A Systematic Mapping Study on Quantum and Quantum-inspired Algorithms in Operations Research

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Quantum and quantum-inspired algorithms have not yet been systematically classified in the context of potential Operations Research (OR) applications. Our systematic mapping is designed for quick consultation and shows which algorithms have been significantly explored in the context of OR, as well as which algorithms have been vaguely addressed in the same context. The study provides rapid access to OR professionals, both practitioners and researchers, who are interested in applying and/or further developing these algorithms in their respective contexts. We prepared a replicable protocol as a backbone of this systematic mapping study, specifying research questions, establishing effective search and selection methods, defining quality metrics for assessment, and guiding the analysis of the selected studies. A total of more than 2 000 studies were found, of which 149 were analyzed in detail. Readers can have an interactive hands-on experience with the collected data on an open-source repository with a website. An international standard was used as part of our classification, enabling professionals and researchers from across the world to readily identify which algorithms have been applied in any industry sector. Our effort also culminated in a rich set of takeaways that can help the reader identify potential paths for future work.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Applied computing → Operations research**; • **Theory of computation → Quantum computation theory**.

Additional Key Words and Phrases: quantum algorithms, quantum-inspired algorithms, operations research, systematic mapping study

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1 INTRODUCTION

We live in a world where economic, social, and environmental challenges abound. Professionals and researchers working within operations research (OR) topics are facing ever-increasing pressure to make operations *green*, in the sense that they have to be sustainable from many viewpoints, including that of the environment and the social well-being of involved parties [56]. An example of this pressure is the recent Glasgow Climate Pact, supported by almost 200 countries that have committed to accelerating measures to keep global temperatures from rising more than 1.5 Celsius degrees [141]. All in all, these challenges culminate in an unprecedented set of objectives and constraints in OR problems that have to be tackled with creativity and innovation.

Optimization problems are becoming more complex with the addition of new objectives, variables, and constraints. For example, the increase in the installation of a large number of new solar and wind electricity generators has resulted in an increase in the number of variables in the electrical grid, as opposed to big conventional installations of large power plants or dams [30, 120]. This higher level of complexity is a challenge for computers, as they will require more time and energy to compute solutions for optimization problems of practical interest. This increase in time and energy is not sustainable, as: i) (correct) solutions need to be provided in a timely manner; ii) energy resources are limited and at some point may not scale; iii) one cannot cool computers from the heat generated from the increased energy usage [96, 166]. Consequently, quantum computers raise significant expectation that they will play an essential role in overcoming some, if not all, of these limitations, as they will be able to solve specific tasks in a much faster and more efficient way.

In the last decade, new advances in the manufacture of quantum processing units have generated a lot of buzz around this unconventional type of computing, with advantages over classical computers already being claimed [9, 177], although some claims are disputed [104]. In other words, the science of quantum computers was settled long ago, but only recently have they been physically realizable. These novel computers promise new ways to solve problems that classical computers would not be able to solve in a timely manner [94]. Algorithms executed in quantum computers are called *quantum algorithms* and are usually applied as part of a hybrid approach. That is, the general approach to using quantum computers is to use classical computers to control the flow of a program, to pre- and post-process data, and only submit specific tasks to a quantum computer, especially when there is an advantage in doing so [151].

Even before the first quantum computer was manufactured, researchers developed classical algorithms that were inspired by the theory of quantum computing. These algorithms take advantage of certain quantum computing properties to achieve higher performance and capabilities when solving problems. We call these *quantum-inspired algorithms* [95].

Considering the emergence of different quantum computing devices, researchers and practitioners are increasingly interested in leveraging them by designing/implementing quantum or quantum-inspired algorithms, especially to address real-world problems from OR. Namely, the industry is making consistent efforts in this line, with more and more companies investing in quantum-based commercial applications [83]. However, since the field is emergent and has not matured enough, we have found its literature to be sparse and not yet systematically classified.

We have identified two particular needs: First, professionals and practitioners from the industry who are interested in leveraging quantum or quantum-inspired algorithms in their areas need to know which algorithms have already been developed, if any, as well as which algorithms would present good potential solutions for their operational challenges. Second, researchers who are interested in joining the research effort want to know what has already been researched and what research questions are still open. Moreover, this need can also arise from researchers who are experienced in quantum algorithms but have not yet applied them to OR problems. In other words, both professionals and researchers need a map of what has already been explored and a list of potential paths for further exploration.

We believe that the best way to meet the identified needs is to perform a systematic mapping study (SMS) on applications of quantum or quantum-inspired algorithms in OR problems [110]. An SMS acts as a significant jump-start for newcomers since its outcome is a mapping of what has been significantly explored, of what has been vaguely addressed by the research community, and also of what has not been researched so far. Moreover, the mapping identifies potential paths for future work. All in all, these are the reasons that we believe a systematic mapping study is the best tool to address the needs mentioned above.

The SMS follows the guidelines from [64, 110, 93]. It is divided into six steps: i) research questions, ii) search, iii) study selection, iv) quality assessment, v) data extraction, and vi) classification and analysis. We designed a protocol that describes these steps in detail and allows the reader to reproduce the systematic mapping study. The protocol was also designed with validity threats taken into account.

While conducting the systematic mapping study, more than 2 000 studies were found[1], a number that decreased to 149 after the search selection step. We extracted and analyzed data from these studies, including features such as quality of the study, quality of the reporting, type of approach (classical, hybrid or quantum), algorithm name, whether the study uses a simulator or a real quantum computer, type of quantum computer, publication year, and publication source.

An important innovation of the SMS is the usage of the International Standard Industrial Classification of All Economic Activities (ISIC) as part of the data classification. This standard was used to classify the OR problems in terms of the industry activity that best relates to them. The classification enables us to identify which industry activities have been researched so far, as well as which industry activities lack any research effort.

The insights stemming from data analysis are discussed and synthesized into a list, itemized by feature. The reader can quickly navigate around the list, with the ability to immediately read the insights related to whatever feature they are interested in. We also developed direct answers to the research questions that we have posed.

Two additional outputs were created as part of the systematic mapping study: a decision flowchart that newcomers can use to find a potential path for future work, and a website with interactive charts that readers can use to explore the data related to the 149 studies.

To sum up the findings, we observed a trend of growth in the number of publications per year. Plus, we found a significant amount of primary studies that apply the following algorithms: *Quantum Particle Swarm Optimization*, *Quadratic Unconstrained Binary Optimization*, *Quantum Genetic Algorithm*, and *Quantum-inspired Evolutionary Algorithm*. We also found a significant amount of evidence surrounding applications on the following industry activities: “electricity, gas, steam and air conditioning supply”, “transportation and storage”, “manufacturing”, “professional, scientific and technical activities”, and “information and communication”.

We conclude that the results of the systematic mapping study meet the need that we identified in the beginning. Some findings negatively surprised us, such as the lack of applications involving gate-based quantum computers. Nonetheless, the results revealed clear paths for future work that

[1]All the studies we analyzed are publicly available here.

newcomers can follow, irrespective of whether their background is in operation research or in quantum computing (or even in neither).

