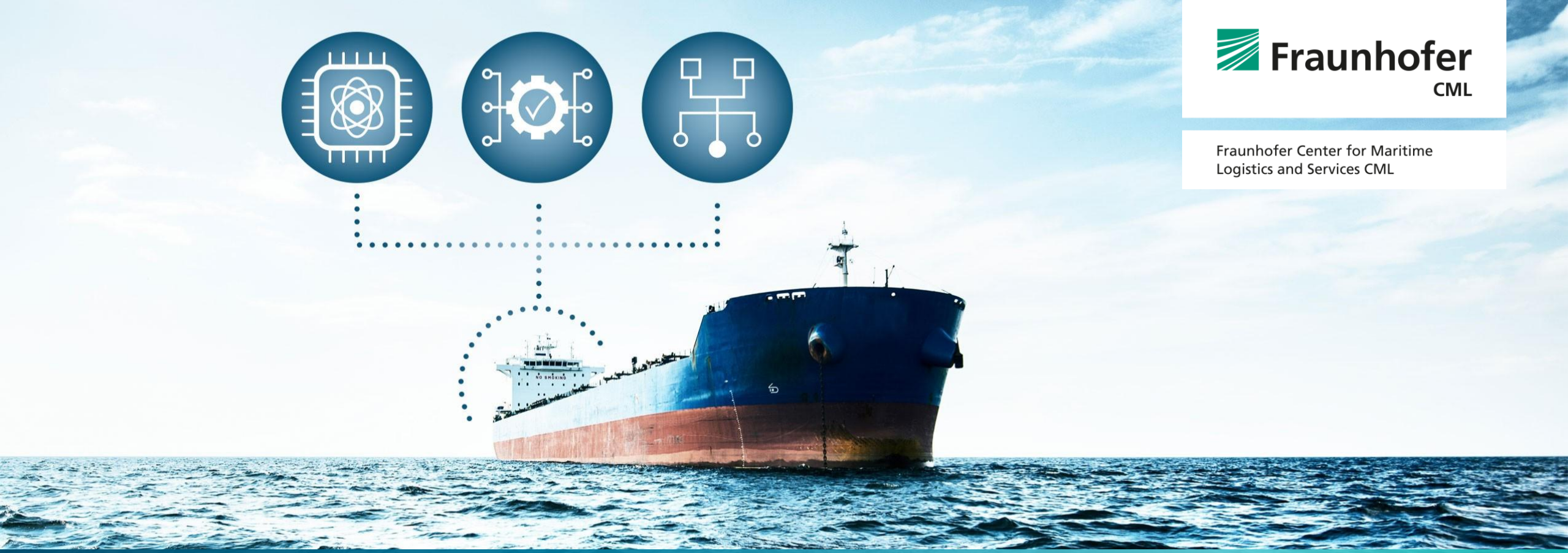

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DECOMPOSITION OF HYBRID OPTIMIZATION PROBLEMS IN MARITIME LOGISTICS

Dr. Valeria Bartsch (presenter), Dr. Anisa Rizvanolli, Oliver Szal, Joshua Dibbern

Fraunhofer CML in Hamburg – Innovating the Maritime Sector

Making shipping, ports and logistics safer, more efficient and more sustainable

Port Development

- Digitalization and AI
- Port Automation
- Hydrogen, Ammonia

Ship Technologies

- Smart Ship Operations
- Autonomous Ship
- Maritime Safety and Security

Logistics Operation

- Process Modeling and Simulation
- Mathematical Optimization
- Quantum Computing

