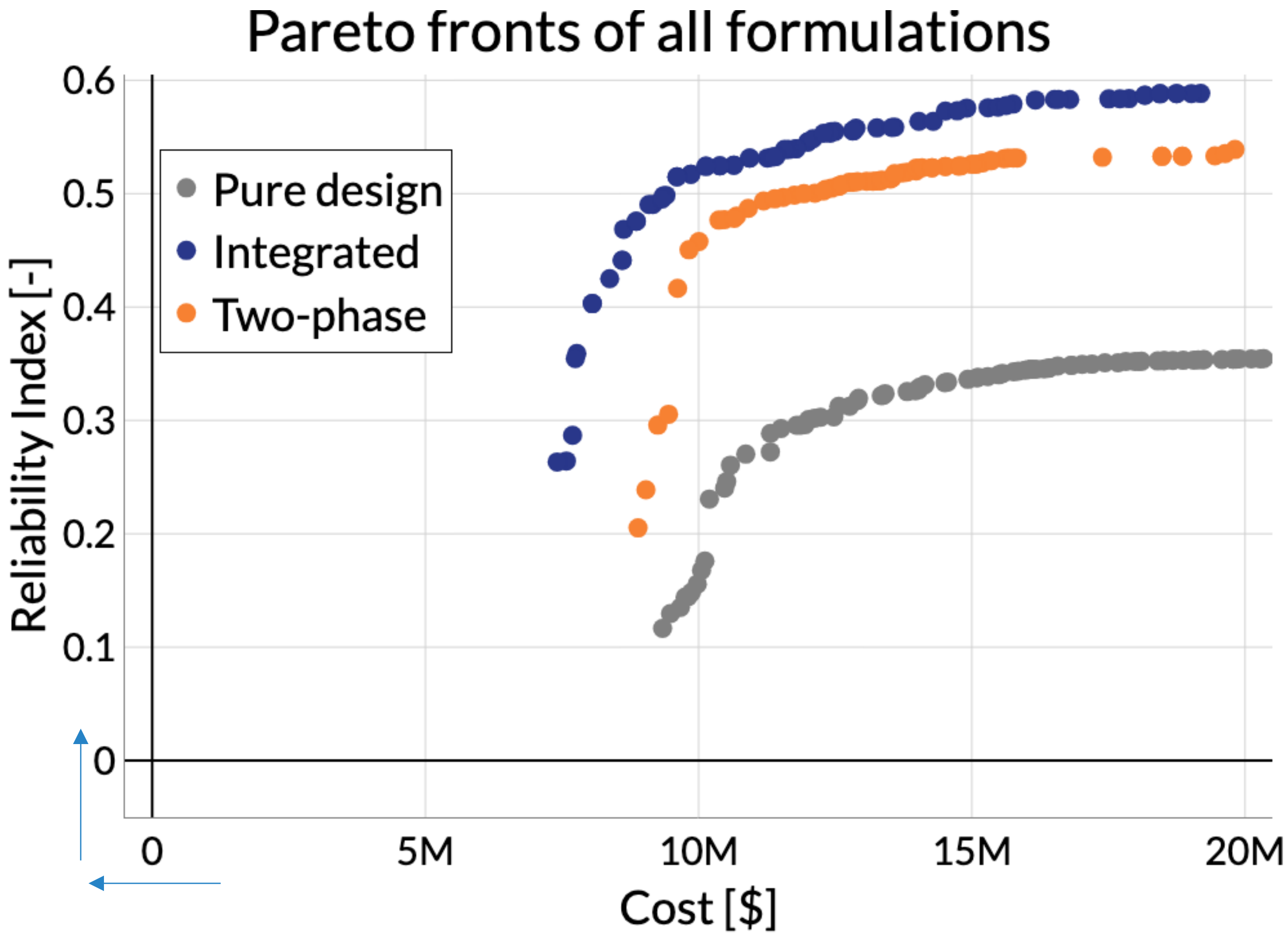
Design Decision Variables $[\underbrace{\langle x_1|d_1\rangle, \cdots, \langle x_i|d_i\rangle, \cdots, \langle x_{35}|d_{35}\rangle}_{\text{Existing pipes: } \langle \text{action}|\text{diameter}\rangle}, \underbrace{d_{36}, \cdots, d_j, \cdots, d_{41}}_{\text{New pipes: diameter}}, \underbrace{\langle t_1^{loc}|t_1^{vol}\rangle, \langle t_2^{loc}|t_2^{vol}\rangle}_{\text{New tanks: } \langle \text{location}'|\text{volume}\rangle}]$