We list the innovations/contributions of this work as follows:

- An extensive search for primary studies was conducted among several search engines, including Scopus, IEEE Xplore, ACM Digital Library, and ScienceDirect. Snowball sampling was performed to increase the search depth. Selection criteria were applied to the search results, resulting in a list of primary studies that are relevant to our research questions.
- Data was extracted from the searched primary studies, culminating in a curated list of relevant primary studies that can be analyzed in several aspects, such as the quality of the study, and the quality of the reporting, among many other features.
- We used the International Standard Industrial Classification of All Economic Activities (ISIC) to catalog the selected primary studies regarding the economic activity that most relates to their OR problem. To the best of our knowledge, this type of classification has never been done before for OR problems.
- We analyzed and condensed all the data into an itemized list highlighting the main takeaways. This list serves as a practical map for researchers and practitioners to get acquainted with what has already been done and what are possible paths for future work.
- We developed a decision flowchart that helps researchers who wish to find a good research question, especially those who are interested in starting their first research work on an application of a quantum or quantum-inspired algorithm in an OR problem.
- We published a website that displays interactive charts, enabling readers to directly explore the data that was collected as part of the systematic mapping study. This website allows readers to gain more insights than they would gain by only reading the full-text.

The reader can get hands-on access to interactive charts of the data collected in this work at our accompanying website.
All our code and data are available in our public GitHub repository.

The paper is outlined as follows:

- Section 2 explores related work in the literature and addresses whether all the conditions to undertake a systematic mapping study are reunited.
- Section 3 reveals the protocol of the systematic mapping study. The protocol specifies what are the steps of the systematic mapping study and details how each step is conducted. The protocol itself should make it possible for any reader to replicate the SMS.
- Section 4 shows the discussion of our findings, which synthesizes the data in an itemized list that facilitates reading. This section also includes direct responses to the research questions that guide the systematic mapping study. A decision flowchart is also included, which helps interested readers who wish to start working in the field.
- Section 5 presents the conclusion of the study. The conclusion includes a subsection dedicated to future work for any researcher who wishes to replicate the systematic mapping study in the future.
- The *Supplementary Material*, published electronically, contains the results of the systematic mapping study, including charts that illustrate the data that was collected, as well as our analysis of the data. We decided to place the results there due to length constraints.

Our paper provides caters to professionals and practitioners in the industry as part of their initial approach to the field of quantum computing, so that they can apply quantum or quantum-inspired algorithms in their sector. We provide relevant material, which could be part of the first step for any OR researchers interested in joining the field of quantum computing, whether they are first-year graduate students or experienced faculty. Last but not least, we also challenge interested quantum computing researchers to read this systematic mapping study as part of their initial move into the field of OR.

2 CONTEXTUALIZATION

Before undertaking a systematic mapping study, it is necessary to perform a literature search to confirm that the need for the mapping has not already been addressed [110]. This confirmation avoids redundant work and unnecessary research effort. Moreover, this is necessary to find whether the literature is sufficiently mature to allow for a systematic literature review instead [64, 110]. Systematic literature reviews require a significant amount of primary, secondary, and possibly tertiary studies to derive findings and conclusions with sufficient validity and generalizability. On the other hand, systematic mapping studies are suitable for research topics that have a significant but small number of primary studies, lack secondary or tertiary studies, and benefit from a detailed mapping of what has been researched.

2.1 Conditions to Undertake a Systematic Mapping Study

We can classify existing studies in the literature as one of the following three types, according to the definitions from [64]:

- Primary studies, which are empirical studies that focus on a specific research question. We also call these studies as *evidences*.
- Secondary studies, that review all the primary studies pertaining to a specific research question. Their goal is to reunite and synthesize existing evidence on the research question.
- Tertiary studies, which are a higher-level type of study, usually only done in fields with a significant amount of evidences and secondary studies. These studies review secondary studies that address a specific research question.

2.1.1 Initial Literature Search. We searched on the literature using a set of relevant electronic databases that we are aware of (Google Scholar, ArXiv, SpringerLink, Scopus, IEEE Xplore, ACM Digital Library, Inspec, Compendex & Knovel, and ScienceDirect), as well as an extensive set of string queries. The results did not return secondary or tertiary studies that addressed applications of quantum or quantum-inspired algorithms in OR problems. Nevertheless, we found primary studies that each addressed a specific application of quantum or quantum-inspired algorithms in a specific OR problem. The number of primary studies that we found relevant was very low—we found fewer than 30 primary studies in this initial search. This number is far from sufficient to undertake a systematic literature review and supports the need for a systematic mapping study [64].

2.1.2 Similar Works. There exists a significant number of works in the literature that survey quantum and quantum-inspired algorithms, especially given that quantum-inspired algorithms were suggested in the 90s by [98]. However, none specifically address their usage in the context of OR problems. We list some of the most closely related works that we have identified:

- [38] presents a detailed survey of quantum-inspired metaheuristics, including descriptions of the algorithms and their class of problems. This paper does not specify the OR problems to which these algorithms are applied, but rather indicates the types of problems these metaheuristics can solve (e.g., feature selection or optimization problems). Our SMS presents itself as a natural extension to this paper, contributing to a good view on the application (if any) of these metaheuristics in the different economic activities included in the ISIC.

- [95] presents another detailed survey of quantum and quantum-inspired algorithms, with descriptive pseudocodes and comparisons with regards to runtime, accuracy, and other complexity metrics. Similarly to the paper mentioned just before, this paper indicates the types of problems these algorithms can solve without listing any of their applications in OR problems. Therefore, our SMS also presents itself as an extension to this paper for the same reasons.
- [73] presents a detailed study of a specific set of quantum and quantum-inspired algorithms, including their descriptions. This paper shows experiments with each algorithm in their typical applications, mostly related to machine learning. These experiments, apart from one that solves a common combinatorial optimization problem, do not attempt to represent the population of possible applications of these algorithms. Our SMS attempts to provide this representation, as accurate and systematic as possible.

We find it necessary to reference [111] as another motivating work, which is a detailed systematic survey covering the extensively studied and established field of classical algorithms for OR. Our SMS, while not as exhaustive due to the nascent stage of quantum and quantum-inspired algorithms in OR, complements this paper by enumerating the applications of quantum and quantum-inspired algorithms.

All aspects considered, we believe that the conditions to design and conduct a systematic mapping study have been reunited. We have identified a need. We found no existing work that addresses that need. We came to the realization that a systematic mapping study is the best effort to meet that need, considering alternatives such as a systematic literature review.

2.2 An Introductory Overview of Quantum and Quantum-inspired Algorithms

In this subsection, we introduce the basic concepts present in many quantum and quantum-inspired algorithms, as well as short descriptions of the Quantum Particle Swarm Optimization, the Quadratic Unconstrained Binary Optimization solvers, and the Quantum Genetic Algorithm. The choice of those algorithms aligns with the three most popular approaches that we have identified in our SMS. For a more detailed and comprehensive reading, we refer to [38, 95, 73, 40, 138].

2.2.1 Quantum and Quantum-inspired Algorithms. Quantum computing uses special and unique properties of quantum mechanics to perform computations. In this form of computing, the most common unit of information is the *qubit*, represented as a quantum mechanical system whose state space is an orthonormal basis formed by the unit vectors $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$ and $|1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$, such that

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,, \tag{1}$$

where α and β are complex numbers that obey $|\alpha|^2 + |\beta|^2 = 1$. This quantum mechanical system can be grouped together with other qubits to form systems of multiple qubits.

Together with *quantum operations* that apply reversible changes to the state of the quantum system, important properties such as *superposition* and *entanglement* can be leveraged to process information in a manner that is not possible in classical systems.

Algorithms that directly leverage quantum phenomena are called *quantum algorithms.* In contrast, algorithms that do not take advantage of quantum phenomena but implement classical subroutines inspired by these phenomena are called *quantum-inspired algorithms.* The rationale behind those algorithms is that, under certain assumptions, they perform better than their classical counterparts, especially in nonlinear optimization problems [38, 95, 73, 40].

