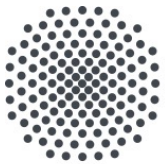
Quantum Hardware Selection



University of Stuttgart

Marie Salm

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Institute of Architecture of Application Systems

Supported by:

Federal Ministry
for Economic Affairs
and Climate Action

on the basis of a decision
by the German Bundestag

About Me

- Marie Salm, 28
- B.Sc. & M.Sc. in computer science
- Ph.D. candidate & research associate
  - @ IAAS of Frank Leymann, University of Stuttgart
  - Since December 2019
  - Project PlanQK
- Research topic: NISQ Analyzer *(see next slides)*

https://www.iaas.uni-stuttgart.de/en/institute/team/Salm/

Tutorial Structure

- Session 1 (09:00 - 10:30): An Introduction to Quantum Computing
- **Session 2 (11:00 - 12:30): Quantum Software Engineering**
  - Quantum software development lifecycle
  - Quantum hardware selection
  - Q/A session
  - Outlook to the afternoon sessions
- Session 3 (14:00 - 15:30): Quantum Workflows
- Session 4 (16:00 - 17:30): Operation of Hybrid Quantum Applications

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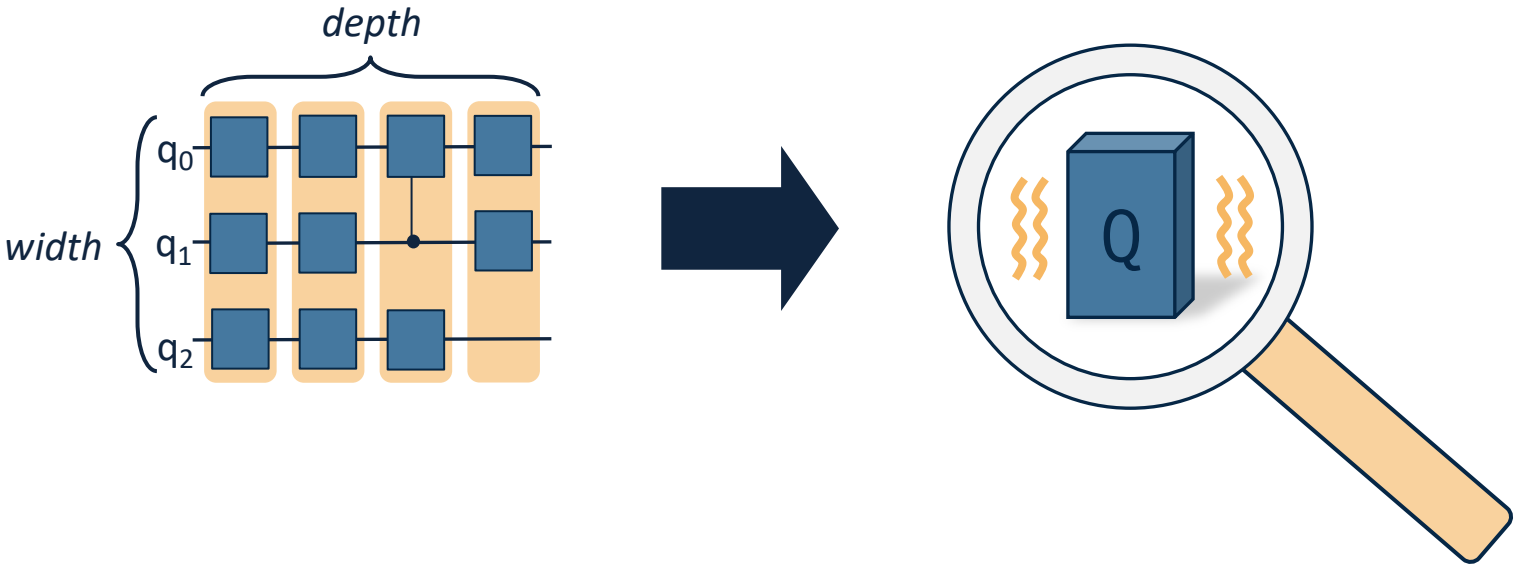
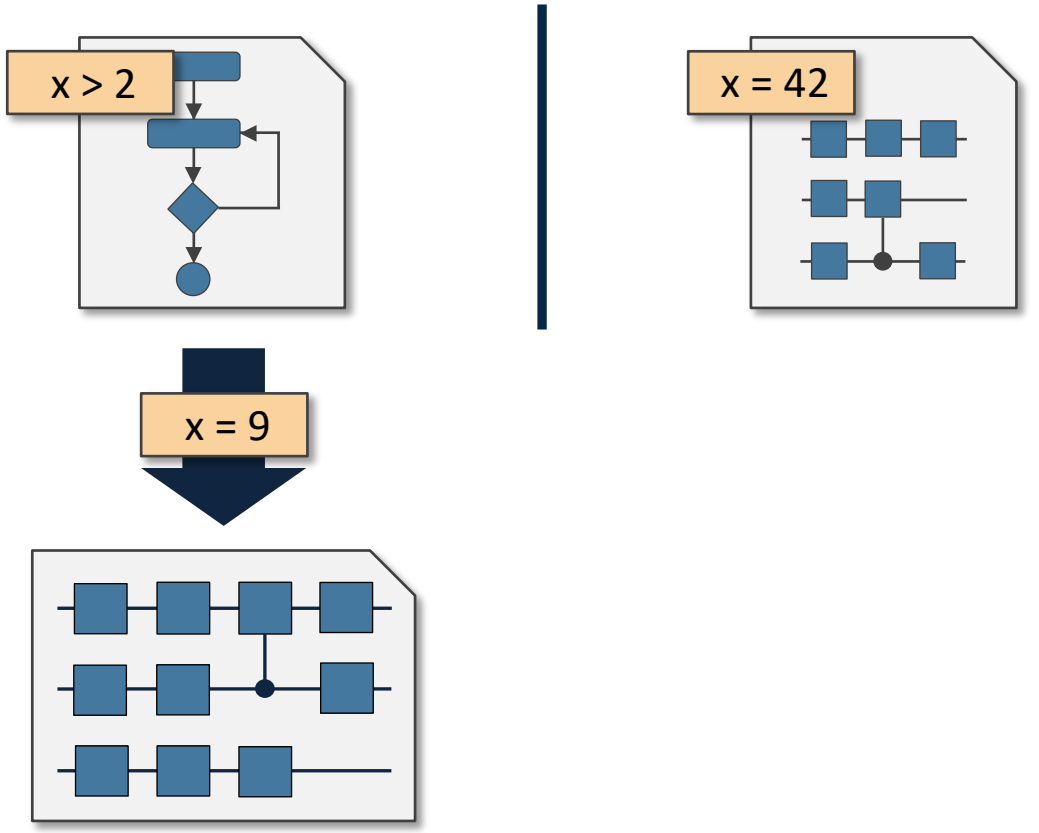
The NISQ Problem

- Currently in **N**oisy **I**ntermediate-**S**cale **Q**uantum era
  - Small number of qubits, high error rates
  - ➢ Limits width & depth of quantum circuits
  - ➢ Design circuits as **resource efficient** as possible



Quantum Implementations

- Varying **implementations** of quantum algorithms
  - Restrictions in input values



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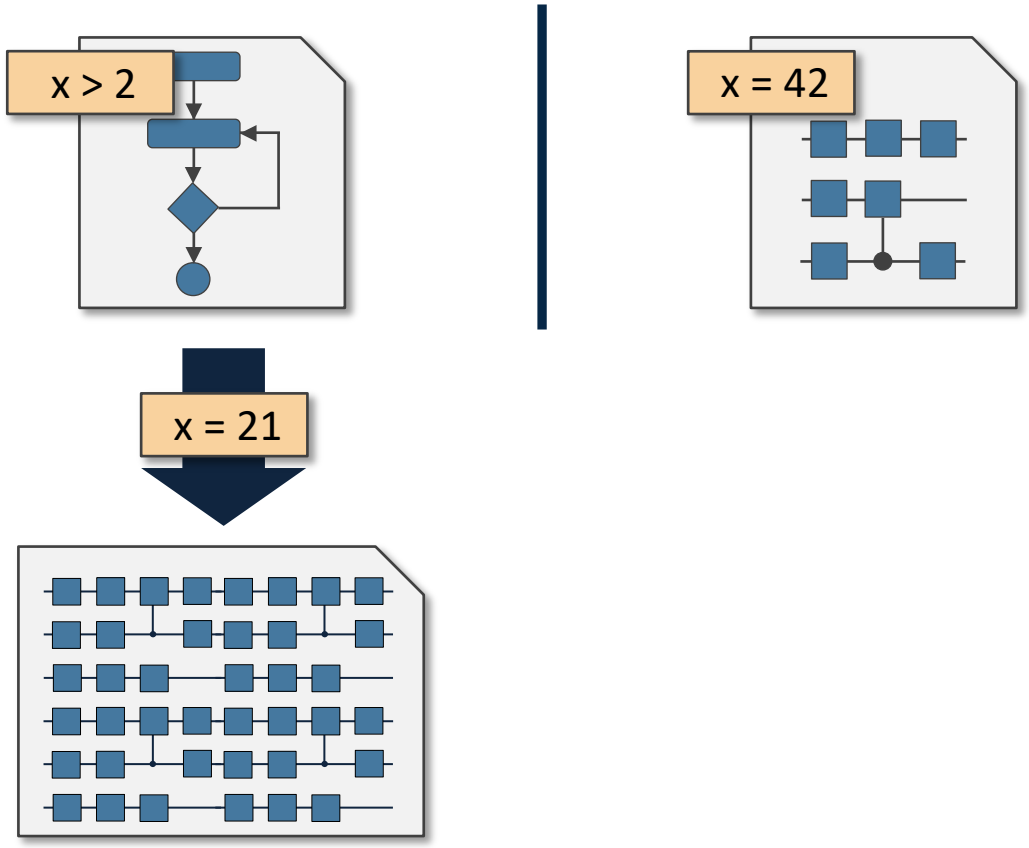
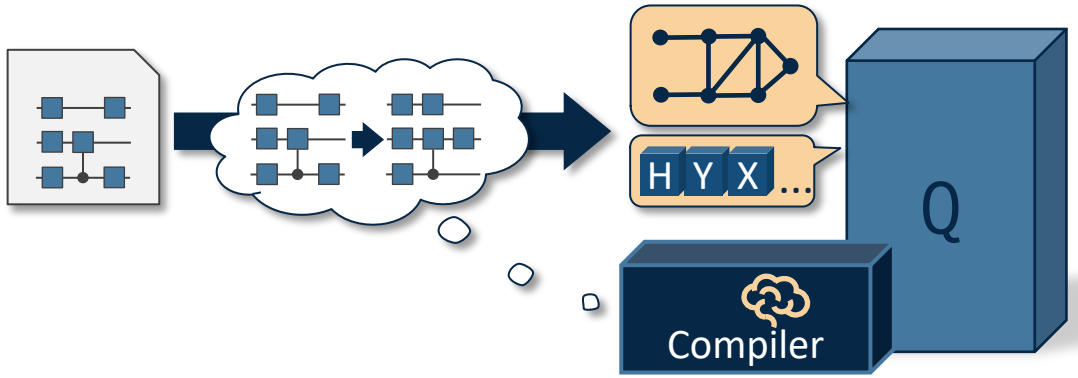