Control Decision Variables $[\underbrace{z_1, \cdots, z_i, \cdots, z_{24}}_{\text{Pump station: \# active pumps at each hour}}]$

Implementation:

Zanutto, 2024
thanks to:
Rossman, 2000
Deb et al., 2002
Biscani and Izzo, 2020

Joint approaches allow for more performance



Integrated

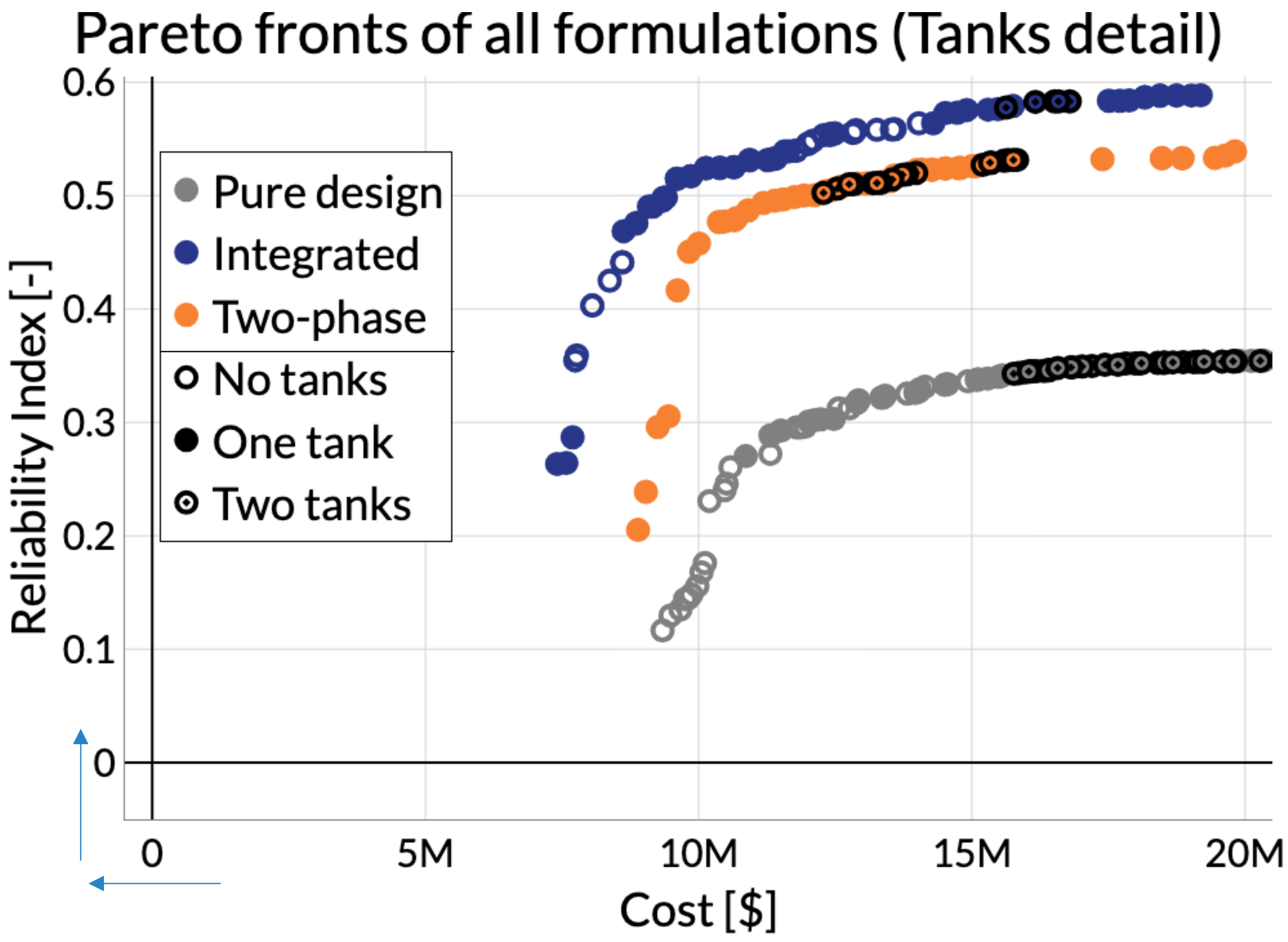
- +180% at 10M
- +70% at 15M

Two-phase

- 150% at 10M
- 55% at 15M

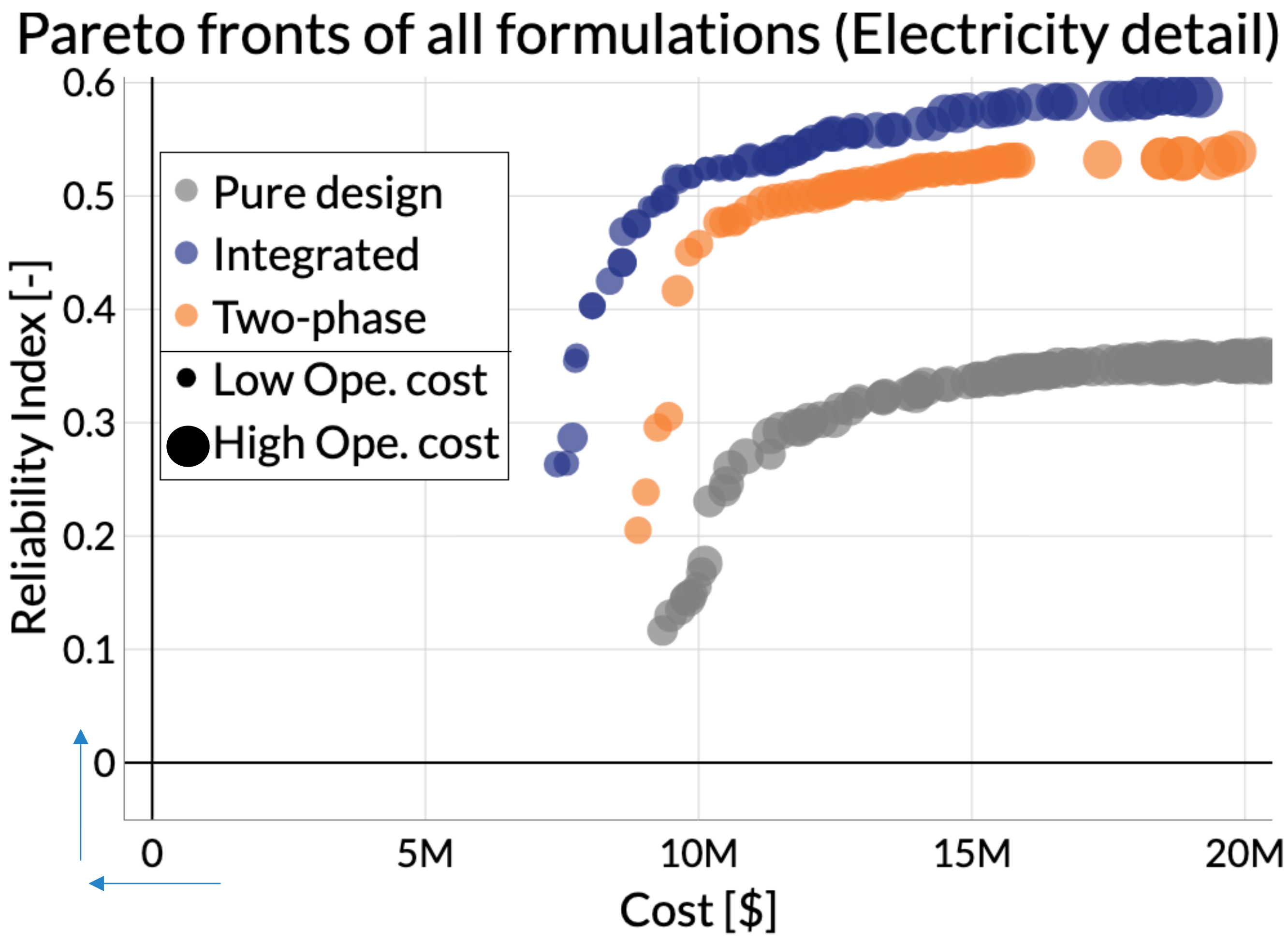
Where does the performance come from?