Fraunhofer CML and the maritime industry

Synergies through complementarity

Fraunhofer CML

Realistic models

Potential of Quantum computing for maritime use cases

Insights in research

HARREN GROUP

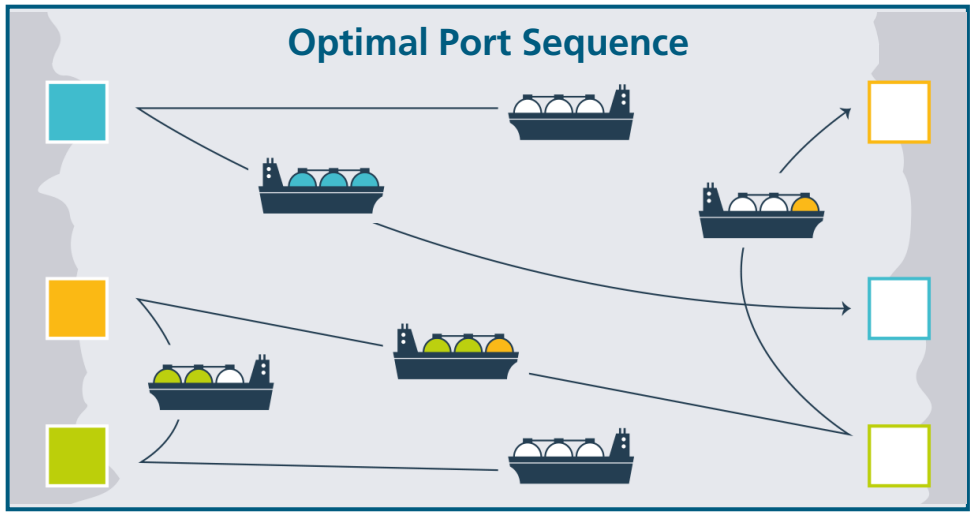
HHLA

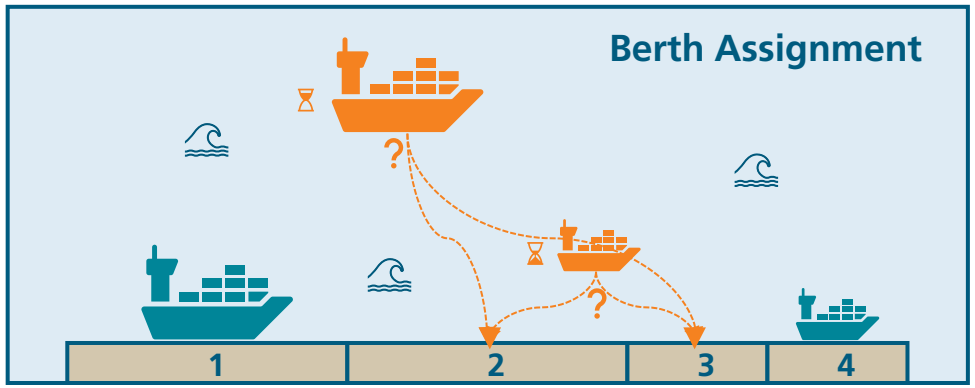
- Mathematical modelling
- Algorithm development
- Quantum and classical

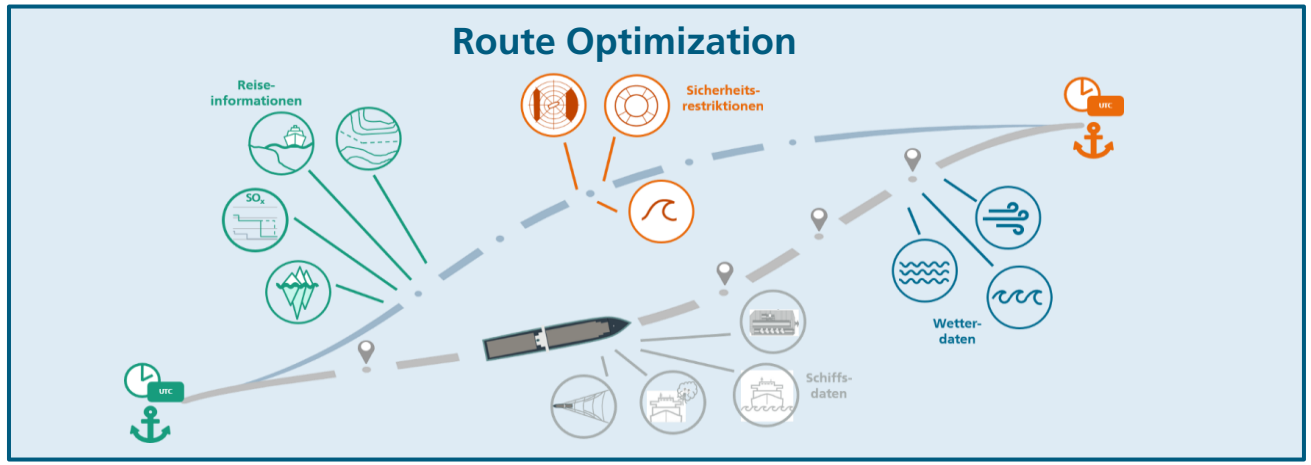
- Shipping and ports
- Use cases
- Scientific insights