2.2.2 Quantum Particle Swarm Optimization. Particle Swarm Optimization is a metaheuristic that deploys multiple particles (also known as generating multiple solutions) in the domain of the optimization problem, and then uses a function to update the position of its particles iteratively. This function uses the aggregated information of all particles to move each particle in a specific direction, balancing exploration and exploitation. Over time, the particles will converge in the global optima of the optimization problem. PSO has a quantum-inspired variant called *Quantum Particle Swarm Optimization* (QPSO), which uses qubit representations for the particles and special functions inspired by quantum operators. QPSO has been empirically shown to converge at a faster rate than the standard PSO [38, 73].

2.2.3 Quadratic Unconstrained Binary Optimization Solvers. There exist some quantum and quantum-inspired computers (and algorithms) that are specialized in solving a specific class of problems called *Quadratic Unconstrained Binary Optimization* (QUBO) [40]. These problems are represented as follows:

$$\min xQx^{\intercal}, \tag{2}$$

where x is a column-vector of binary variables and Q is a symmetric square matrix with diagonal elements representing the *linear coefficients* and off-diagonal elements representing the *quadratic coefficients*. This representation has been shown to be capable of representing any problem in the complexity class NP. Due to the straightforward representation, the usage of QUBOs has become increasingly popular among users of certain quantum and quantum-inspired computers, such as D-Wave Systems Inc. [138, 41]. In fact, most software stacks for universal quantum computers also include specialized utilities to solve problems in the QUBO form. In the remainder of our paper, whenever QUBO is mentioned, we refer to the entire approach of solving a problem with a QUBO.

2.2.4 Quantum Genetic Algorithm. Genetic algorithms (GAs) are a specific class of algorithms that start with an initial population of solutions, which are iteratively refined until they reach the optimal solution for the optimization problem [38, 95, 73, 40]. These algorithms are inspired by concepts from the field of genetics, as the operators that iteratively refine these populations are called *mutation* and *crossover* operators. A mutation operator applies isolated changes to some elements of the new copies of the population. A crossover operator mixes different values amongst different elements of the population. Both operators allow GAs to explore the domain of the optimization problem without getting trapped in a local optimum, especially in nonlinear optimization problems. Quantum Genetic Algorithms are a variation of GAs that use quantum-inspired representations of the elements in the population, as well as quantum-inspired mutation and crossover operators. For example, some QGAs represent elements in the population with quantum states and apply quantum rotation gates as mutation operators, as well as crossover operators that emulate interference between quantum states [72].

3 RESEARCH METHOD

In this section, we present the protocol that we designed and implemented for our systematic mapping study, which follows the guidelines from [64, 110]. The main idea behind the protocol is to provide a way to facilitate the reproduction of the study, as well as to avoid or minimize the introduction of bias from the researchers conducting it.

First, in subsection 3.1, we specify the research questions that drive the entire SMS. Second, in subsection 3.2, we describe the search methods that are used to find studies that are related in some way to the specified research questions, as well as how primary studies are selected among the set of studies identified in the search. Afterwards, the selected studies pass through a quality assessment step, described in subsection 3.3. Next, in subsection 3.4, we describe which data is extracted from the selected studies. After that, in subsection 3.5, we show how this data is analyzed and how the outcomes of the analysis are discussed. Finally, in subsection 3.6, we discuss the validity and reliability of our study.

3.1 Research Questions

The goal of our systematic mapping study is to "summarize and disseminate research findings" [7], by giving a comprehensive overview over the application of Quantum and Quantum-inspired algorithms in Operations Research (OR). This overview will serve as an inventory for papers and as a good starting point for anyone who wishes to enter in this area, such as graduate students early during their Ph.D. studies [64, 110].

Concretely, our motivation is to assess what has been done with quantum algorithms and quantum-inspired algorithms in the field of OR. We expect to identify evidence clusters and evidence deserts in this area, which may guide or incentivize researchers to perform primary studies in specific sub-areas.

Considering our motivation and goal, as well as the structure of an SMS, we developed the following set of research questions that are to be answered as part of our SMS:

- **RQ1.** What existing approaches apply quantum or quantum-inspired algorithms to the field of Operations Research?
- **RQ2.** In which sources, in which years, and in which quantities were approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research published?
- **RQ3.** Which research questions related to approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research are addressed by a significant amount of evidence (evidence clusters)?
- **RQ4.** Which research questions related to approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research are addressed by a scarce amount of evidence (evidence deserts)?

Having specified the research questions, we can develop the search strategy to be followed when conducting the study, which is presented in the next subsection.

3.2 Search and Study Selection

A systematic mapping study should strive for a selection of papers that constitute a good representation of the population. Hence, more papers is not necessarily better, as it may induce a distorted view of the overall research extant in the area. Nonetheless, if very few papers have been published so far in the area, it may be adequate to search for the maximum amount of papers possible [110].

In our case, a simple and quick search in electronic databases suggests that very few papers apply quantum or quantum-inspired algorithms in the context of OR (e.g., by searching in IEEE Xplore for the keywords `"Quantum"` and `"Operations Research"`). Hence, during our search step, we will be targeting the maximum amount of studies while still keeping the number of studies feasible. Particularly, we should avoid steps in our search strategy that lead to an explosion in the number of findings.

For our SMS, three search strategies are used: electronic database search, reverse snowball sampling, and forward snowball sampling. In the following subsubsections, each search strategy is described in the order they are performed. We call the reader to take into account that those strategies are used while doing study selection between them, a step that is described in the next subsection. Figure 1 illustrates the order of these search and study selection steps during the SMS, which resulted in a list of 149 primary studies [176, 15, 79, 162, 109, 131, 34, 33, 84, 107, 106, 119, 147, 14, 164, 42, 81, 123, 172, 45, 158, 35, 99, 103, 36, 137, 132, 133, 122, 77, 125, 67, 136, 31, 143, 161, 58, 25, 39, 17, 8, 154, 155, 160, 85, 47, 89, 128, 113, 149, 44, 12, 60, 59, 26, 55, 118, 121, 101, 16, 32, 50, 46, 90, 139, 43, 24, 78, 82, 142, 68, 53, 135, 171, 170, 23, 150, 178, 169, 62, 22, 75, 92, 80, 87, 86, 108, 145, 159, 129, 140, 97, 13, 37, 173, 179, 146, 124, 51, 74, 49, 61, 157, 168, 1, 167, 71, 175, 156, 153, 52, 76, 152, 102, 116, 134, 144, 66, 126, 127, 112, 115, 114, 117, 27, 130, 148, 163, 2, 6, 10, 11, 65, 105, 19, 54, 18, 20, 29, 100, 165, 174, 3, 4, 5, 48, 91, 69, 70].

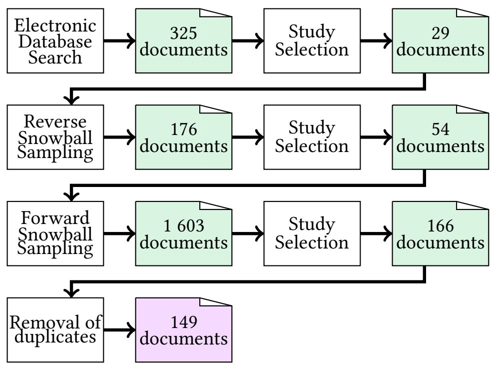

Fig. 1. Illustration of the steps taken while searching and selecting studies and the number of selected documents after each step.