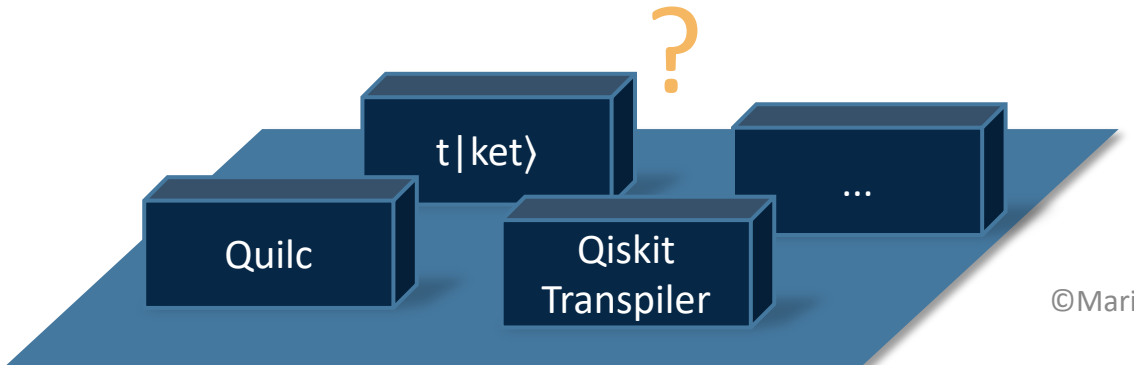
  - Resulting **circuit size** depends on **input**

Influencing Circuit Size

- **True size** of circuit depends on
  - Qubit topology
  - Implemented gate set
  - Mapping & optimization by compiler

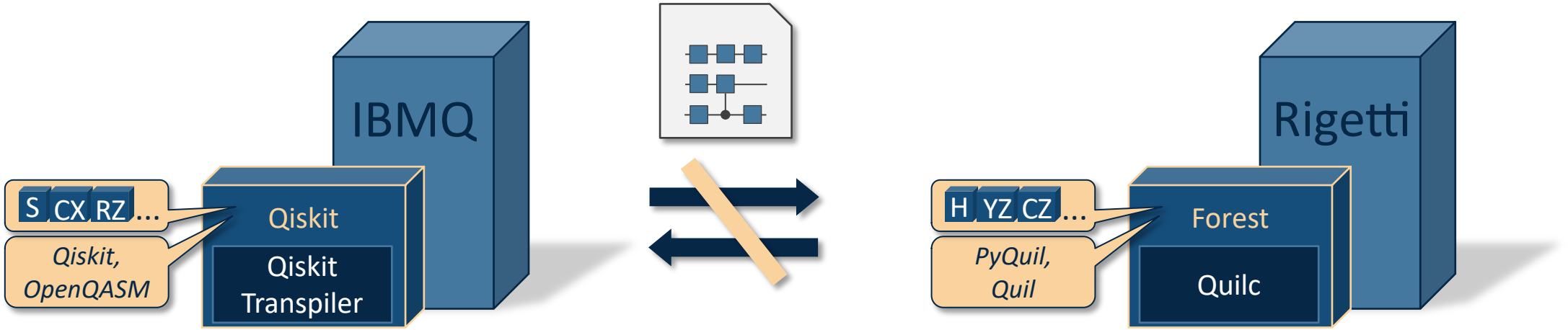


- **Variety** of quantum compilers exists
- Given a circuit: which compiler delivers "**best" compilation result**?
- Comparison is required ...



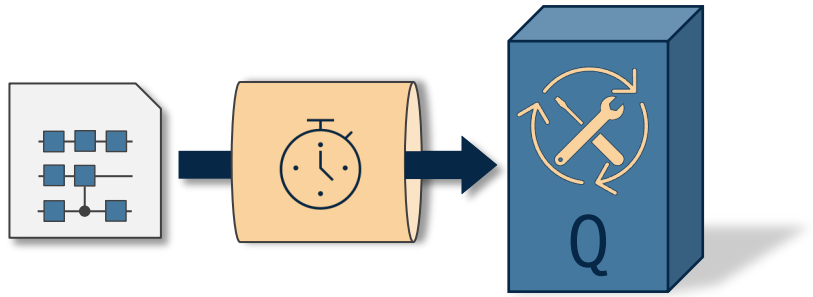
Usage of Quantum Compilers

- Most compilers **accessible via SDKs** differing in
  - Gate sets
  - Programming languages
  - Vendors of QPUs



In Addition ...

- QPUs are regularly re-calibrated
  - Changes in error rates
- Cloud providers regulate computing access
  - Resulting in waiting times
- Execution of quantum algorithm
  - Implementation
  - SDK
  - QPU
  - Compiler
  - Access regulations

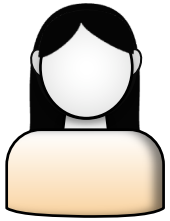


*"How can the **selection** of quantum algorithm **implementations** & **suitable quantum resources** be **automated** based on the **input data** of the chosen algorithm & the **user's needs**?"*

The Vision

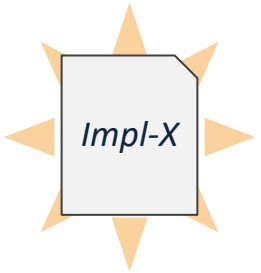
Vision

Factorizing

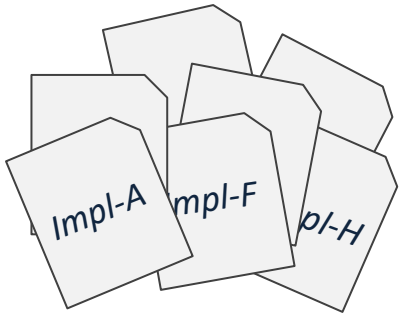


N = 144

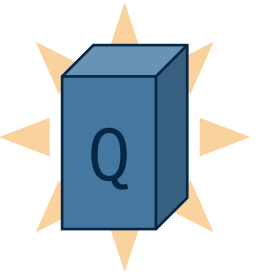
Shor!



✓ *144*

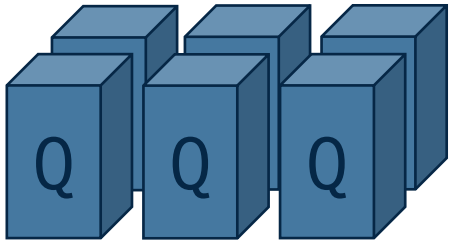


+

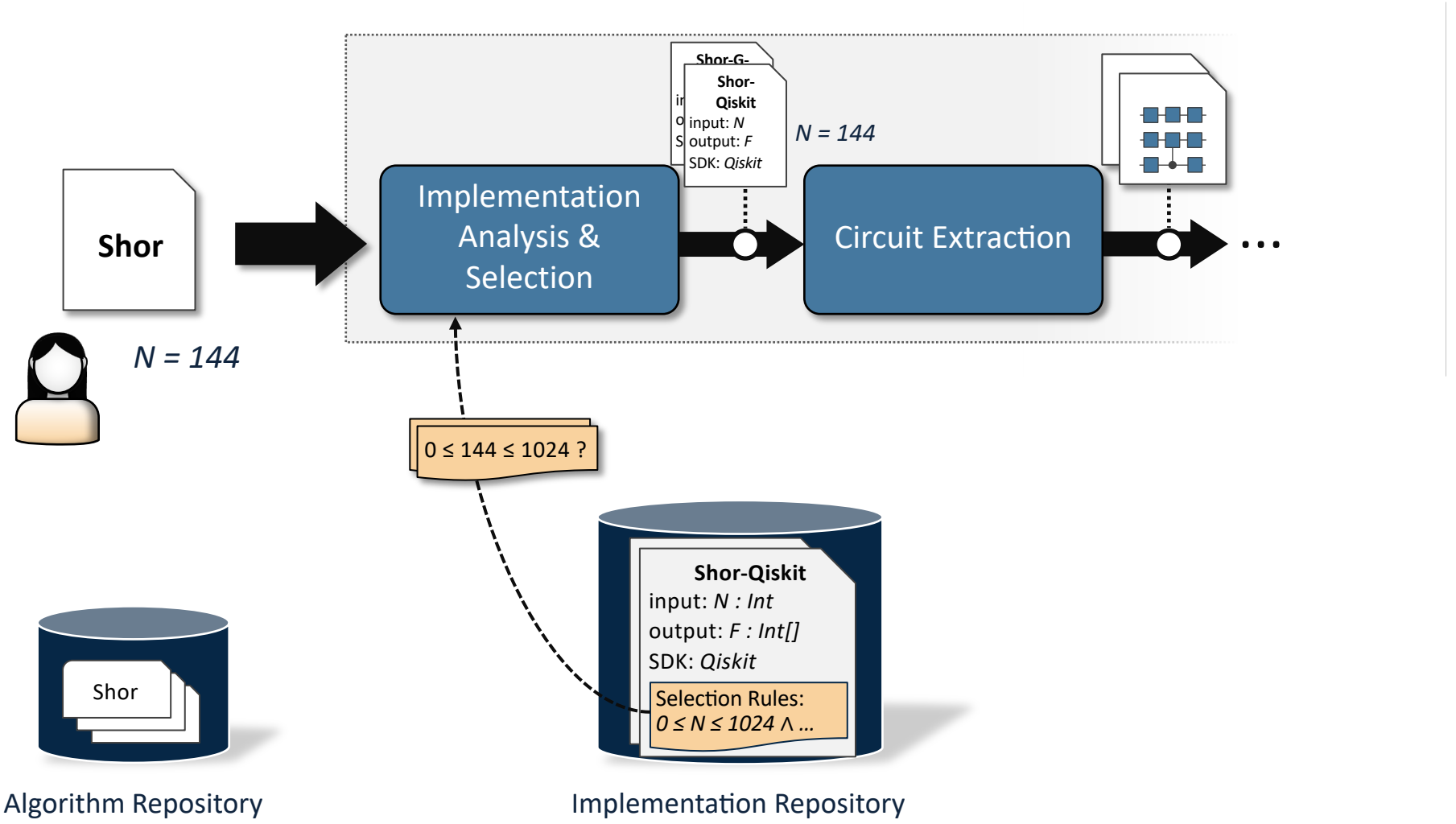


enough

- ✓ *qubits*
- ✓ *decoherence time*
- ✓ *…*

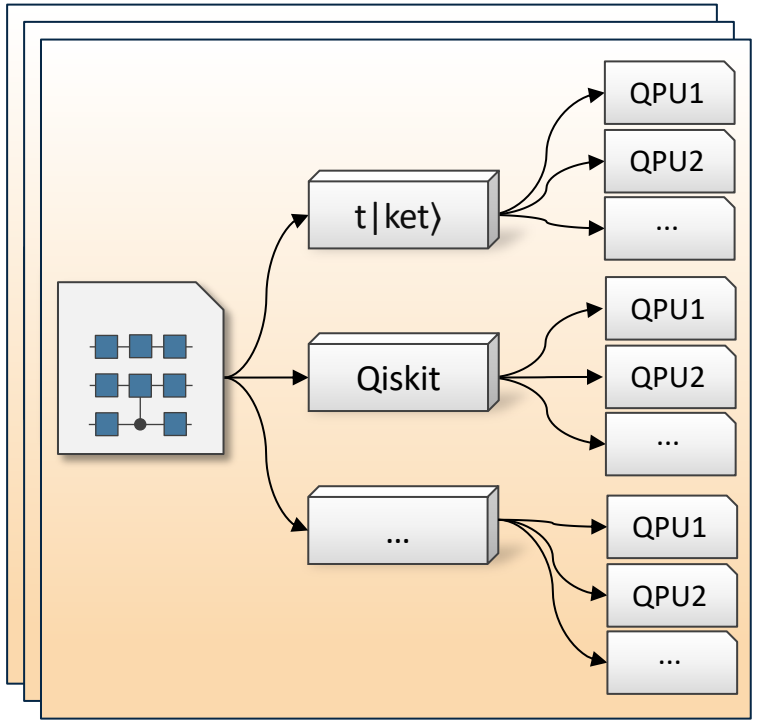


Selection of Quantum Implementations



Salm, Marie; Barzen, Johanna; Breitenbücher, Uwe; Leymann, Frank; Weder, Benjamin; Wild, Karoline: The NISQ Analyzer: Automating the Selection of Quantum Computers for Quantum Algorithms. In: Proceedings of the 14th Symposium and Summer School on Service-Oriented Computing (SummerSOC 2020), Springer International Publishing, 2020.