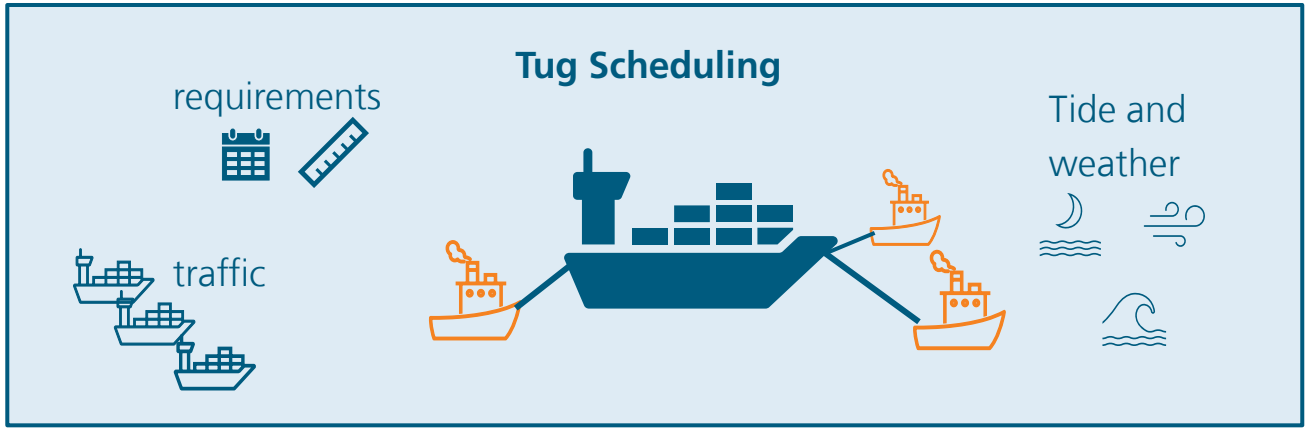
Maritime Use Cases

Combinatorial explosion in high impact operations





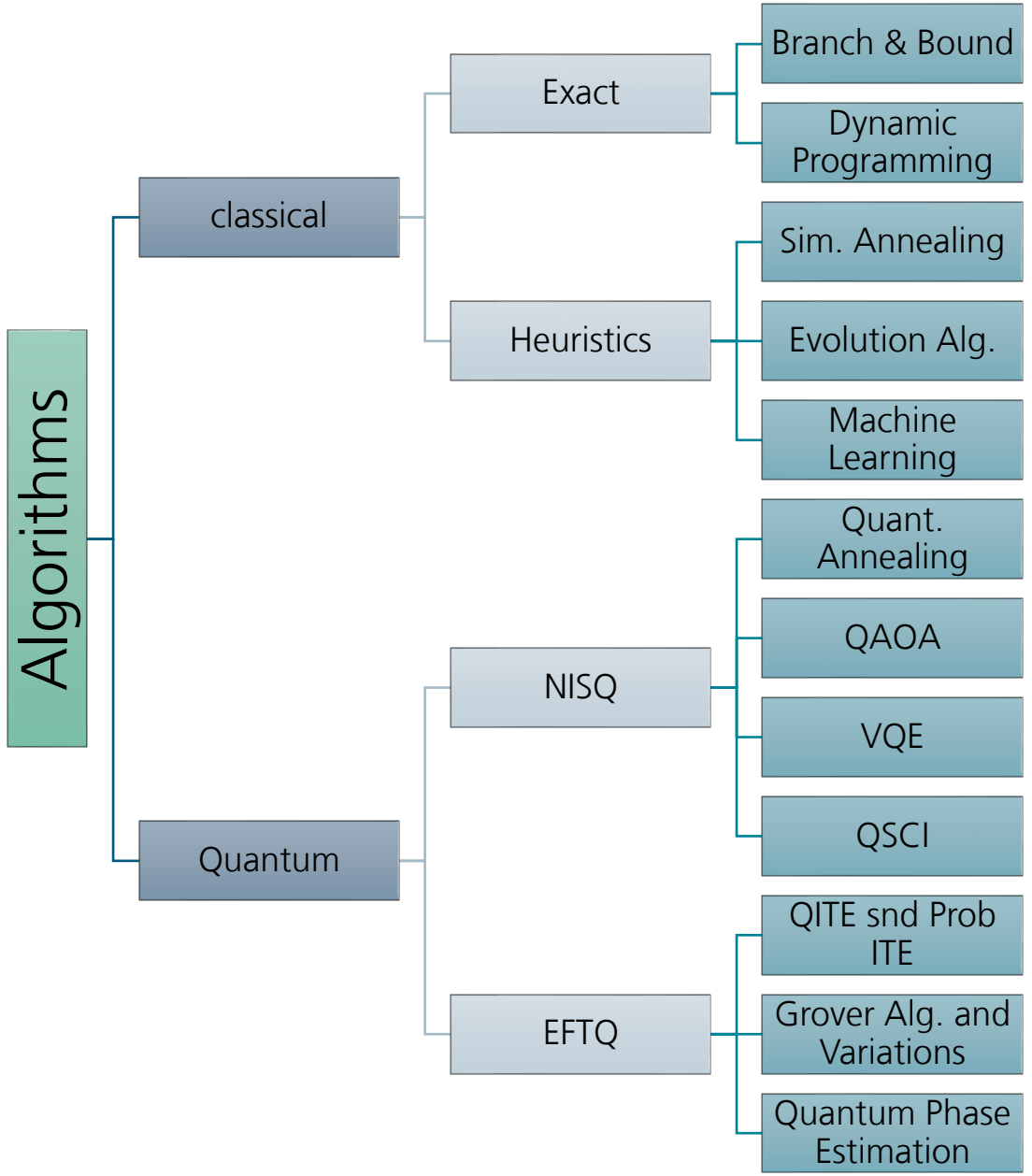




Suitable Algorithms

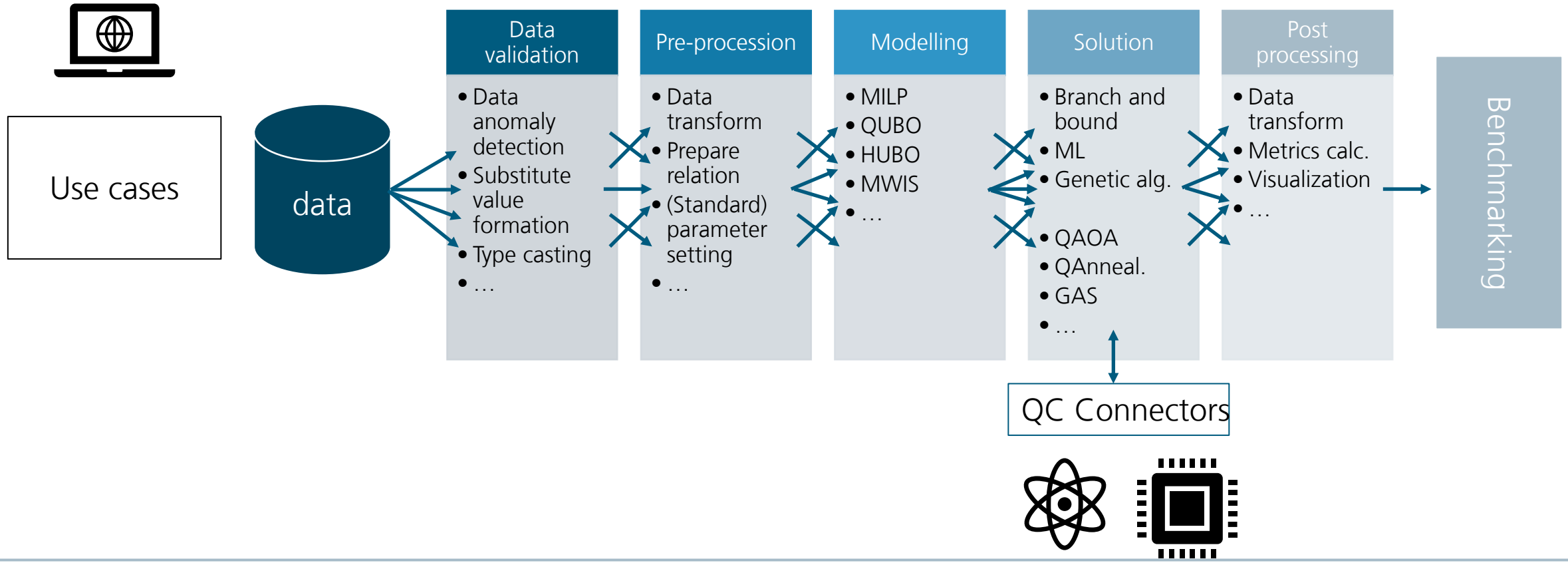
Overview over Algorithms to explore

- Lots of possible optimization algorithms
- In classical world branch and bound commonly used
- In addition to algorithms, a long validation, preprocessing and modelling pipeline necessary



Processing pipeline for optimization problems

Whole pipeline needs to be adapted



Progress in MILP Solvers: How much?

Developments from 2001-2020 with two main intertwined drivers: Hardware & Software

6 orders of magnitude speedup

Hardware development (clock speed & memory bandwidth)

- Move from 32-bit to 64-bit processor (2001)
- Improved optimizing compilers: gcc 2.95 (2001
- More efficient processing of instructions
- New instructions: Fused-Multiply-Add (FMA) and Advanced Vector Extensions (AVX)
- Highly optimized subroutines (e.g. ATLAS, OpenBLAS, or IMK)

Algorithm developments

MILP (Mixed Integer Linear Programming)

- New heuristics: RINS, local branching
- Cutting planes: new/improved cuts (e.g., MCF cuts)
- Tricks and tooling: conflict analysis, symmetry detection, solution polishing, dynamic search
- Trends: exploit problem structure or address specific shortcomings

But hardware development comes to an end

How about QC?