Improved performance is not because of tanks…



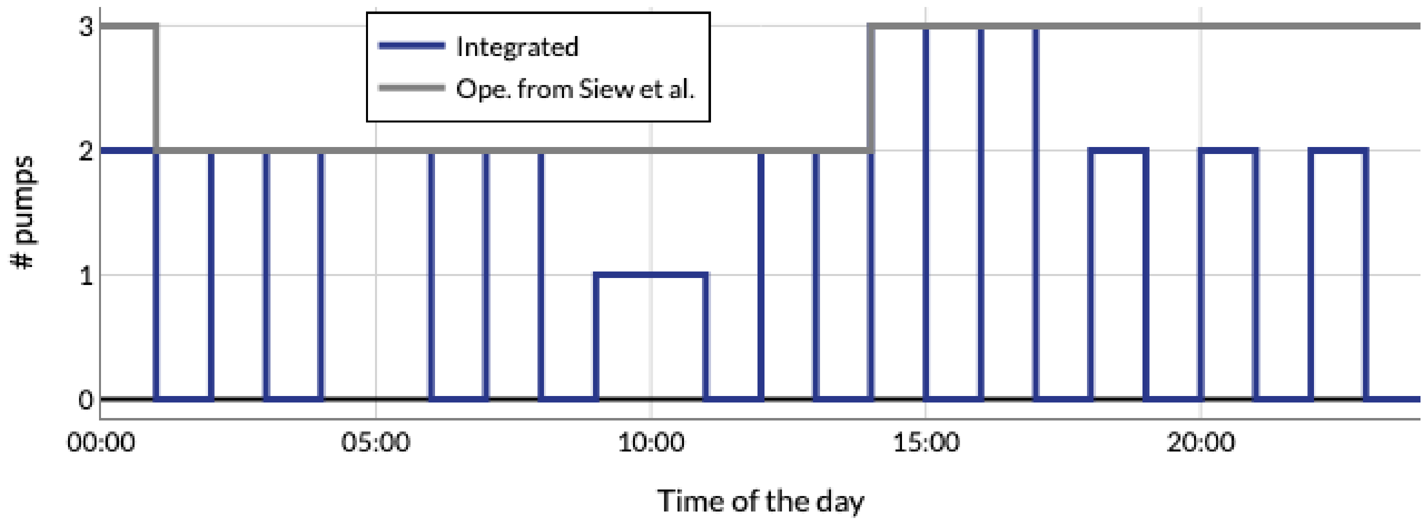
Only the pure design solutions need two tanks for high reliability!

It's not how much you spend either…



A similar dot size means similar operational costs between the approaches.

It’s about how you spend!



The opt algo exploits the problem by finding a very specialized pattern.

Unfortunately, this pattern is unfeasible.

The additional performances of the joint approaches come from the way the system is operated, but this is a consequence of how the optimization algorithm exploits the problem.

So, we need to rethink the problem formulation more deeply and challenge all assumptions made for design-only problems.