Estimation of Quantum Resources



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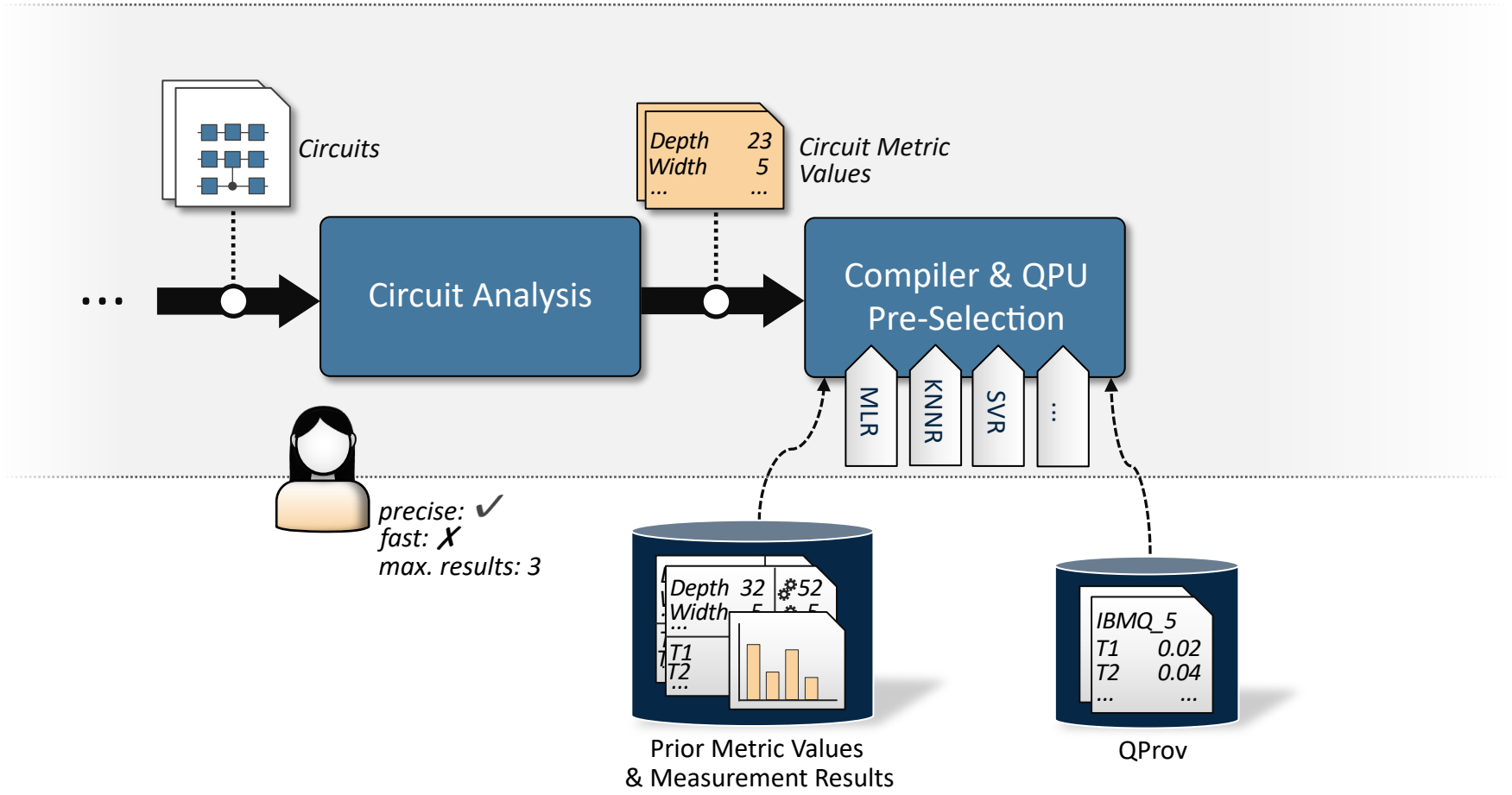

Salm, Marie; Barzen, Johanna; Leymann, Frank; Wundrack, Philipp: How to Select Quantum Compilers and Quantum Computers Before Compilation. In: Proceedings of the 13th International Conference on Cloud Computing and Services Science (CLOSER 2023), SciTePress, 2023.

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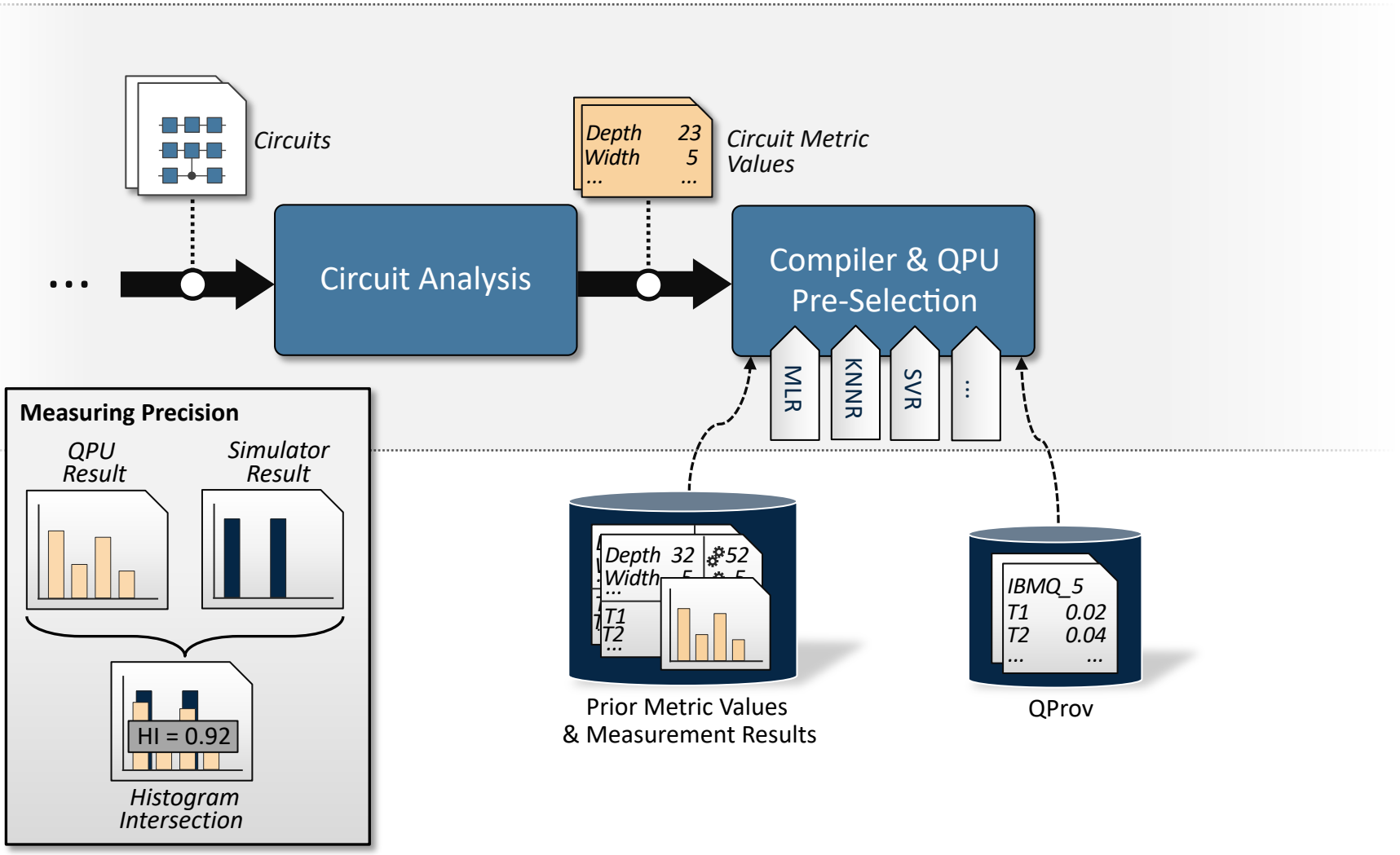

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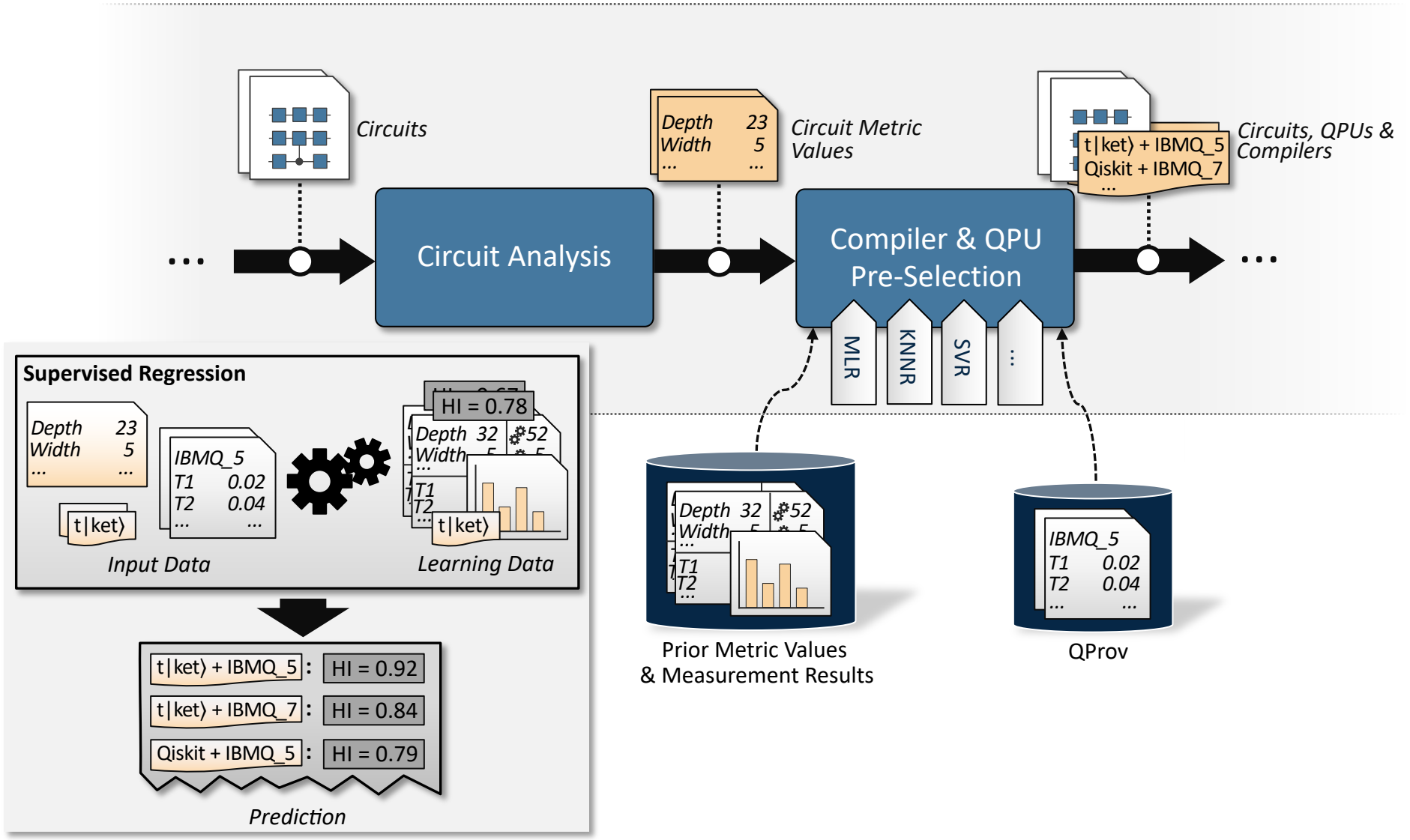