The search step is followed by the study selection step, where the collected studies pass through a selection process that decides which studies are candidates for answering some or all of the specified research questions. For this step, we read the title and abstract of each study.

The selection process consists of checking each study against a set of inclusion and exclusion criteria. This means that, by default, a study is excluded. To be included, the study must meet all the inclusion criteria. However, once the study meets any of the exclusion criteria, it is immediately excluded. With respect to our inclusion criteria, we only accept peer-reviewed studies written in English and published during or after 2011. We chose 2011 because it was in this year that the first commercially available quantum computer was released—D-Wave One, from D-Wave Systems, Inc. Moreover, a quick search in electronic databases also suggests that research on real-world applications with quantum and quantum-inspired algorithms only started to become significant during the years after 2011. With respect to our exclusion criteria, we avoid studies that are not a primary study or whose full-text is not accessible to us.

In order to validate the study selection, for each study, we find its ranking based on the SCImago Journal & Country Rank (SJCR) or on the conference rankings from the Computing Research and Education Association of Australasia (CORE), depending on whether the study is part of a journal or of a conference. For studies that belong to journals, we chose to use the SJR Indicator, as it is a good measure of the influence of the journal, enabling us to compare each study in terms of its journal's influence [88]. We also take into account the SJR Best Quartile for the same purposes. For studies that belong to conferences, we chose to use the CORE rankings, since their method assigns each conference to a specific category with an associated prestige and impact [21]. However, we note that those indicators are limited and cannot be taken at face value.

Once we have determined the rankings associated with each of the studies, we validate the selection process by analyzing the distribution of selected studies among the rankings, since it provides an evidence on whether our process generally selects studies associated with journals and conferences with a higher prestige.

For a more detailed description of the search and study selection steps, we refer to Appendix A. There, reproducible instructions for all the different search and selection strategies are included.

3.3 Quality Assessment

Once the search and study selection steps are finished, the collection of included studies passes through a quality assessment. The objective of this step is to assess the quality of each study, such that we take into account the outcomes of the studies with their associated quality, giving more importance to studies with better quality.

For the purpose of our systematic mapping study, our quality assessment should focus on whether the evidence was well collected (quality of study) and on whether the evidence was well reported (quality of reporting). This assessment may help us identify evidence clusters that lack quality in their study or in their reporting.

To evaluate the studies on the quality of their study and their reporting, we developed two checklists. The first checklist, concerned with assessing the quality of the study, is shown in table 1. The other checklist, concerned with assessing the quality of the reporting, is shown in table 2. These checklists were made according to the guidelines of [64, 110] and are adjusted to our particular research questions. As is good practice, both tables include a *checkmark (✓) column* to visually remind practitioners to ensure they answer all questions for each study.

Table 1. Checklist to assess the quality of the study.

ID	Question	✓
SS01	Does the study have a comparison or control application?	
SS02	If the study compares its application with another application, are both applications compared among different scenarios or settings?	
SS03	Does the study use a real-world scenario or case study for its application, even if it is simplified?	
SS04	If the study does not use a real-world scenario or case study for its application, does the study use benchmarks?	
SS05	If the variables and/or scenarios in the study were defined randomly, does the study specify and justify the randomization?	
SS06	If the variables and/or scenarios in the study were defined arbitrarily, does the study explain the reasoning behind the definitions?	
SS07	Does the study use statistical analysis to assess the behavior of its application?	
SS08	Does the study use statistical tests to check hypotheses?	
SS09	Are validity and reliability threats addressed in the study?	
SS10	Does the study debate on possible future work?	

For each checklist, the final score is calculated as follows:

$$S = \frac{\text{Number of checkmarks } (\checkmark)}{\text{Number of applicable questions}} \times 100\%, \tag{3}$$

where S ranges from 0% to 100%, and the higher the score the better is the assessed quality.

We use a Microsoft Excel file to fill these checklists for each study, calculating the *study quality score* (S_S–SS00) and the *reporting quality score* (S_R–SR00) for each study. The results are then exported to a comma-separated values (CSV) file which is publicly available and that can be analyzed with any statistical program.

To validate this step, we use the SJCR and CORE Rankings once again and then correlate those rankings with the study quality and reporting quality scores. We expect higher rankings to be associated with higher scores, which would serve as evidence that our quality assessment is representative of the quality of the studies.

Table 2. Checklist to assess the quality of the reporting.

ID	Question	✓
SR01	Does the study present in the beginning of the text its overall structure?	
SR02	Does the study present the motivation behind the work?	
SR03	Does the study indicate in the beginning of the text the research questions or research goals?	
SR04	Does the study summarize in the beginning of the text the methodology?	
SR05	Does the study summarize in the beginning of the text the conclusions?	
SR06	Does the study describe its methodology in such a way that it is reproducible?	
SR07	Does the study present the implementation of its application by means of a reproducible pseudocode listing, code repository, or any other specification?	
SR08	If the study uses a comparison or control application, does the study present the implementation of its comparison or control application by means of a reproducible pseudocode listing, code repository, or any other specification?	
SR09	If the study uses scenarios or settings, does the study present a reproducible specification of those scenarios or settings?	
SR10	If the study uses statistical analysis, does the study detail this step in such a way that it is reproducible?	
SR11	Does the study use images or tables to present its results?	
SR12	Are all the tables and images referred to and explained in the text of the study?	
SR13	Does the study use all its references in its text?	
SR14	Does the study present the implementation of its application by means of a code repository?	
SR15	If the study presents a code repository, is the code used in the study documented in any way?	
SR16	Does the study describe the contributions that have been made?	

Table 3. Extraction form.

ID	Query	Possible Values
D010	Type of Approach	Classical OR Quantum OR Hybrid.
D020	Algorithm Name	
D030	Does the study use a simulator or a real quantum computer?	Quantum Computer OR Simulator OR Not Applicable
D040	Type of Quantum Computer	Gate-based OR Annealer OR Not Applicable
D050	ISIC Section	A to U.
D051	ISIC Division	01 to 99.
D052	ISIC Group	011 to 990.
D053	ISIC Class	0111 to 9900.
D060	Publication Year	2011 to 2021.
D070	Publication Source	Journal; Conference; Workshop; Other.

3.4 Data Extraction and Classification

The data extraction step is responsible for extracting most of the data that will be fundamental to answer the research questions. Hence, we have to develop a form to be filled in for each selected study. This form should specify which data to be extracted and the instructions to extract each data should be as objective and concise as possible.

In table 3, we present the extraction form of our study. The information extracted will constitute the majority of the data used to answer the research questions, with the remaining data coming from the previous steps, mainly the quality assessment step. Further instructions or clarifications of the extraction form are also presented together with the table, which should help with the reproducibility of this step.

The first query categorizes the approach of the study in respect of the algorithms it uses. We use this information as part of our answer to the research question **RQ1**. Concretely, a classical approach only contains classical and quantum-inspired algorithms; a quantum approach only contains quantum algorithms; and a hybrid approach contains classical, quantum and quantum-inspired algorithms. In other words, classical approaches only use classical computers, quantum approaches only use quantum computers, and hybrid approaches use both computers.

The second query extracts the name of the relevant algorithm of the study. Variants of the same algorithm should be attributed to the same name since we are not interested in the specifics of each application. Our goal with this query is to find which general algorithms have been used (**RQ1**).