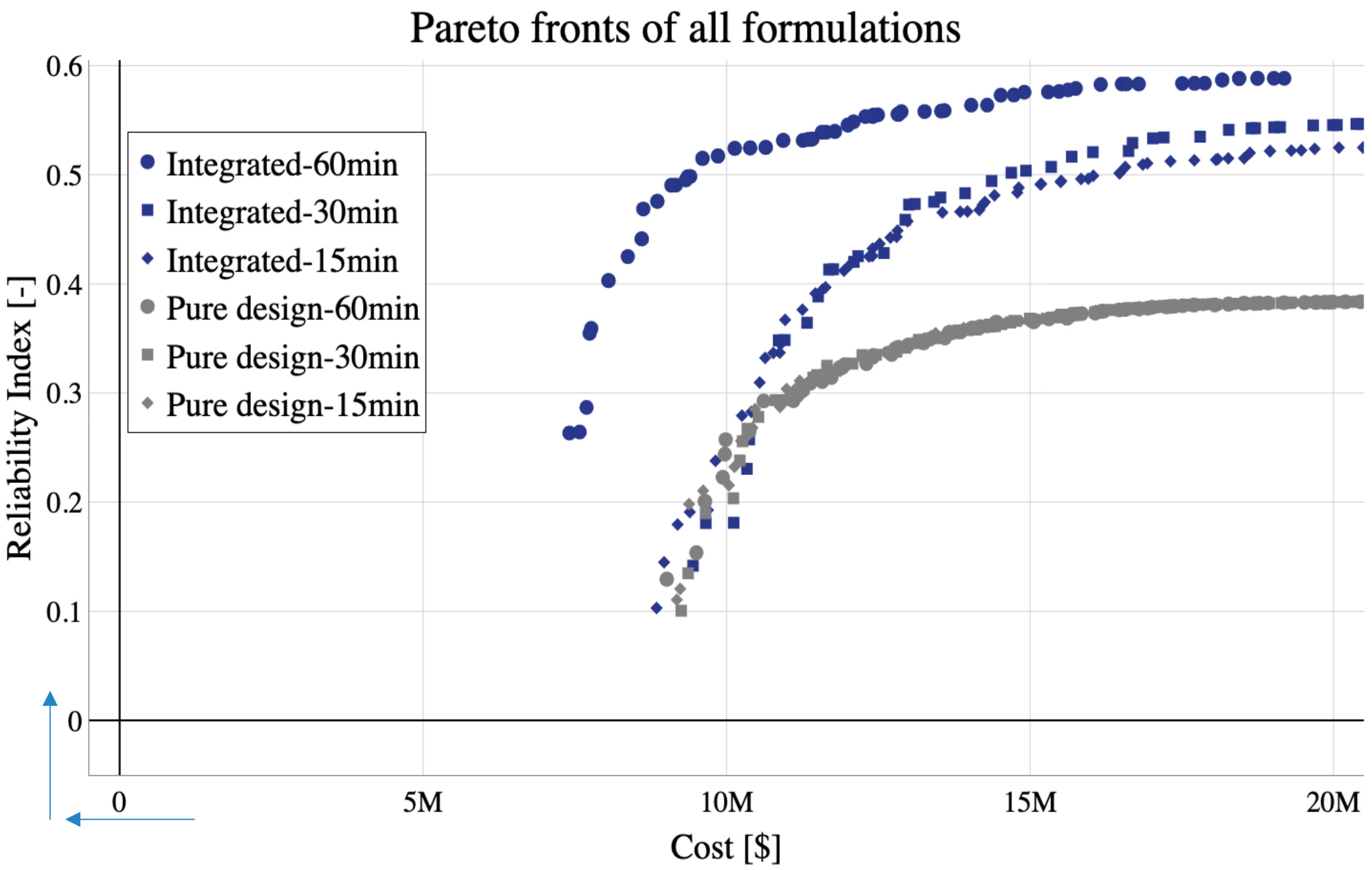
Conclusions

- Joint approaches improve over design-only optimization

- Operations can strongly affect the design optimization process

- The additional degree of freedom from operations is powerful, but it needs careful consideration

The classic timestep for design is not appropriate for operation



The opt algorithm can exploit the EPANET hydraulic timestep and even differences between the hydraulic and reporting timestep.

Material and Contacts

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Source code (WIP)

Zenodo (results)

water futures

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References

Case study:

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- Todini, E. Looped Water Distribution Networks Design Using a Resilience Index Based Heuristic Approach. *Urban Water* **2000**, *2*, 115–122, doi:10.1016/S1462-0758(00)00049-2.