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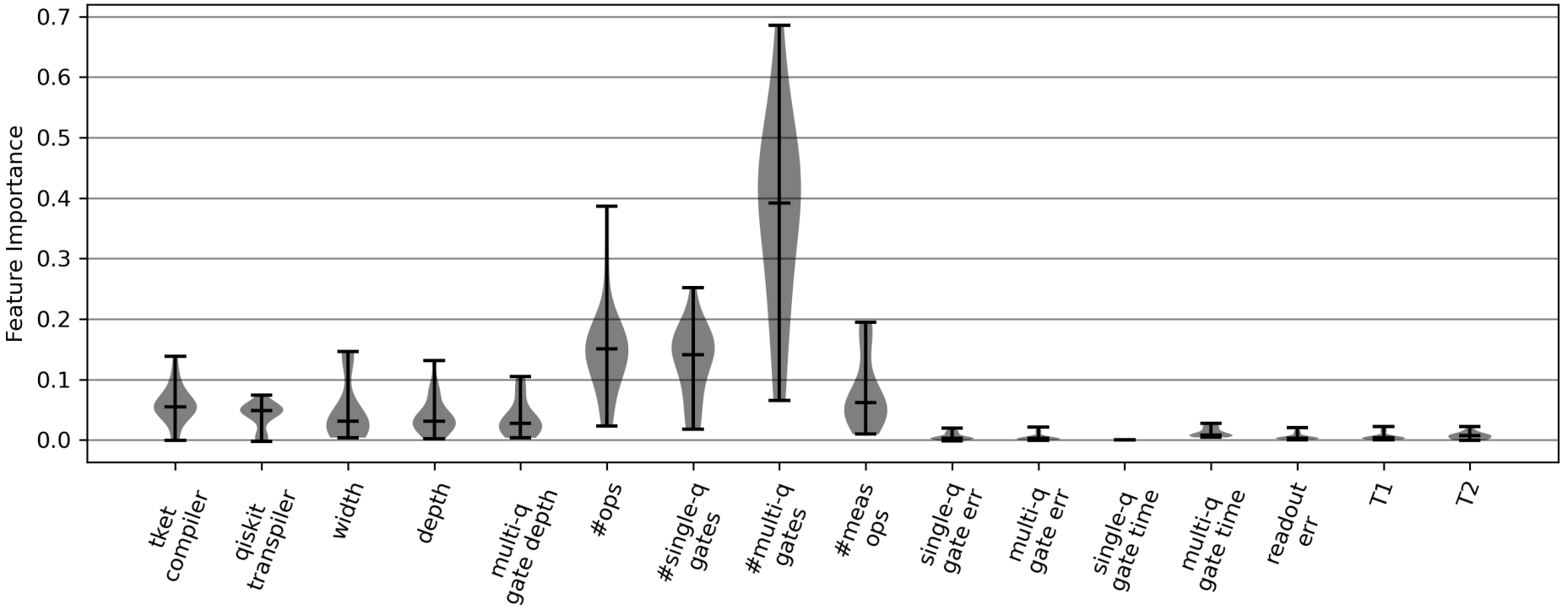
Case Study – Setup

- IBMQ 5-qubit QPUs & simulator
- Qiskit transpiler & t|ket⟩ compiler
- 52 input circuits
  - 3 algorithmic circuits
  - randomized circuits with Clifford gates
  - ➢ 229 compiled & executed circuits

- support multiple variants of ML algorithms
  - decision trees
  - SVR
  - KNN regression
  - multiple linear regression

Case Study: Influence of Metrics



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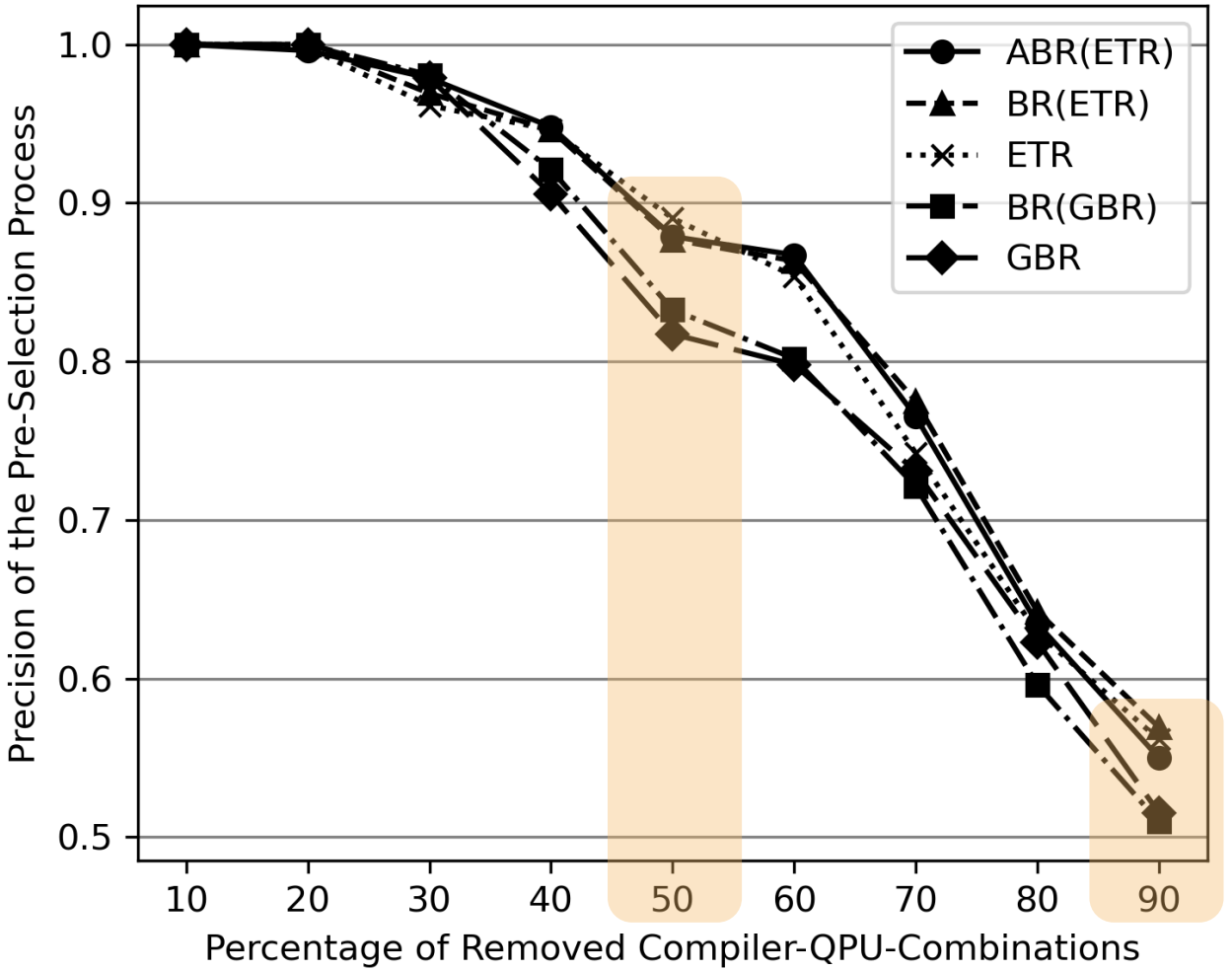
Case Study: Precision of Pre-Selection



meta estimators:
ABR: Ada Boost Regressor
BR: Bagging Regressor

regression algorithms:
ETR: ExtraTreesRegressor
GBR: Gradient Boosting Regressor

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Case Study: Runtime Analysis

Table 1: Median runtimes of our approach removing various percentages of compiler-QPU-combinations (in seconds).

Circuit	0%	50%	70%	90%
Gr3	84.34	51.72	42.01	31.56
RC4	108.80	63.05	51.49	39.32
RC5	109.81	65.65	54.39	42.88

40% faster

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51% faster

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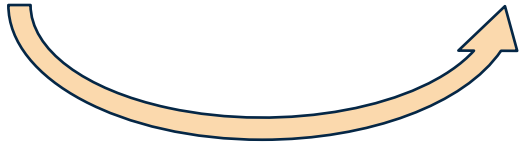