New formulations of optimization problems on current QC hardware

Recipes in the NISQ era:

- MILP problems need to be converted in QC type of solvers (typically QUBOs)
- Modelling and preprocessing needs to be adapted (solutions can be sensitive to modelling)
- Problem sizes are usually too large to be solved on QC, thus problems need to be decomposed

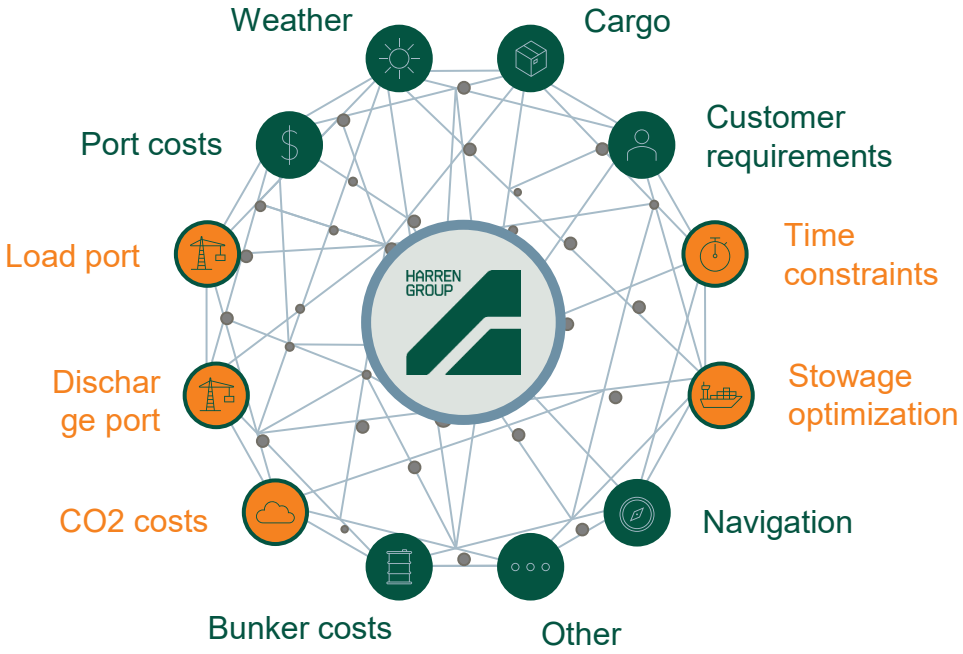
New issues arising:

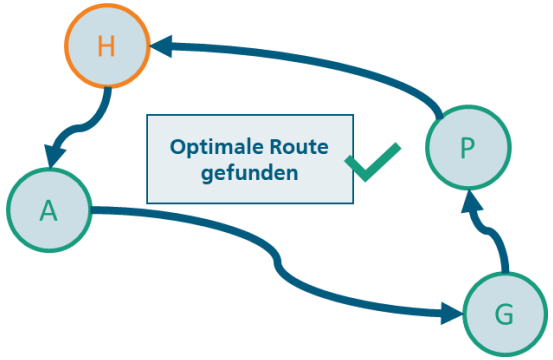
- Experience in modelling usual classical MILP problems not easily transferred to QUBOs
- Taking hybrid to the next level by decomposing problems

Checking if classical decomposition methods can help to port larger QC optimization problems

Cargo Routing for Bulkshipping

Goal: find optimal route and speed for minimal fuel consumption





Starting situation:

- Bulk carrier with a depot (home port)
- A set of ports that must be visited exactly once
- Consider time constraints arising form port availability
- Contractual delivery times and tidal restrictions

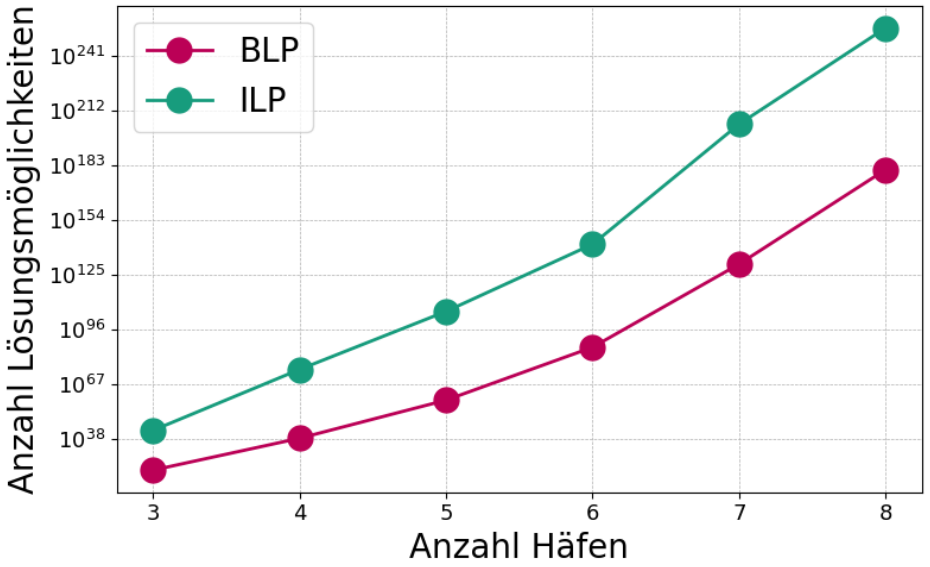
Task:

- Route optimization considering bunker and CO2 costs
- Shortest path vs. fuel consumption

Modelling Optimization Problems

Solution is sensitive to modelling

- Main approach
  - Discretize vessel velocity and foreach velocity
  - Solve with quantum annealing the problem of finding the shortest way to visit all ports within the given timeframes (Traveling Salesman Problem with Time-Windows)
  - Compare classically the solutions for all velocities and pick the best one
- In more detail:
  - TSPTW as MILP (for classical simulation)
  - TSPTW as QUBO (for quantum simulation)
- Scaling behavior strongly dependent on the model:
  - Dense structure of QUBO and logarithmic encoding of integers
  - Generates rugged energy landscape
  - Reduces the probability to reach group state efficiently



time to solution on quantum computers is modelling sensitive

Hybrid Computing: Benders Decomposition

Solving large-scale optimization problems by Divide & Conquer

Use Cases

- Route planning, port optimization,…
- *Facility Location Problem*

The Master problem

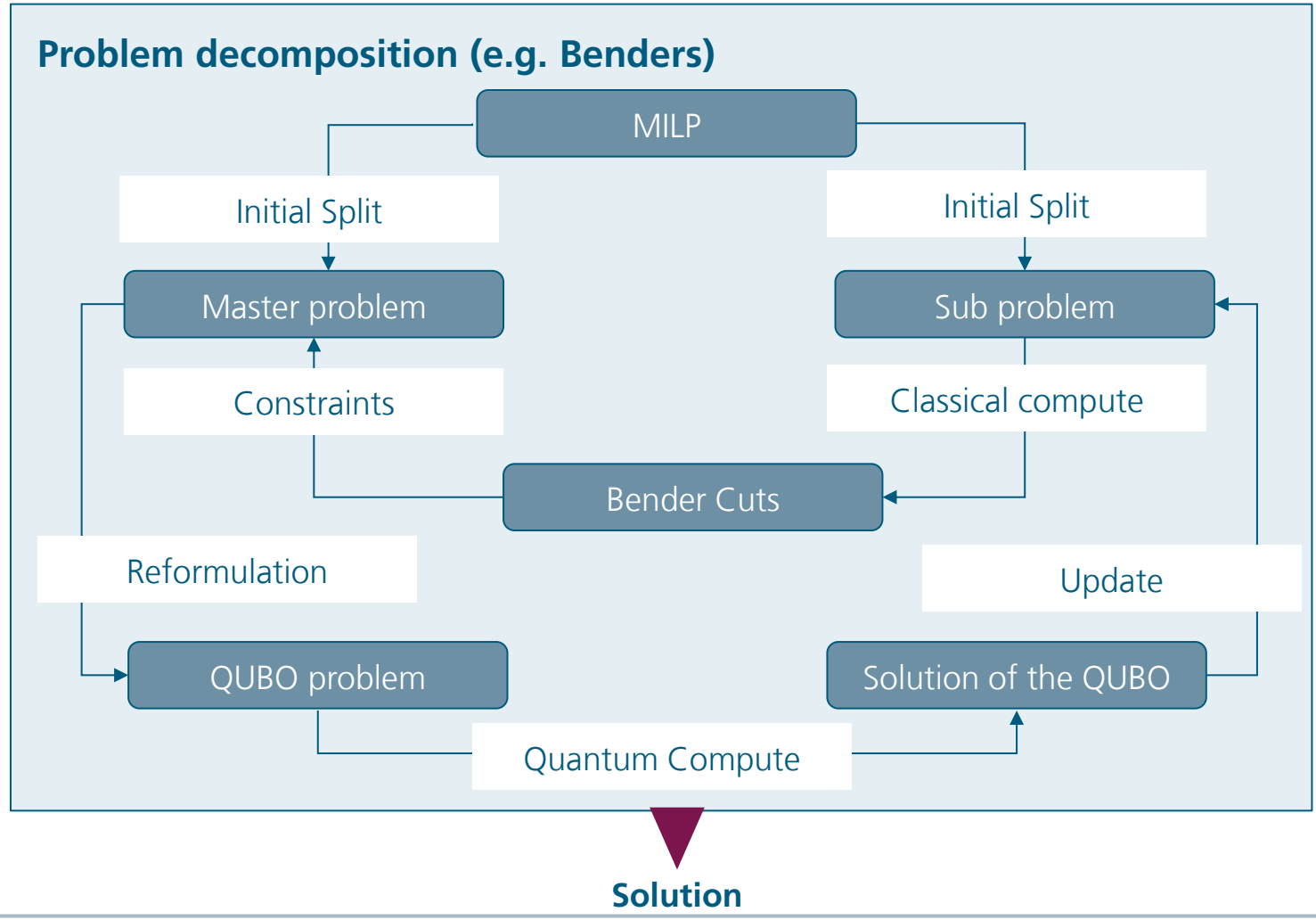
- Contains the harder, integer variables
- Often: fixed costs

The Sub problem

- Variable costs dependent on the decision in the Master Problem

With Quantum Computing?