For the particular cases in which the approach is categorized as hybrid or quantum, we categorize the study in respect of its usage of a real quantum computer or a simulated quantum computer. We also categorize the study in respect of the type of quantum computer it uses, such as *gate-based quantum computer* or *quantum annealer*. Both queries are relevant to answer the research questions **RQ1**, **RQ3**, and **RQ4**.

A piece of relevant information to be extracted, particularly for the research questions **RQ3** and **RQ4**, would be the industry where the application is used or intended to be used. To retrieve this information, we decided to use the ISIC standard [28] for several reasons: first, this standard was developed by the Department of Economic and Social Affairs of the United Nations Secretariat, with the purpose of providing a single standard to be used by countries when collecting and reporting statistics about productive activities; second, the unified nature of this standard makes it possible to compare productive activities among different countries or studies; last, the standard enables us to find not only which industry sectors and activities have applications of quantum and quantum-inspired algorithms, but also which industry sectors and activities lack applications.

The procedure that is followed to choose an appropriate ISIC section, division, group, and class for each study is described as follows: given the study, we choose the ISIC section that is most relevant to the activity conducted by the application of the study. The same strategy is used for choosing the division, group, and class. If there are doubts about which choice to take, we keep the possible choices into account and then we use the information of the following sublevel to choose one of the choices. As an example, let us assume that for a study we are undecided between ISIC section M or P. We take both sections into account and check the following division. We then determine that the study actually is best corresponded to the division 73; thus, we discard section P.

Finally, we also extract the publication source and year from the studies, which are particularly useful to answer the research question **RQ2**. With this information, we can obtain insights such as which type of publication source has provided the most meaningful research so far, as well as the overall research trend over the years.

3.5 Analysis

Once the quality assessment and the data extraction and classification steps are finished, a significant amount of information is collected for each study. This information is composed of *features*, with each feature corresponding to the information collected about a specific query or data extraction.

These features need to be systematically analyzed such that we have good grounds for answering the research questions. For this reason, the analysis is divided into three parts: *analysis of individual features* (3.5.1), in which each feature is individually analyzed; *analysis of relationships between pairs of features* (3.5.2), in which we attempt to find relevant relationships between any pair of features; and *exploratory data analysis* (3.5.3), which concerns the exploration of the information with the goal of finding relevant relationships and insights that may not have been captured in the previous two parts of the analysis.

Before proceeding to the analysis, we have to define a set of features that are considered relevant and will be analyzed as part of the first two parts of the analysis. The relevance of the features is determined by their importance in answering the research questions and by their redundancy. Table 4 shows the features that we have selected as relevant, uniquely coded with an ID for future reference.

Table 4. Features selected for individual analysis.

#	Feature ID	#	Feature ID	#	Feature ID	#	Feature ID
1	SS00	12	SR00	23	SR11	29	D010
2	SS01	13	SR01	24	SR12	30	D020
3	SS02	14	SR02	25	SR13	31	D030
4	SS03	15	SR03	26	SR14	32	D040
5	SS04	16	SR04	27	SR15	33	D050
6	SS05	17	SR05	28	SR16	34	D051
7	SS06	18	SR06			35	D052
8	SS07	19	SR07			36	D053
9	SS08	20	SR08			37	D060
10	SS09	21	SR09			38	D070
11	SS10	22	SR10				

3.5.1 Analysis of Individual Features. In the first part of the analysis, the features are individually analyzed. The type of analysis depends on the possible values of the feature. The goal of this part of the analysis is to achieve in a clear and concise way a good visualization of how the studies are distributed among the values of their features, potentially identifying any trends or insights.

Features with a percentage value (SS00 and SR00) are analyzed with violin plots. These visualizations should help us understand what is the distribution of the studies with respect to their S_S or S_R.

Features with a small number of categorical values (SS01 to SS10, SR01 to SR16, D010, D030, D040, D070) are analyzed with stacked bar charts that show their proportion. We can group some of the bar plots together for increased clarity. Particularly, we can group SS01 to SS10 and also SR01 to SR16. These stacked bar plots will be useful to get a general idea of which share of the studies belongs to a certain categorical value from a feature.

For the features D020 and D060, their different values will be plotted on simple bar charts. With this visualization, we will be able to compare the number of occurrences of each value among all the studies.

Finally, for the features D050 to D053, we will prepare a series of bar charts that follows the ISIC hierarchy. First, for the ISIC sections, we present a bar chart with the number of studies corresponding to each ISIC section. Next, we select the ISIC sections that are most relevant in number of publications (5 or more). We present a bar chart with the number of studies corresponding to each ISIC division from the selected relevant ISIC sections. Afterwards, if we identify any bar that is relevant in number of publications, we select the corresponding ISIC section and prepare a bar chart with the number of studies corresponding to each ISIC group from the selected ISIC section. Once again, if there is still a bar that stands out from the others, we repeat the process by preparing a bar chart with the number of studies corresponding to each ISIC class from the selected ISIC section.

Moreover, since the ISIC standard is a hierarchical classification, there are some charts that are well suited to visualize this type of data, avoiding the need for making many different charts that would overwhelm our analysis. Two of these charts are the treemap chart and the icicle chart. However, these two charts are not suited for paper, so we provide an interactive treemap chart and an interactive icicle chart on a webpage.

3.5.2 Analysis of Relationships between Pairs of Features. In the second part of the analysis, the relationship between certain pairs of features is analyzed. The goal of this part is to find insights between any features, such as which industry sectors are more associated with quantum annealers.

Due to the large number of features, analyzing every possible pair is not feasible nor illuminating. Instead, we select which pairs will be analyzed, as illustrated in table 5. A total of 34 pairs were selected according to their relevance to the research questions.

Table 5. Pairs of features selected for analysis.

Pair #	Feature 1	Feature 2	Pair #	Feature 1	Feature 2
1	SS00	D010	18	D020	D050
2		D020	19		D060
3		D030	20		D070
4		D040	21	D030	D040
5		D050	22		D050
6		D060	23		D060
7		D070	24		D070
8	SR00	D010	25	D040	D050
9		D020	26		D060
10		D030	27		D070
11		D040	28	D050	D060
12		D050	29		D070
13		D060	30	D070	D060
14		D070	31	SS03	D040
15	D010	D050	32		D050
16		D060	33		D060
17		D070	34		D070

A violin plot or a bar chart is developed for each pair, depending on the features. These charts enable us to analyze the relationship between the features of the pair. Afterwards, the relationship is verified with an appropriate statistical test, which also depends on the features. We expect the Mann–Whitney U test to be a statistical test that is very well suited to analyze these relationships, since we cannot assume the distributions are normal distributed.

3.5.3 Exploratory Data Analysis. In the third and last part of the analysis, we perform a non-systematic data analysis that attempts to find any insight that has not been captured by the first two parts of the analysis. This may include any pair of features that was not deemed relevant as part of the protocol.

3.6 Threats to the Validity of the Study

Just like all research works, this systematic mapping study is subject to threats to its validity that come from us and from the data [64, 110]. Hence, we are responsible for planning, conducting, and reporting the SMS in a manner that minimizes bias and error. To address these threats, we placed several measures that are listed as follows:

Bias. To minimize systematic error, we made sure to use well-established code to extract and visualize the data, such as the Python libraries `Pandas`, `numpy`, and `plotly`. Potential bias may also arise from the set of identified electronic databases, data collection techniques, inclusion criteria, and exclusion criteria, which limits the exhaustivity of the data collection. We also avoided manually extracting the data from electronic databases as much as possible. Potential bias may still come from the quality assessment and the data extraction and classification steps, as they require assessment and classification from humans. All things considered, we believe that we have minimized the potential for bias as much as possible.