62% faster

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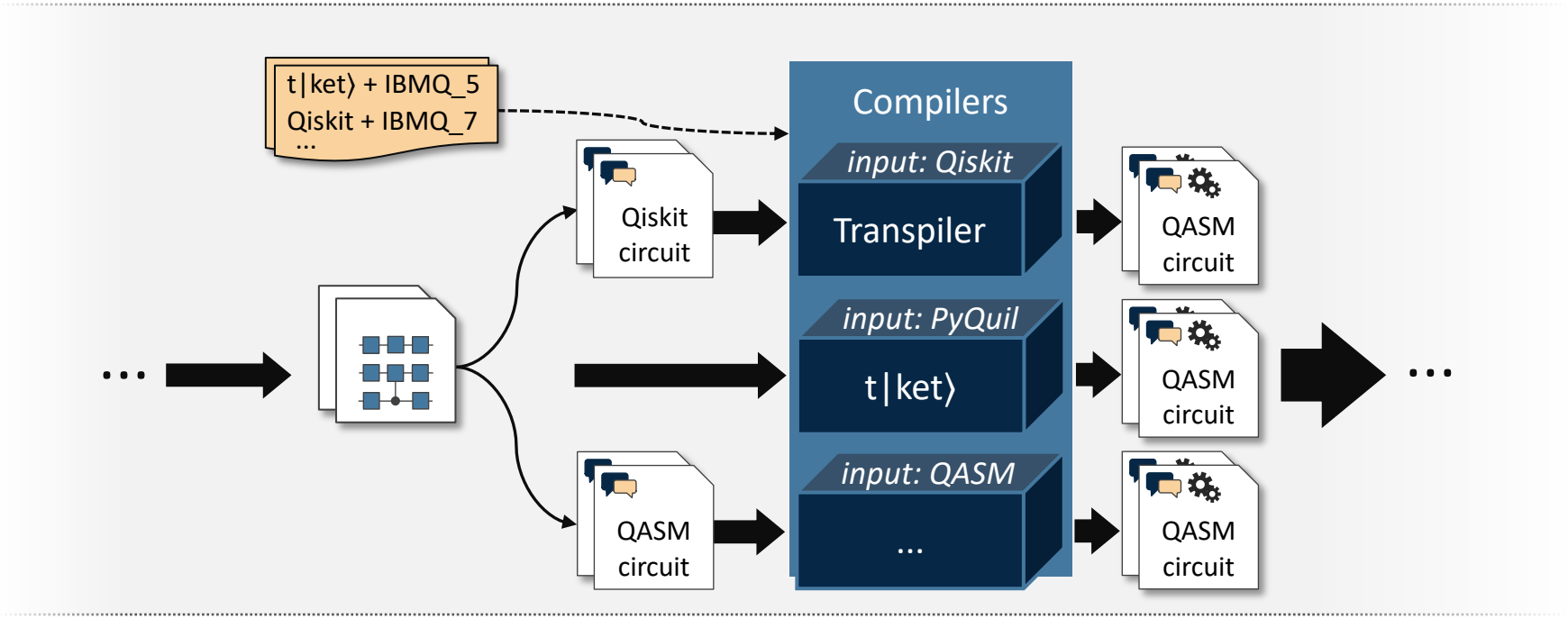
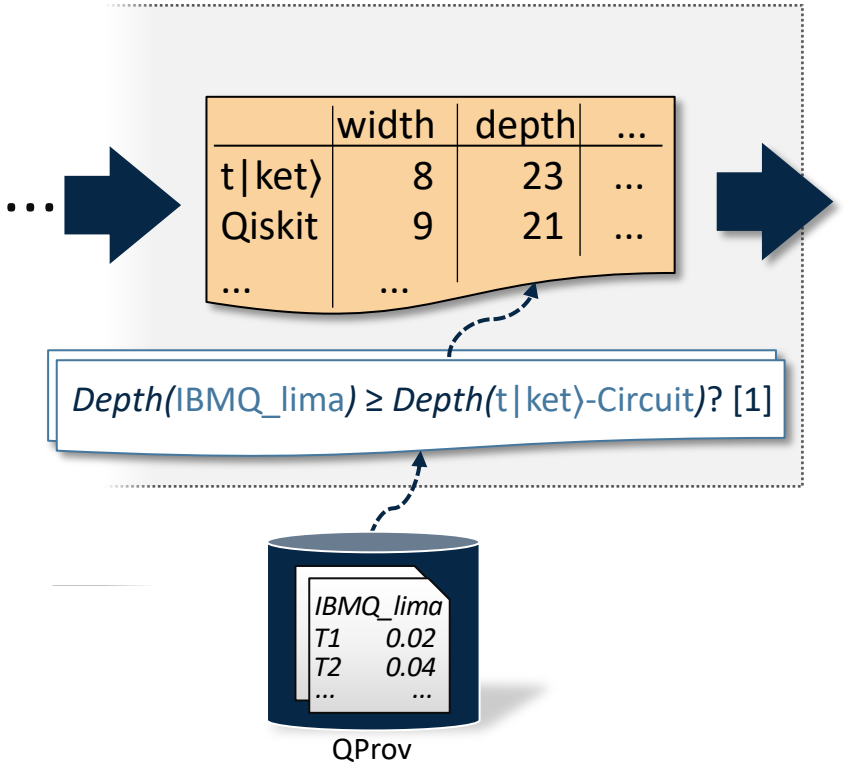
Translation & Compilation of Quantum Circuits



Salm, Marie; Barzen, Johanna; Leymann, Frank; Weder, Benjamin; Wild, Karoline: Automating the Comparison of Quantum Compilers for Quantum Circuits. In: Proceedings of the 15th Symposium and Summer School on Service-Oriented Computing (SummerSOC 2021), 2021.

Analysis of the Executability of Compilation Results



Backend Name	Provider	SDK	Width	Depth	Multi-Qubit Gate Depth	Total Number of Operati
ibmq_qasm_simulator	ibmq	pytket	3	14	6	21
ibmq_bogota	ibmq	pytket	3	27	9	45
ibmq_bogota	ibmq	qiskit	3	30	13	51
ibmq_lima	ibmq	pytket	3	27	9	45

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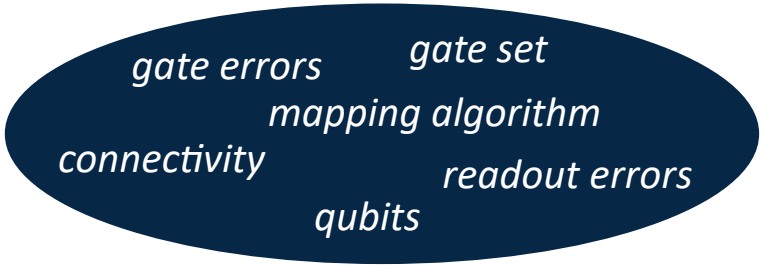
- Salm, Marie; Barzen, Johanna; Leymann, Frank; Weder, Benjamin: Prioritization of Compiled Quantum Circuits for Different Quantum Computers. In: Proceedings of the 2022 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER 2022), IEEE, 2022.
- Weder, Benjamin; Barzen, Johanna; Leymann, Frank; Salm, Marie; Wild, Karoline: QProv: A provenance system for quantum computing. In: IET QuantumCommunication. Vol. 2(4), Wiley Online Library, 2021.

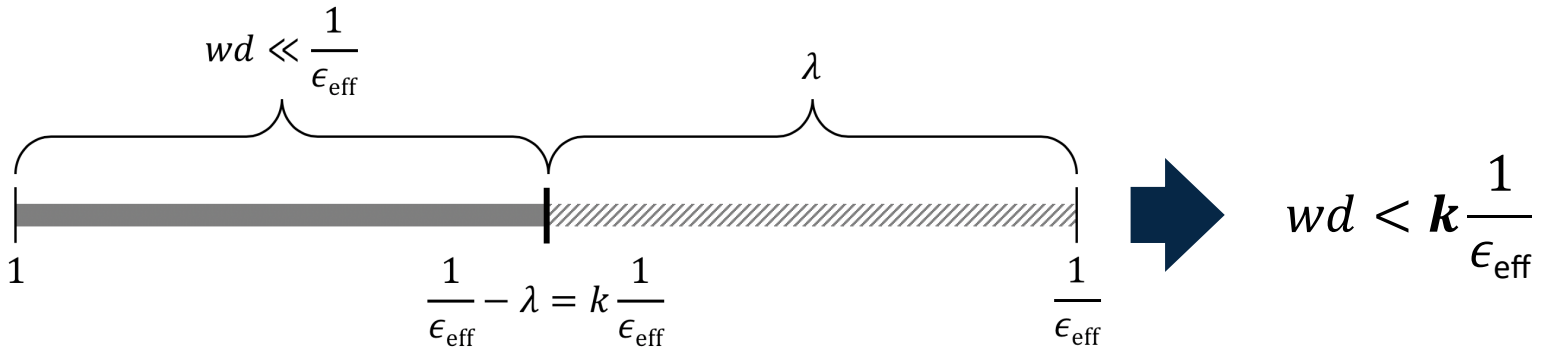
Analysis of the Executability of Compilation Results

$$wd \ll \frac{1}{\epsilon_{\text{eff}}} \text{ [2,3]}$$

- w: width of circuits, d: depth of circuit, ε_{eff}: effective error rate
- $wd \approx \frac{1}{\epsilon_{\text{eff}}}$ → execution probably fail [4]
- Composition of ϵ_{eff}:



- Sharpening the equation from ≪ to <:



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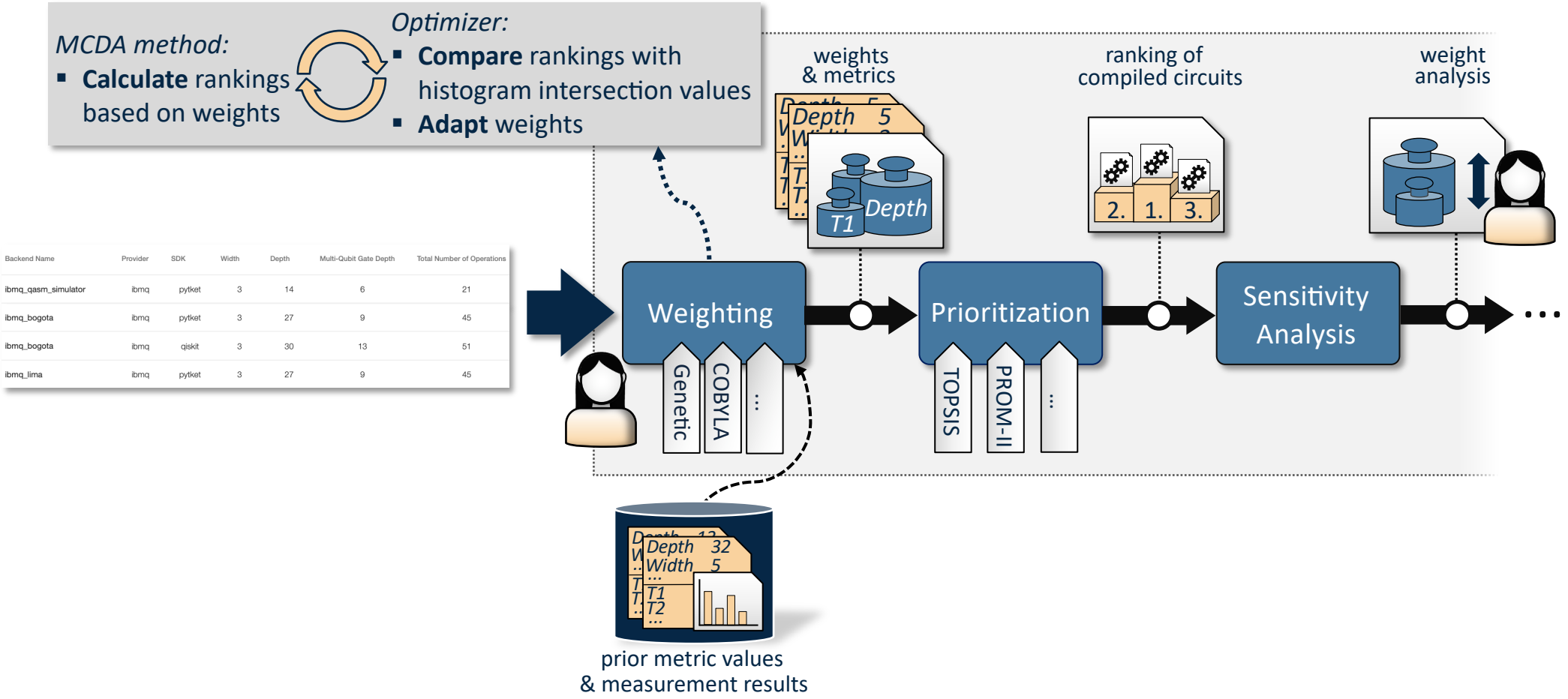
Preference-based Prioritization of Compilation Results