- Hybrid algorithm: solves master problem with quantum computing and sub problem on classical computer

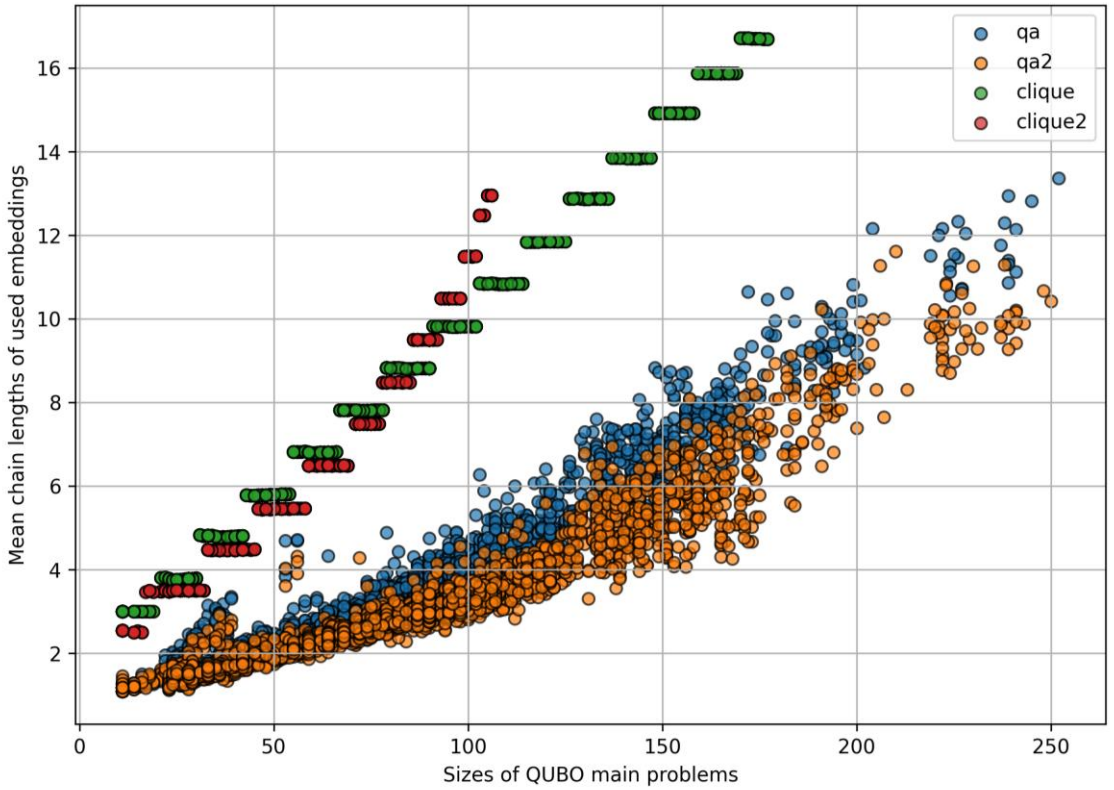


Hybrid Benders for Cargo-Routing

Qubit embeddings

- In addition to modelling Qubit Embeddings also play a role
- Here shown for Quantum Annealer (but similar logic applies for gate-based machines)