Coding:

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- K. Deb, A. Pratap, S. Agarwal and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," in IEEE Transactions on Evolutionary Computation, vol. 6, no. 2, pp. 182-197, April 2002, doi: 10.1109/4235.996017.
- Biscani et al., (2020). A parallel global multiobjective framework for optimization: pagmo. Journal of Open Source Software, 5(53), 2338, https://doi.org/10.21105/joss.02338

Other:

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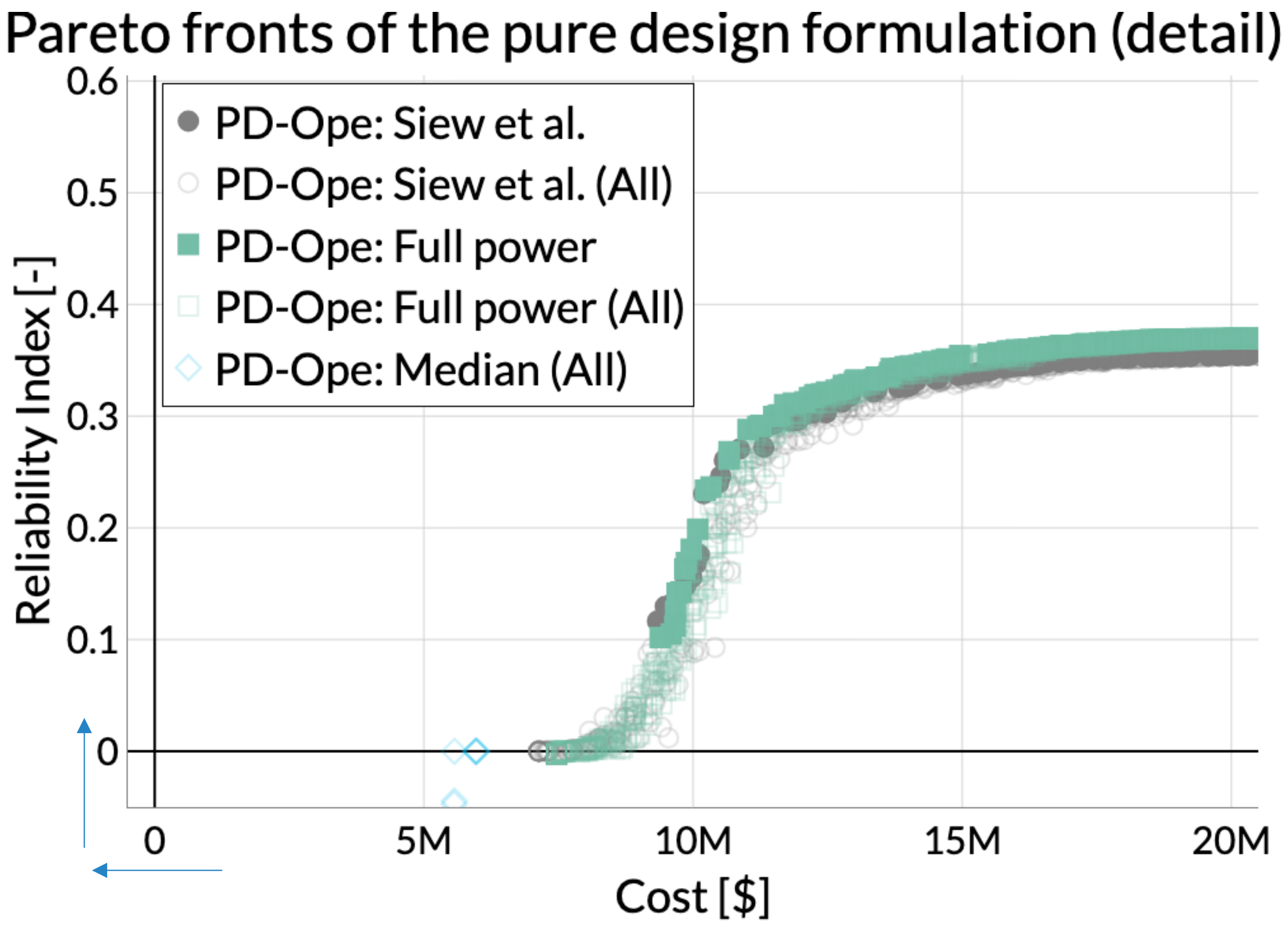
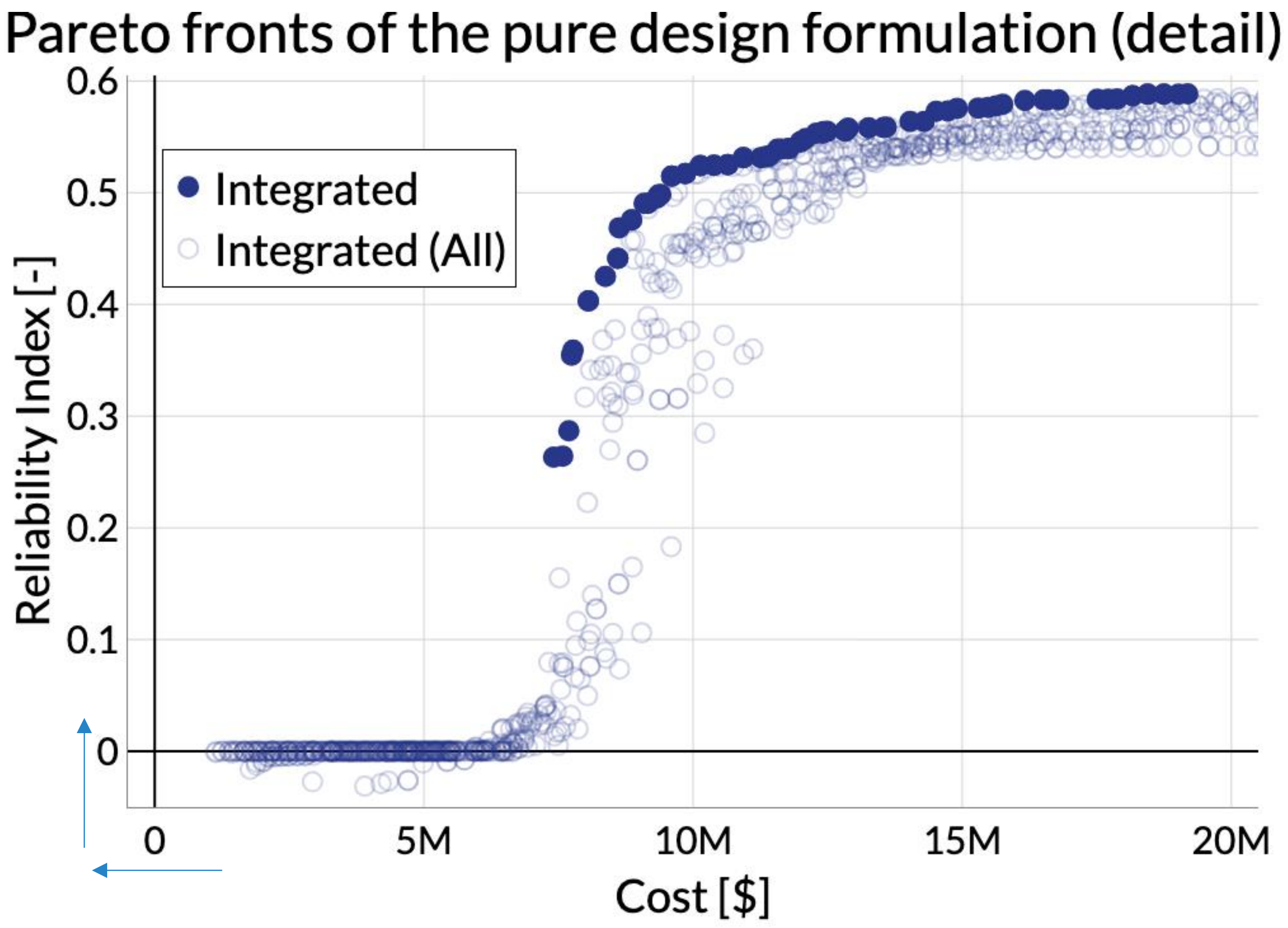
Results- pure design detail-



These are pretty standard results.