Backend Name	Provider	SDK	Width	Depth	Multi-Qubit Gate Depth	Total Number of Operations
ibmq_qasm_simulator	ibmq	pytket	3	14	6	21
ibmq_bogota	ibmq	pytket	3	27	9	45
ibmq_bogota	ibmq	qiskit	3	30	13	51
ibmq_lima	ibmq	pytket	3	27	9	45

- Salm, Marie; Barzen, Johanna; Leymann, Frank; Weder, Benjamin: Prioritization of Compiled Quantum Circuits for Different Quantum Computers. In: Proceedings of the 2022 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER 2022), IEEE, 2022.
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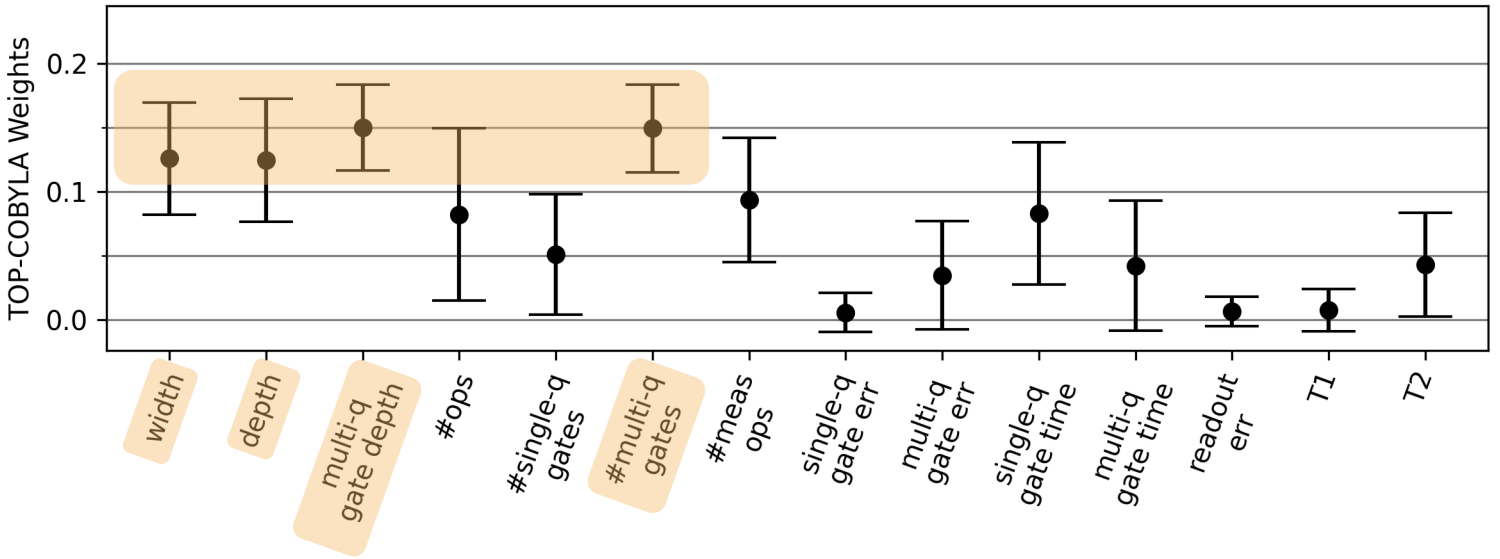
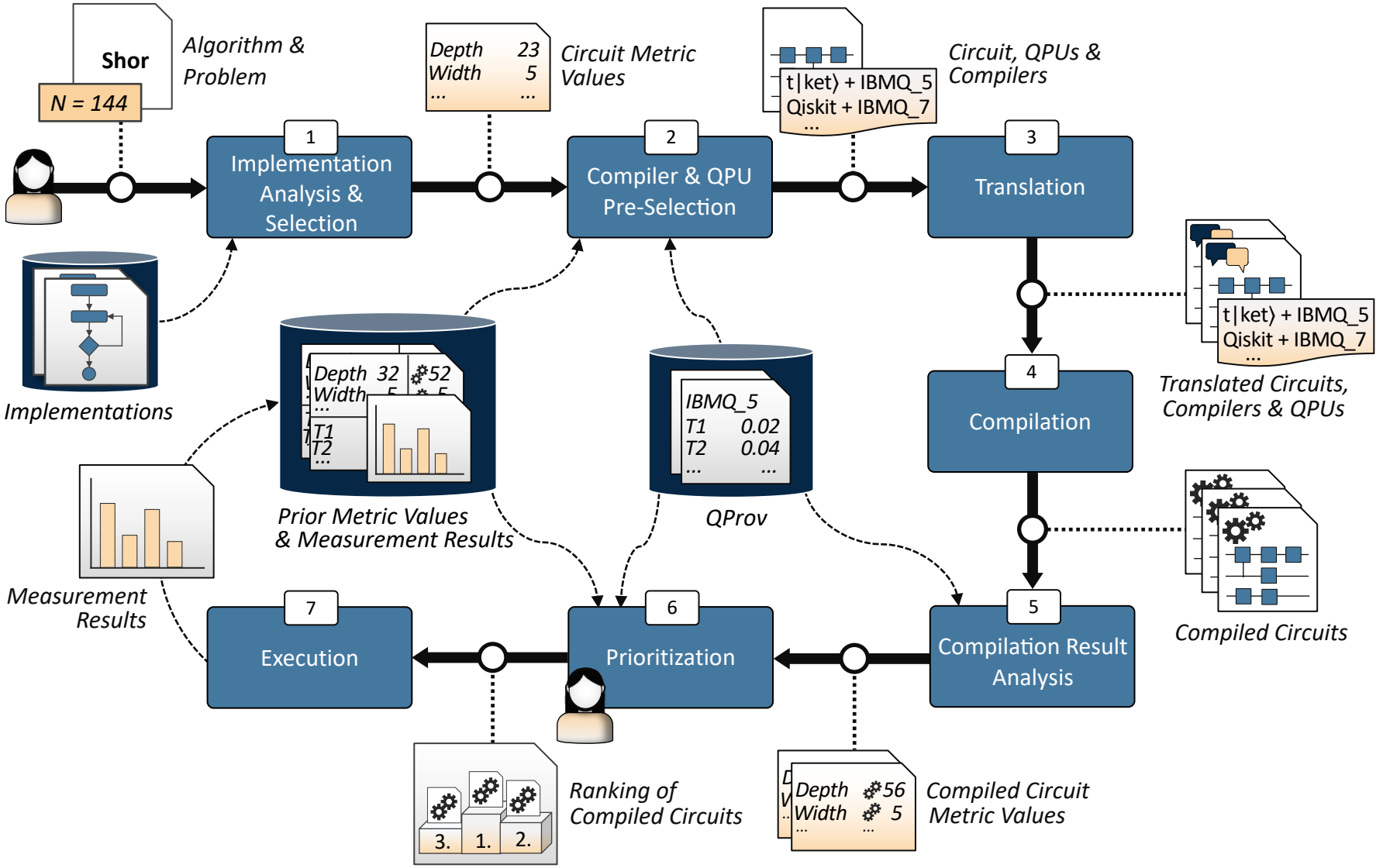
Preference-based Prioritization of Compilation Results – Case Study

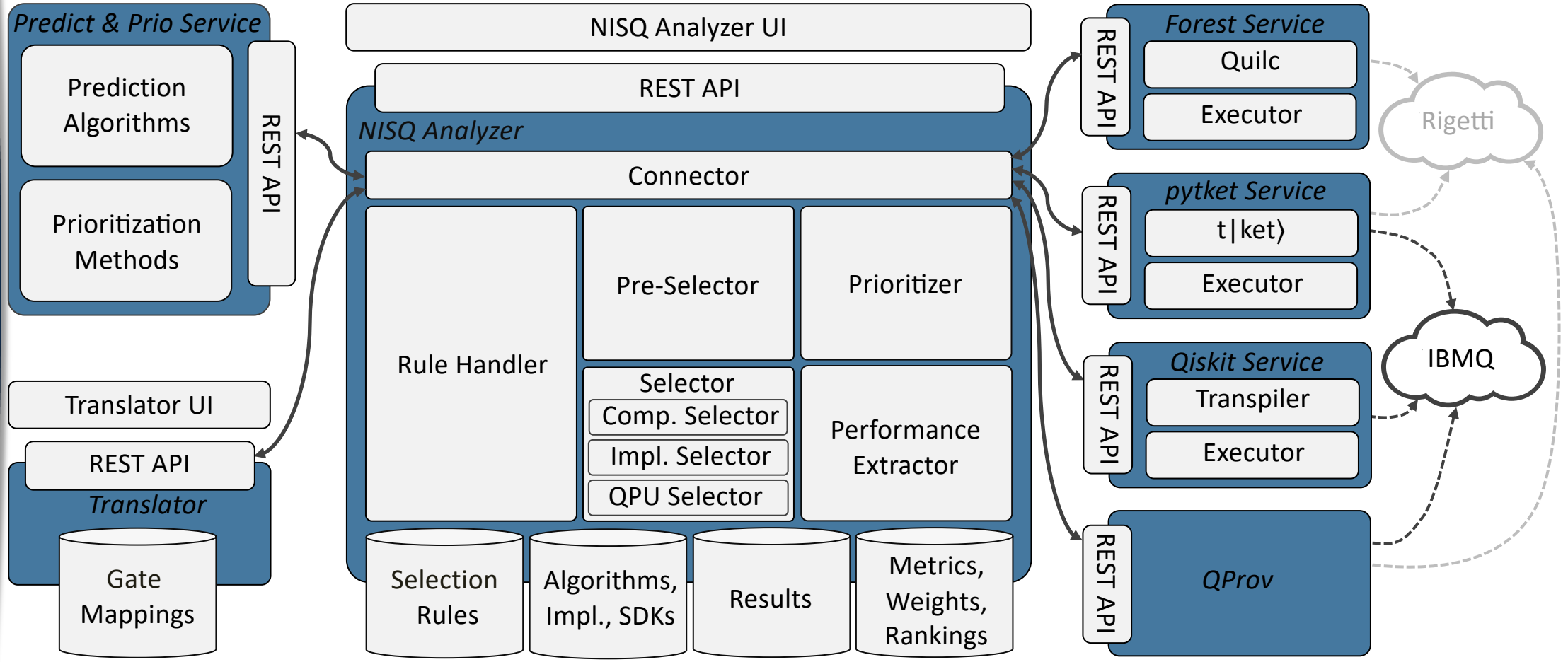


Salm, Marie; Barzen, Johanna; Leymann, Frank; Wundrack, Philipp: Optimizing the Prioritization of Compiled Quantum Circuits by Machine Learning Approaches.In: Proceedings of the 16th Symposium and Summer School on Service-Oriented Computing (SummerSOC 2022), Springer, 2022.