Internal Validity. The protocol was designed in such a way that the quality checklists and the extraction form are as concise and unambiguous as possible. We also made sure to label every response so as to avoid mislabeling errors and loss of data. We believe that this design is likely to prevent systematic error in the study.

External Validity. The systematic mapping study was designed to be reproducible and verifiable. The protocol is very detailed and the extracted data is publicly available. There is potential loss of generalizability due to the steps that involve human subjectivity. More concretely, different humans may return different outputs when doing the quality assessment and the data extraction and classification steps. Nonetheless, we believe that this potential loss of generalizability is addressed by the design of the protocol.

4 DISCUSSION

In this section, the results are summarized and discussed in an itemized list of main takeaways, following the order of the features denoted in table 4, as shown in subsection 4.1. The list is followed by subsection 4.2, which presents our answer to the research questions that guided the systematic mapping study.

4.1 Main Takeaways

The following itemized list presents the main takeaways from the systematic mapping study. Some of the takeaways will be highlighted in a pink box due to the relative importance we have given to them.

- **Study Quality Score —** S_S We believe this indicator is a good representation of the quality of the study. Compared with the other indicator, S_R, the distribution of S_S among the studies appears more sparse. We would like to see new studies using hybrid approaches for a better S_S. More concretely, hybrid approaches that use gate-based quantum computers have a very bad S_S and would benefit from new studies subject to much higher quality standards. On the other hand, certain classical algorithms, such as the quantum genetic algorithm, also lag behind in terms of S_S and would benefit from new studies with better quality. Regarding the ISIC sections, the section "Transportation and storage" has some studies with a very low S_S and would benefit from more studies subject to higher quality standards.
- **SS01** The significant majority of the studies use comparison algorithms. We believe that this majority should be kept for future studies, as it enables us to evaluate novel algorithms in comparison to existing ones.
- **SS02** We also observed a majority of the studies comparing their algorithm with existing algorithms across multiple scenarios. We believe that this majority enables us to accurately evaluate new algorithms among different conditions, which brings more conclusions and reliability to their findings. This majority should be striven for in the future.

SS03

We observed that just under half of the studies use real-world scenarios. However, we believe that there should be more studies using real-world scenarios—particularly, studies involving gate-based quantum computers, as well as studies in certain ISIC sections, such as "Information and communication" and "Public administration and defence; compulsory social security".

- **SS04** Considering the studies that do not use real-world scenarios, almost all of these studies use benchmarks. Despite not being as representative of the real world as real-world scenarios are, benchmarks are still a good assessment tool for when real-world scenarios are not possible or feasible. For this reason, we believe that future work should strive for benchmarks when real-world scenarios are not possible.

- **SS05** We observed that very few studies used randomized variables and scenarios as part of their methodology, which was expected, since we also observed that a great majority of the studies use benchmarks or real-world scenarios. Among these studies, we observed that just over half of the studies explain and justify how the randomization process is done. We believe that this majority should be significantly larger in the future, as it would bring more credibility to their findings, help readers interpret the results, and bring more reproducibility to the study.
- **SS06** A significant majority of the studies explain the reasoning behind variables that are defined arbitrarily in their methodology. However, there is still a noticeable portion of around 21% that does not. We believe that this portion should be decreased in the future, for increased credibility, reliability, and reproducibility.
- **SS07** Almost all the selected studies use statistical analysis as part of their analysis. We believe that this trend should be kept in the future, because statistical analysis brings more credibility and reliability to the conclusions.

SS08

Few articles used statistical tests to check their hypotheses. Statistical tests are valuable tools that enable us to check hypotheses under a significance level. We urge future work to resort to these type of tests, since these tools bring significant credibility and reliability to the conclusions.

- **SS09** A total of zero studies reported addressing any validity or reliability threats. We believe that this finding should be avoided in future work, since we believe that studies that address validity and reliability threats are more transparent and less prone to bias.
- **SS10** A significant majority of the selected studies address future work. However, we believe that there is a significant margin for improvement in this feature. Future studies should address future work to illuminate possible paths for further research, as well as to provide readers with short-term goals for future studies.
- **SR00** We also believe that this indicator is a good representation of the quality of the reporting. No significant difference was observed between the S_R of studies that use a purely classical approach and the S_R of studies that use a hybrid approach. However, among the studies that use a hybrid approach, those that involve gate-based quantum computers have a much lower S_R than those that involve quantum annealers. This is another evidence that supports our belief that future studies using gate-based quantum computers would benefit from much better quality standards.
- **SR01** A significant majority of the selected studies present their overall structure in the beginning of their text. However, a significant portion of studies still do not. We hypothesize that this is due to text constraints placed by conferences (and possibly journals), as evidenced by the exploratory data analysis. We observed that almost 66% of the studies sourced from journals present their overall structure, while only 50% of the studies sourced from conferences do it. We believe that studies should present their overall structure if possible, as it helps reader to navigate quickly and easily.

- **SR02** We observed that almost all of the selected studies present the motivation behind their work. We believe that future work should also follow this trend, since motivation is what justifies the need for conducting the work.
- **SR03** A great majority of the studies present their research questions or goals in the beginning of the text. With a similar reasoning as in feature SR02, we also believe that future work should follow this trend.
- **SR04** We observed that few studies summarize their methodology in the beginning of the text. We believe that this is detrimental for readers who wish to perform a quick lookup before reading the full-text, and also that future work should aim for summarizing the methodology in the beginning of the text. An example of this summary that was identified among the studies is a brief text that describes the methodology as a series of high-level steps.
- **SR05** A significantly small portion of the selected studies does not summarize conclusions in the beginning of the text. We believe that this is also detrimental for readers who wish to perform a quick lookup before reading the full-text. Hence, we believe that future publications should aim to summarize the conclusions at the beginning of the text. One good example of this summary that was observed among the studies would be a bulleted list of the conclusions.
- **SR06** Almost all of the selected studies presented their methodology in a way that it is reproducible. We believe that future work should strive to keep this trend.
- **SR07** Among the selected studies, almost all of them present their application in a way that its implementation can be reproduced. This is another trend that we believe future work should strive for.
- **SR08** We observed that very few studies present their comparison algorithms in a way that their implementation is possible. We believe that this is detrimental for readers who wish to reproduce or check the implementation, and that future work should strive to share the details of the implementation.
- **SR09** A great majority of the studies share details that make it possible for readers to reproduce the scenarios, settings or variables used in their work. Once again, this is a trend that we believe future studies should aim for.
- **SR10** Almost all of the studies describe their statistical analysis in a way that makes it reproducible. We expect future work to continue this trend.
- **SR11** All the selected studies use images or tables when presenting their results. Images and tables are effective tools to summarize and display results, and we expect future work to keep relying on these visualization tools.
- **SR12** Almost all the articles refer to and explain all the tables and images that are shown. The few articles that do not are usually associated with lower quality scores. There is margin for improvement, as we believe that there should not be as many articles not referring to and explaining their images. Hence, future work should improve this metric.
- **SR13** All but very few articles use all their references in the text. The few that do not are usually associated with lower quality scores. We expect future studies to maintain this trend.

SR14

Only three of the 149 studies have released a publicly available code repository where readers can consult implementation details. We find this number disappointing, because we believe that code repositories are one of the most effective tools to replicate research work. For this reason, we believe that future work should share their implementation details with publicly available code repositories, complete with documentation.