Results- integrated detail-

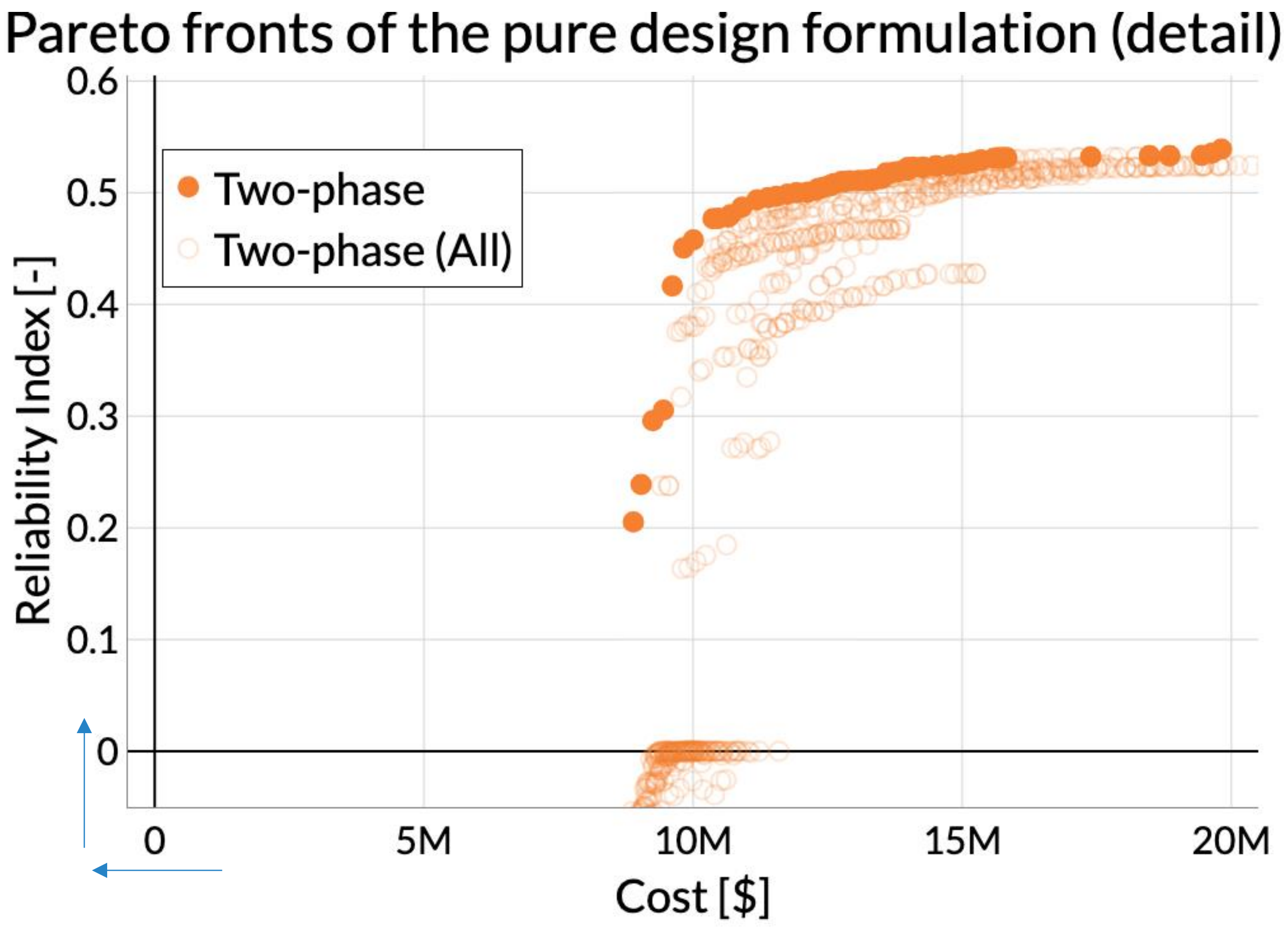


More local optimum.

Big attractor at $I_r = 0$.

Convergence issues.

Results- 2ph looped detail-



Higher stability.

Greater confusion.

Different attractor.