Approach of the NISQ Analyzer

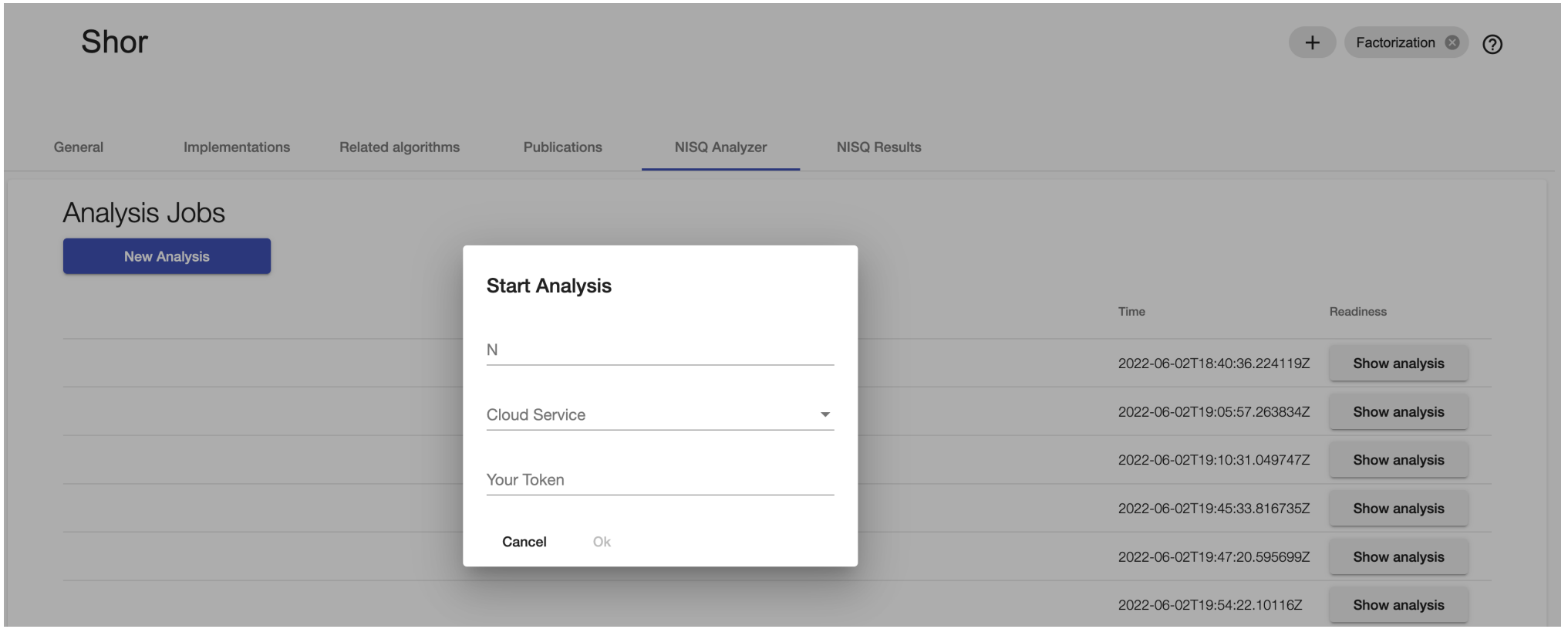


Architecture



How It Looks ...

Use Case 1: Analysis Based on Algorithm



https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

Compilation Results of Different Implementations

Implementation: **shor-fix**

Backend Name	Provider	SDK	Width	Depth	Multi-Qubit Gate Depth	Total Number of Operations	Number of Single-Qubit Gates	Number of Multi-Qubit Gates	Number of Meas
ibmq_qasm_simulator	ibmq	qiskit	5	7	4	10	2	5	
ibmq_santiago	ibmq	qiskit	5	15	3	24	15	6	
ibmq_bogota	ibmq	qiskit	5	17	8	26	12	11	
ibmq_lima	ibmq	qiskit	4	12	5	14	6	5	
ibmq_belem	ibmq	qiskit	5	12	7	17	6	8	
ibmq_quito	ibmq	qiskit	5	12	7	17	6	8	
simulator_statevector	ibmq	qiskit	5	7	4	10	2	5	
simulator_mps	ibmq	qiskit	5	6	4	9	1	5	
simulator_extended_stabilizer	ibmq	qiskit	3	7	2	9	4	2	
ibmq_manila	ibmq	qiskit	5	11	5	16	5	8	

Implementation: **shor-general**

Backend Name	Provider	SDK	Width	Depth	Multi-Qubit Gate Depth	Total Number of Operations	Number of Single-Qubit Gates	Number of Multi-Qubit Gates	Number of Meas
ibmq_qasm_simulator	ibmq	qiskit	5	7	4	10	2	5	
ibmq_santiago	ibmq	qiskit	4	18	6	25	16	6	
ibmq_lima	ibmq	qiskit	4	12	5	14	6	5	

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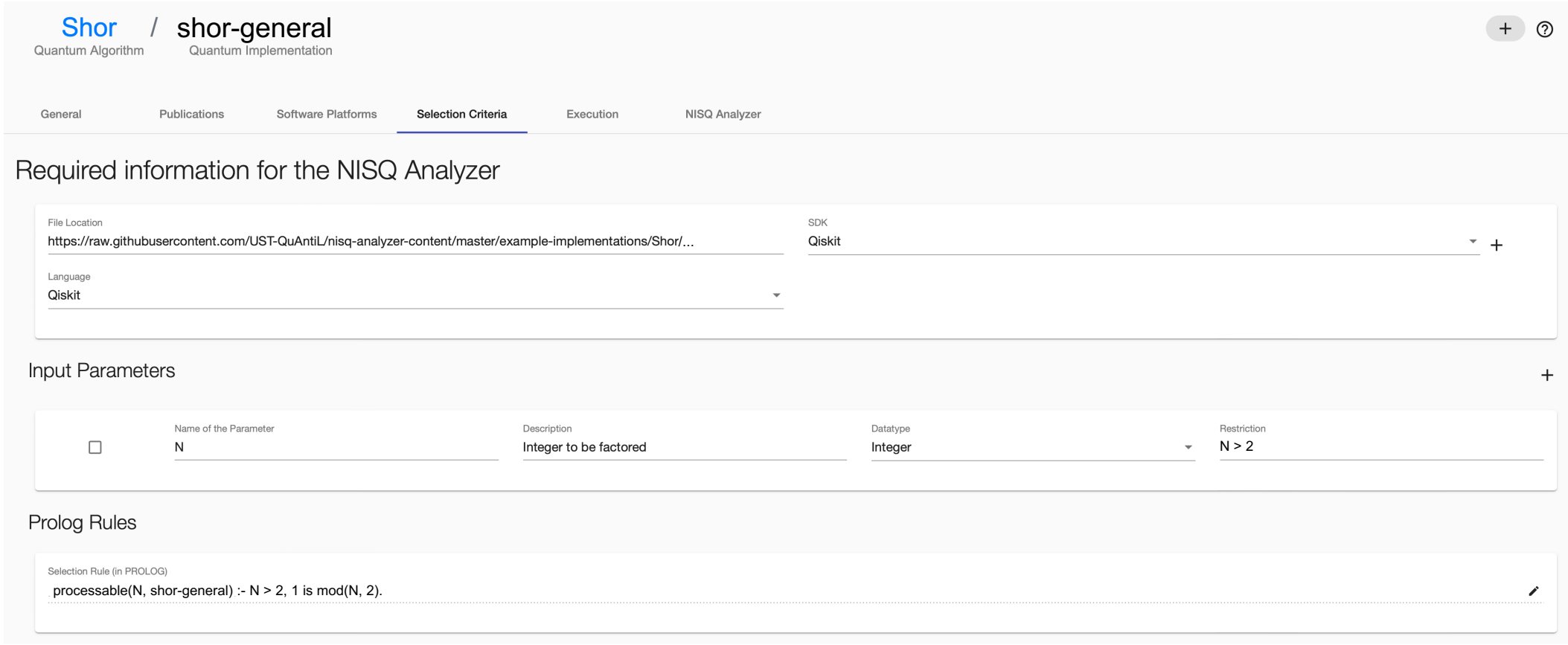
https://quantil.readthedocs.io/en/latest/

Required Information



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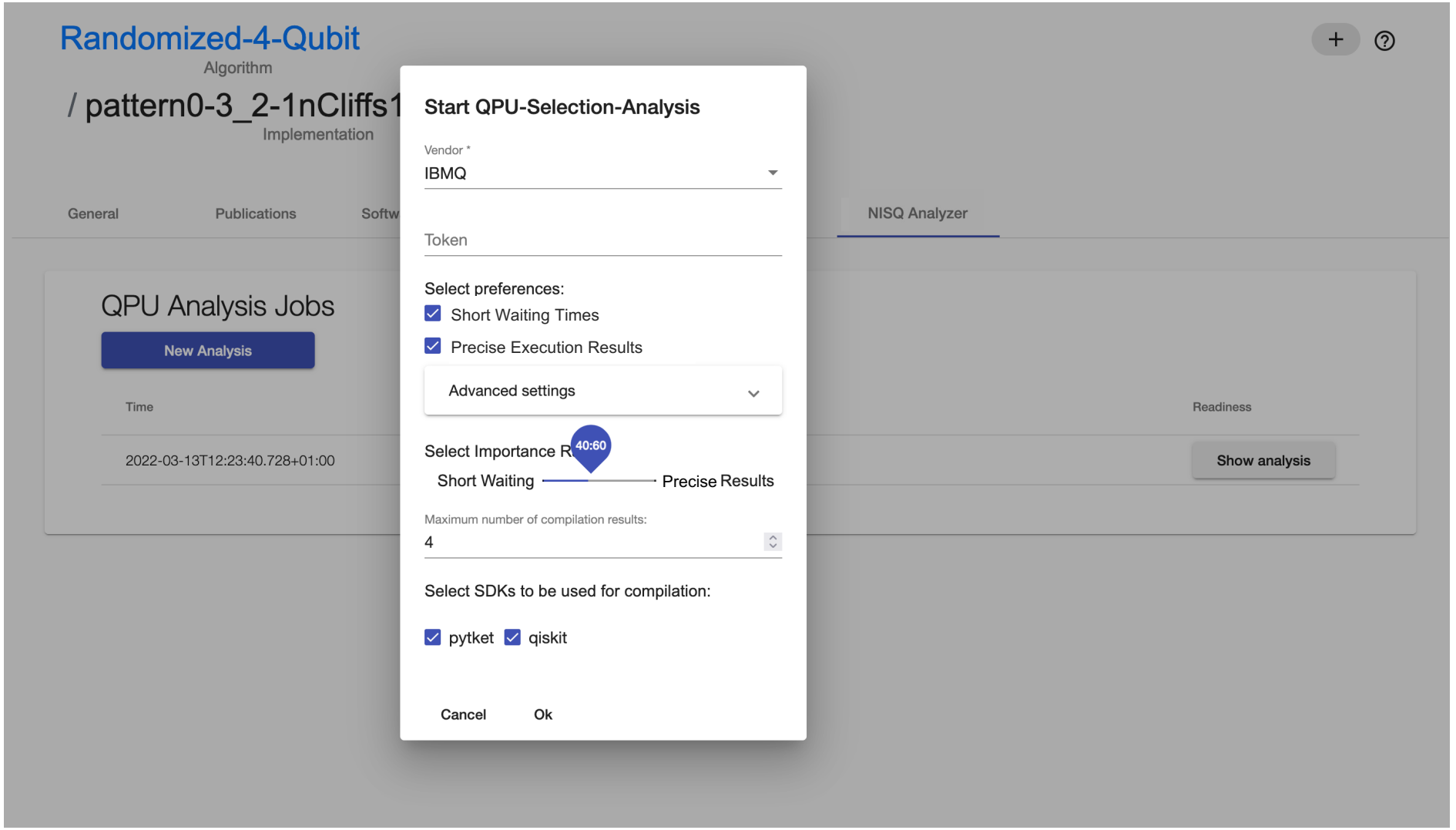
Use Case 2: Analysis Based on Implementation



https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

Analysis Results

Randomized-4-Qubit

Algorithm

/ pattern0-3_2-1nCliffs1seed2

Implementation

General | Publications | Software Platforms | Selection Criteria | Execution | NISQ Analyzer