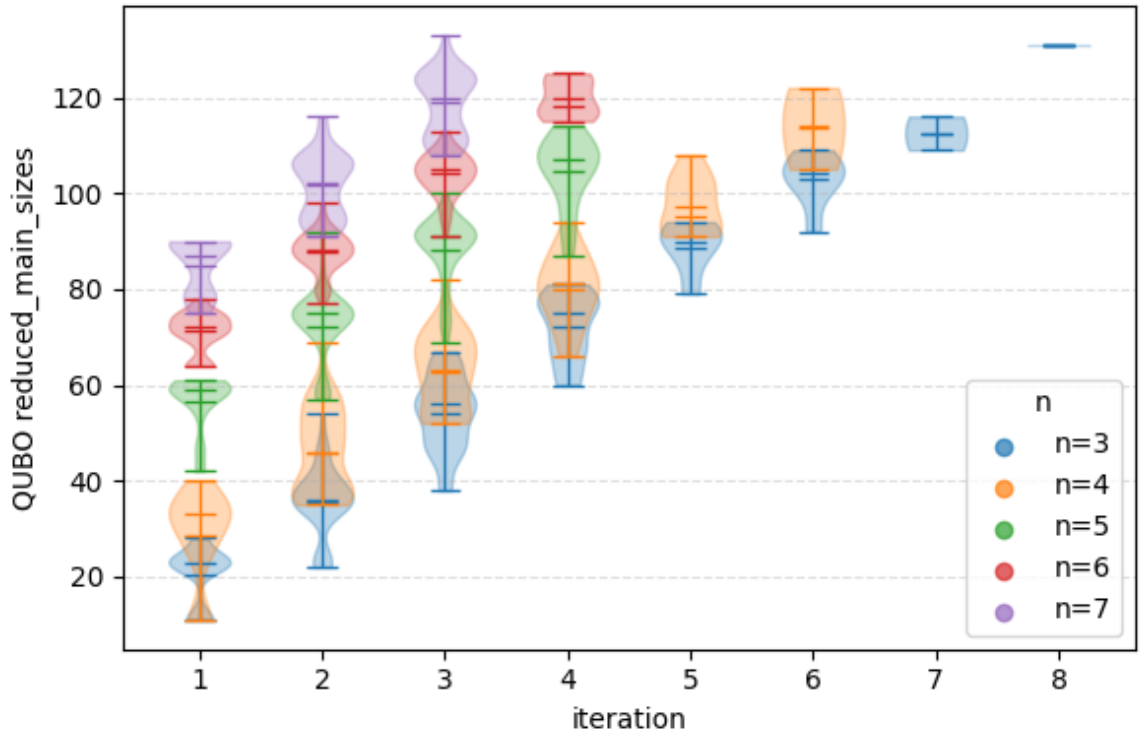
Still need to optimize and not rely on defaults due to small-scale machines



Hybrid Benders for Cargo-Routing

Decomposition allows to run larger problems with QC

- Benders decomposition allows for larger problems to be simulated
- Benders decomposition has effect that QUBO size increases for each iteration
- For small problem sizes only few iterations necessary (limitations due to NISQ era)
- Bigger problem sizes quickly can not be ported to a real machine



Size of QUBO for each iteration and different problem sizes n for runs with Clique embeddings

Decomposition important tool for optimization (also in QC) to compute realistic problems

Need to find best way for decomposition yet

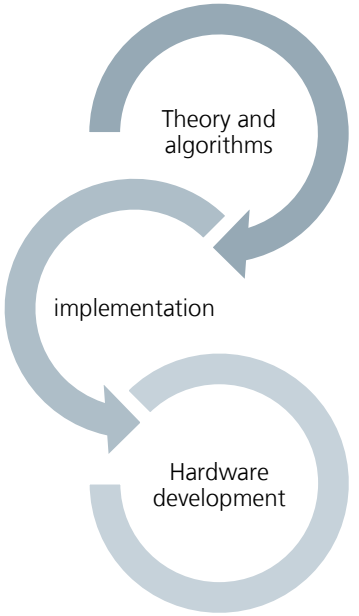
Relevance of a holistics Ansatz

Applications <-> Algorithms <->Hardware

1

Strenghten the **interplay of hardware- and software** development

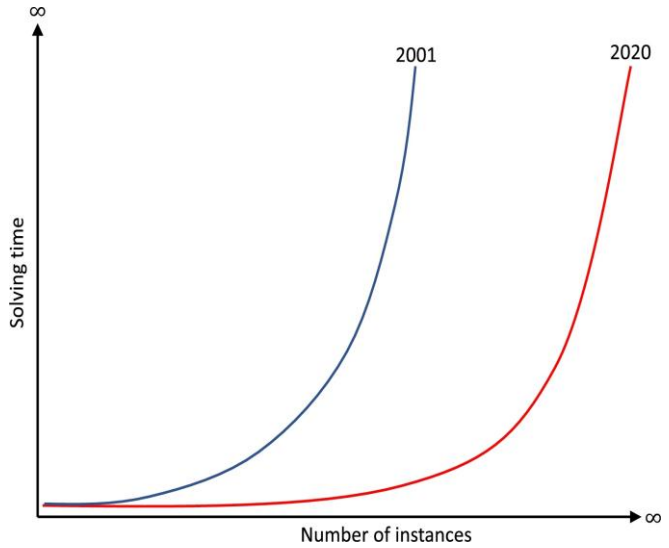
- Minimize the gap between between newest hardware and using it for industrial use cases
- Use **decomposition** in order to utilize expensive and limited QC resources as early as possible



2

Strong dependence of the solution performance from the modelling in QC (as in classical operation research in the 80ies)

- Smart Formalisation necessary
- **Development of new algorithms**



On classical systems

3

QC & classical compute for real problems in hardware and algorithms:

- **Interplay between domain knowledge and methodological expertise** important for resource utilization
- **Heuristics** inevitable: interdisciplinary collaboration with industry

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Contact

Dr. Valeria Bartsch
Tel. +49 40 2716461-1465
Valeria.bartsch@cml.fraunhofer.de