- **SR15** Fortunately, the three studies with a publicly available code repository also documented their code. This is another expectation that we believe future work should attend to. Publicly available code repositories lose their effectiveness if readers are not capable of understanding the implementation details.
- **SR16** A significant majority of the studies do not directly describe their contributions. We believe that future work should summarize their contributions, whether in the beginning or in the end of the text. A good example of this would be a bulleted list of the contributions shown in the introduction or in the conclusion, as some of the selected studies do.

DO10

We observed that the great majority of the studies use a purely classical approach ($\approx 81\%$). The remaining studies follow a hybrid approach. Although there is some merit in bringing quantum inspirations to purely classical approaches, we believe that future work should focus more on leveraging quantum computers in hybrid approaches, especially as we are currently witnessing a rapid growth in the capabilities of quantum machines. Moreover, certain ISIC sections lack any hybrid approach so far, such as "electricity, gas, steam and air conditioning supply", and also others that have very few hybrid applications in comparison to purely classical applications, such as "Manufacturing", "water supply; sewerage, waste management and remediation activities", and "professional, scientific and technical activities". To sum up, we believe that underexplored ISIC sections present valuable opportunities for future work, especially if it involves a hybrid approach.

- **DO20** We observed 26 different types of algorithms among the selected studies, which is a promising sign of quantum inspirations being applied in many different algorithms. However, all but six algorithms only have one or two studies. In fact, the *Quantum Particle Swarm Optimization* algorithm is used in around 43% of the studies, followed by the *Quadratic Unconstrained Binary Optimization* approach, which accounts for almost 17% of the studies. Other promising algorithms include the *Quantum Genetic Algorithm*, the *Quantum-inspired Evolutionary Algorithm*, and the *Quantum Bat Algorithm*. We also found that the QPSO is dominant in studies in the ISIC section "electricity, gas, steam and air conditioning supply", whereas the QUBO approach is dominant in the ISIC section "transportation and storage". The QUBO approach stands out from the other algorithms because it is a very recent approach that first appeared in 2017 and is already on its way to surpass the QPSO in number of publications per year, which is aligned with the availability of quantum annealers in the market. In terms of publication source, we found that the QUBO approach also stands out from other algorithms because it has more publications from conferences than from journals. We believe that future work should explore the application of QUBO in ISIC sections not yet explored, such as "electricity, gas, steam and air conditioning supply". Moreover, we believe that there is opportunity to extend work on underexplored algorithms, so as to achieve both good quantity and good quality.

- **D030** Among the studies that use algorithms that can be used in quantum computers, all but one used a real quantum computer. The remaining one used a simulator. For this reason, our analysis of this feature in comparison with other features was not feasible. Nonetheless, as simulators are becoming increasingly unable to keep up with the size of current quantum computers, we do not foresee a strong need for more studies using simulators. Therefore, we expect future work to follow this trend of using only real quantum computers.

D040

Quantum annealers are associated with all but two of the studies that use algorithms that can be used in quantum computers. The other two studies are associated with gate-based quantum computers. This low number hindered our ability to analyze this feature with respect to other features. The very low number of studies involving gate-based quantum computers was expected, since currently available gate-based quantum computers are still of very small size and unable to handle problems of realistic size. Nonetheless, given the rapid growth of gate-based quantum computers that we are witnessing, future work should focus on leveraging these computers once they become feasible.

D050

Considering the 21 ISIC sections, seven have no associated studies, another seven have only one or two associated studies, and another seven are associated with the great majority of the studies. These 14 underexplored ISIC sections present opportunities for future work. The two most frequent ISIC sections are "electricity, gas, steam and air conditioning supply" and "transportation and storage", amounting to around 48% of the studies. The next two most frequent ISIC sections are "manufacturing" and "professional, scientific and technical activities", amounting to almost 29% of the studies. The other three ISIC sections are "information and communication", "water supply; sewerage, waste management and remediation activities", and "public administration and defence; compulsory social security". When also considering the publication year of the studies, we noticed that the ISIC section "water supply; sewerage, waste management and remediation activities" appears to be subject of a renewed research interest in recent years (2020 and 2021).

- **D051** When considering the ISIC divisions of the studies, we observed two divisions that reflected almost 45% of the studies: "electricity, gas, steam and air conditioning supply" and "warehousing and support activities for transportation". Other divisions are not as expressive but are still significant, such as "public administration and defence; compulsory social security", "architectural and engineering activities; technical testing and analysis", "activities of head offices; management consultancy activities", "water collection, treatment and supply", "information service activities", and "repair and installation of machinery and equipment". The remaining divisions are not significant or have no associated studies. We refer the reader to the treemap chart and icicle chart in the webpage to explore the selected studies in terms of the ISIC hierarchy.

- **D052** Examining the ISIC groups of the studies reveals that certain groups stand out due to their large amount of associated studies. Namely, “electric power generation, transmission and distribution”, “support activities for transportation”, “architectural and engineering activities and related technical consultancy”, “repair of fabricated metal products, machinery and equipment”, “data processing, hosting and related activities; web portals”, “activities of head offices”, and “water collection, treatment and supply”. The remaining ISIC groups have very few or no studies.
- **D053** Considering the last subdivision of the ISIC, some classes that have significant expression, such as “electric power generation, transmission and distribution” with around 24% of the studies, “other transportation support activities” with almost 15%, “architectural and engineering activities and related technical consultancy” with around 8%, “data processing, hosting and related activities” with around 5%, “activities of head offices” and “repair of machinery” both with almost 5%, “service activities incidental to air transportation” with just over 4%, and “water collection, treatment and supply” with just over 3%, among others. For more details, we refer the reader to our webpage.
- **D060** We have identified a growing trend in the number of publications per year. This growth is expected as the number of active researchers in the field of quantum computing has been growing, as well as the availability and capabilities of quantum computers. We believe that this growth in the number of publications will continue during the coming years.
- **D070** Examining the last feature, we observe that a significant majority of the selected studies were sourced from journals, while all but two the remaining studies were sourced from conferences. There are two studies sourced from workshops. We noticed that the conference-sourced studies started becoming expressive in numbers only during recent years, with a big spike in 2021. We think that this growth spur in recent years is aligned with the market availability of quantum computers, as well as with the existence of conferences dedicated as a whole or in part to quantum algorithms. We also noticed a big spike in journal publications in 2020, many of which are related with the ISIC class “electric power generation, transmission and distribution”. The reason for this spike was not identified. All in all, we expect conference-sourced studies to gain more expression in comparison to journal-sourced studies during the coming years. We also expect more workshop-sourced works to be published, as motivation to bring new researchers to the field is currently increasing.

4.2 Answers to the Proposed Research Questions

Now that the findings have been analyzed and discussed, we are ready to formulate our answers to the research questions that were posed.

RQ1. *What are existing approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research?* We have identified two types of approaches that apply quantum or quantum-inspired algorithms to the field of OR: approaches that are purely classical, and approaches that are hybrid. Each type has its own associated set of possible algorithms.