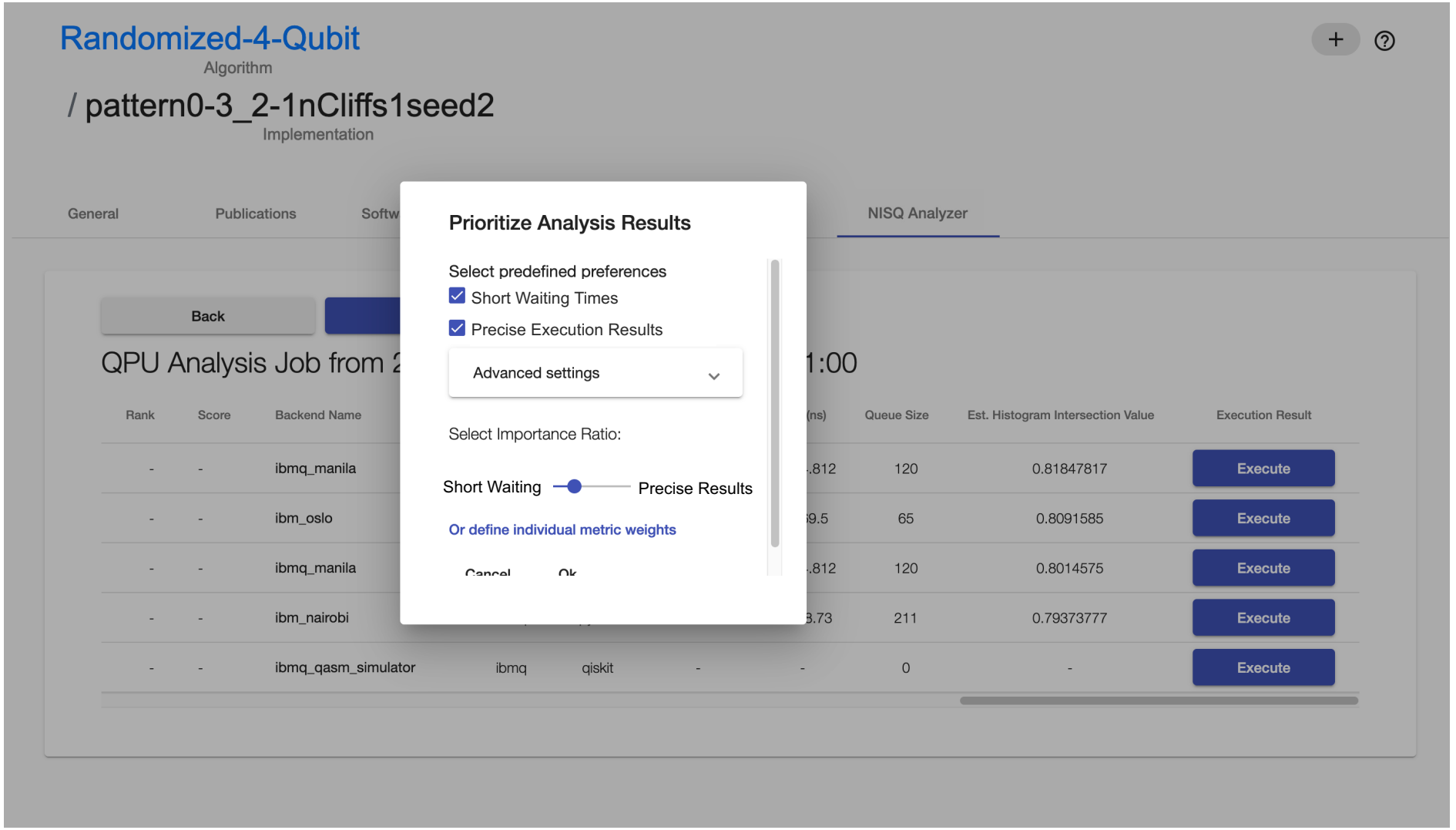
Back | Prioritize

QPU Analysis Job from 2022-11-17T16:37:39.966644+01:00

Rank	Score	Backend Name	Provider	SDK	Width	Depth	Multi-Qubit Gate Depth	Total Number of Operations	Number of Single-Qubit Gates
-	-	ibmq_manila	ibmq	pytket	4	19	2	53	45
-	-	ibm_oslo	ibmq	pytket	4	19	2	53	45
-	-	ibmq_manila	ibmq	qiskit	4	22	4	50	40
-	-	ibm_nairobi	ibmq	pytket	4	19	2	53	45
-	-	ibmq_qasm_simulator	ibmq	qiskit	4	11	4	28	18

https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

Prioritization



https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

Ranked Results

Randomized-4-Qubit

Classic Algorithm

/ pattern0-3_2-1nCliffs1seed2

Classic Implementation

General | Publications | Software Platforms | Selection Criteria | Execution | NISQ Analyzer

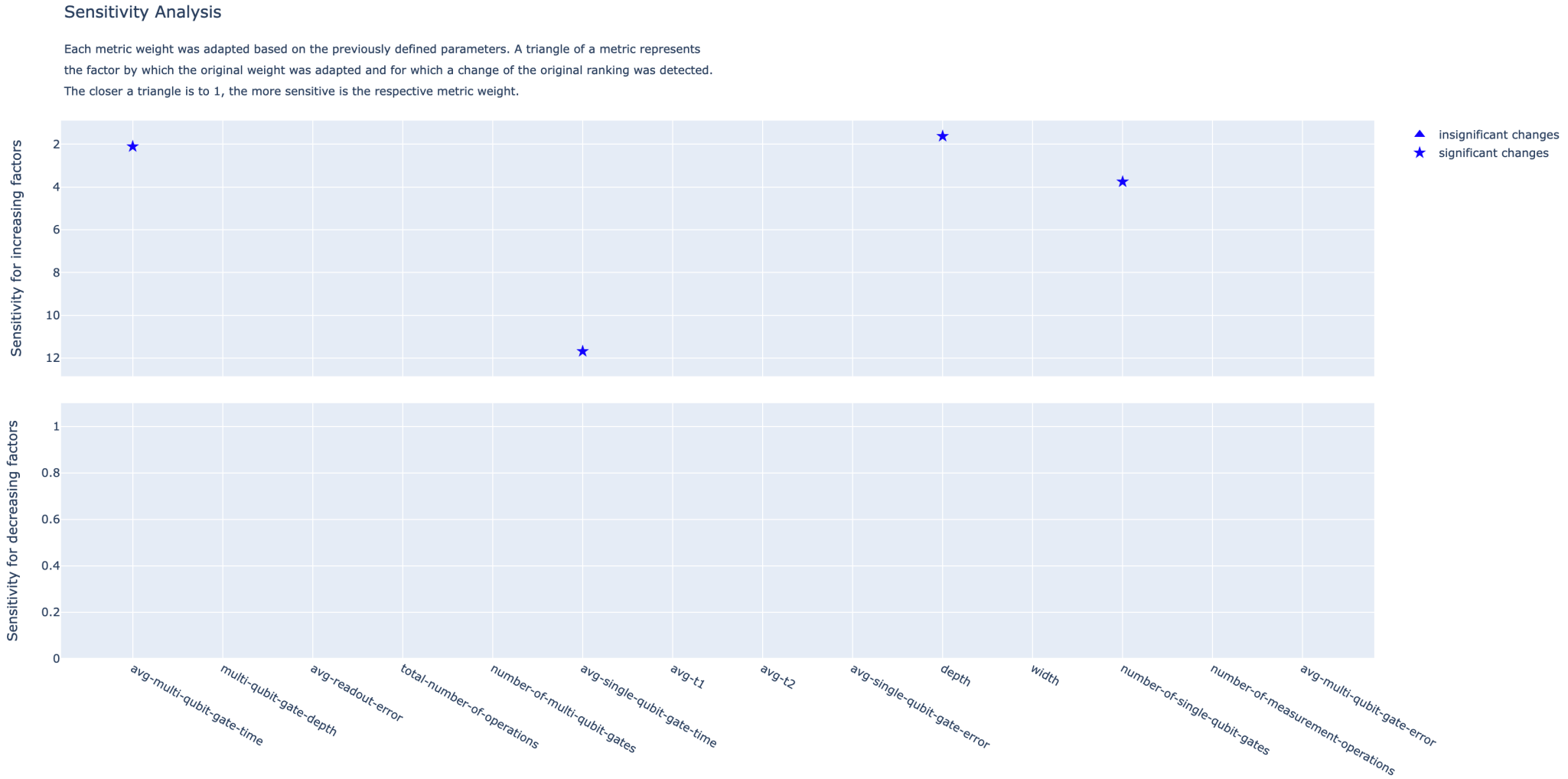
Back | Prioritize | Analyze Rank Sensitivity

QPU Analysis Job from 2022-11-17T16:37:39.966644+01:00

Rank	Score	Backend Name	Provider	SDK	Avg. T1 (ns)	Avg. T2 (ns)	Queue Size	Est. Histogram Intersection Value	Execution Result
1	-	ibm_oslo	ibmq	pytket	151106.8	87569.5	65	0.8091585	Execute
2	-	ibm_nairobi	ibmq	pytket	105642.945	80908.73	211	0.79373777	Execute
3	-	ibmq_manila	ibmq	pytket	192275.75	52704.812	120	0.81847817	Execute
4	-	ibmq_qasm_simulator	ibmq	qiskit	-	-	0	-	Execute
5	-	ibmq_manila	ibmq	qiskit	192275.75	52704.812	120	0.8014575	Execute

https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

Analysis of Ranking



https://github.com/UST-QuAntiL/quantil-docker
https://quantil.readthedocs.io/en/latest/

How It Feels ...

Evaluation

- Implementation constraints via Prolog hard
- Desired features
  - export of compilation & execution results
  - error correction & mitigation
  - variational algorithms
- Positive feedback
  - comparison
  - prioritization
  - time saving
  - recognizing dimensions & differences between compilers

Conclusion & Future Work

- Automated selection & recommendation of quantum resources
  - Translation of quantum circuits
  - Compilation with different quantum compilers
  - Prediction of execution result precision
  - Plug-in based, supports extensibility

- In the future
  - Additional circuits, compilers, QPUs
  - Further metrics, e.g., monetary metrics

Thank you!

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