Considering the approaches of the purely classical type, the following algorithms were applied to OR problems, listed from most applied to least applied (an identifier is placed next to each algorithm, for future reference):

- Quantum Particle Swarm Optimization (ALG1)
- Quantum Genetic Algorithm (ALG2)
- Quantum-inspired Evolutionary Algorithm (ALG3)
- Quantum Bat Algorithm (ALG4)
- Quadratic Unconstrained Binary Optimization (ALG5)

- Quantum-inspired Shuffled Frog Leaping Algorithm (ALG6)
- Quantum Ant Colony Algorithm (ALG7)
- Quantum-behaved Pigeon-inspired Optimization (ALG8)
- Quantum-Behaved Lightning Search Algorithm (ALG9)
- Bi-direction Quantum Crossover Based Clonal Algorithm (ALG10)
- Quantum-inspired Tidal Firefly Algorithm (ALG11)
- Quantum-inspired Binary TVIW-GSA-PSO (ALG12)
- Quantum-based Grey Wolf Optimizer (ALG13)
- Quantum Inspired Grammar-based Linear Genetic Programming (ALG14)
- Quantum Multi-Agent Based Neural Network (ALG15)
- Chaotic Quantum Bee Colony Algorithm (ALG16)
- Quantum Dragonfly Algorithm (ALG17)
- Quantum Discrete Self-Organizing Migrating Algorithm (ALG18)
- Quantum Chaotic Animal Migration Optimization Algorithm (ALG19)
- Logistic Chaotic Quantum Dot Cellular Automata (ALG20)
- Hierarchical Quantum Entropy (ALG21)
- Real-parameter Quantum-inspired Evolutionary Clustering Algorithm (ALG22)

On the other hand, the list of algorithms that were applied in hybrid approaches is short:

- Quadratic Unconstrained Binary Optimization (ALG5)
- Quantum Generative Training (ALG23)
- Quantum Circuit (ALG24)
- Decomposition into QUBOs (ALG25)
- Quantum Alternating Operator Ansatz (ALG26)

Almost all of the hybrid approaches leverage quantum annealers, and the remaining few took advantage of gate-based quantum computers. More concretely, *Quadratic Unconstrained Binary Optimization*, *Decomposition into QUBOs*, and *Quantum Generative Training* were used in approaches that use quantum annealers, while *Quantum Circuit* and *Quantum Alternating Operator Ansatz* were used in approaches that use gate-based quantum computers.

RQ2. *In which sources, in which years, and in which quantities were approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research published?* For the second research question, we refer to figure 50, which discriminates the selected studies by their source and their year of publication, while also illustrating the number of publications per year. A total of 149 studies were selected and analyzed, and the years 2020 and 2021 are the years with most publications.

RQ3. *Which research questions related to approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research are addressed by a significant amount of evidence (evidence clusters)?* Considering the possible research questions that may be posed when applying quantum or quantum-inspired algorithms to OR problems, our findings suggest that research questions related to certain algorithms and certain industry activity sectors have been addressed by a significant amount of evidence. That is, our findings suggest that research questions involving the application of each of the following algorithms in OR problems have been addressed by a significant amount of evidence: ALG1 (64 primary studies); ALG5 (25 primary studies); ALG2 (17 primary studies); and ALG3 (10 primary studies).

Moreover, research questions involving the following industry sections have also been addressed by a significant amount of evidence:

- Electricity, gas, steam and air conditioning supply (37 primary studies)

- Transportation and storage (35 primary studies)
- Manufacturing (22 primary studies)
- Professional, scientific and technical activities (21 primary studies)
- Information and communication (13 primary studies)

More specifically, also involving the following industry activities:

- Electric power generation, transmission and distribution
- Support activities for transportation
- Architectural and engineering activities and related technical consultancy

The remaining algorithms and industry sections do not have a sufficient amount of evidence for us to be comfortable with the validity and generalization of their findings.

For more details regarding the number of primary studies that have been done for each algorithm and each industry activity, we refer the reader to the subsection B.4 and to our website, which displays interactive charts such as a treemap chart and an icicle chart.

RQ4. *Which research questions related to approaches that apply quantum or quantum-inspired algorithms to the field of Operations Research are addressed by a scarce amount of evidence (evidence deserts)?* Any research questions that were not addressed with a significant amount of evidence, such as the ones identified in **RQ3.** are the answer to **RQ4.** Nonetheless, answering this research question with a response of the type “anything that is not...” is non-illuminating and not useful. To avoid this situation, we employed the ISIC standard to classify the OR problems addressed by the studies in a way that enables us to know which industry activities have been addressed and which have not.

Our findings show that research questions involving OR problems belonging to the following ISIC sections remain underexplored:

- Agriculture, forestry and fishing
- Mining and quarrying
- Water supply; sewerage, waste management and remediation activities
- Construction
- Wholesale and retail trade; repair of motor vehicles and motorcycles
- Accommodation and food service activities
- Financial and insurance activities
- Real estate activities
- Administrative and support service activities
- Public administration and defence; compulsory social security
- Education
- Human health and social work activities
- Arts, entertainment and recreation
- Other service activities
- Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use
- Activities of extraterritorial organizations and bodies

Moreover, our findings show that research questions involving the following algorithms remain underexplored: `ALG4` ; `ALG6`; `ALG7`; `ALG8`; `ALG9`; `ALG10`; `ALG11`; `ALG12`; `ALG13`; `ALG14`; `ALG15`; `ALG16`;

`ALG17`; `ALG18`; `ALG19`; `ALG20`; `ALG21`; `ALG22`; `ALG23`; `ALG24`; `ALG25`; and `ALG26`.

We also found primary studies involving gate-based quantum computers to have very low quality and very low quantity. That is, only two studies were found, with subpar quality.

Again, for more details regarding the number of primary studies that have been done for each algorithm and each industry activity, as well as more insights, we refer the reader to the subsection B.4 and to our website.
We also remind the reader that our code and data are available in our public GitHub repository.

4.3 Decision Flowchart

We developed a decision flowchart that guides researchers in finding a new research question to tackle. It is aimed for researchers who are interested in starting their first work on an application of a quantum or quantum-inspired algorithm on an OR problem. The flowchart is shown in figure 2. By answering the top and bottom questions, we receive suggestions for research ideas. Both research ideas can be joined to create a path for future work.

5 CONCLUSION

The increasing complexity of operations research (OR) problems and the emergence of quantum and quantum-inspired algorithms has brought a new research field: applications of quantum or quantum-inspired algorithms in OR problems. This field is still in its infancy, due to its low number of primary studies. We identified two necessities that arose from this situation: researchers starting research work in this field need to know what research has been done and what are the potential paths for future work; and professionals need to know what are the most promising applications for operational problems in their industry sector.

After a literature search, we reunited all the conditions to begin a systematic mapping study. We believe that this is the best way to meet the aforementioned needs, especially considering that the existing literature is still far from being sufficiently developed to perform a systematic literature review.

We designed a protocol that specifies every step of the systematic mapping study in detail. This makes it possible for any reader to reproduce the systematic mapping study. The protocol begins with a set of research questions that are aimed to be answered by the systematic mapping study. In short, the main goal is to find existing approaches that apply quantum or quantum-inspired algorithms to OR problems, while also detailing which applications are addressed by a significant amount of evidence and which applications are addressed by a scarce amount of evidence.

We resorted to several electronic databases as part of our search step, using string queries constructed with the aid of the PICOC criteria. We found 325 documents with the electronic databases. This search was extended with reverse snowball sampling and forward snowball sampling, which are methods that add the documents in the references and the citing documents. In the end, more than 2 000 documents were added and considered.

The study selection step is done in an alternate fashion at the same time as the search step. That is, we selected the studies right after the electronic database search, right after the reverse snowball sampling, and right after the forward snowball sampling. The selection step consists of the application of inclusion and exclusion criteria, with the goal of selecting only studies that are

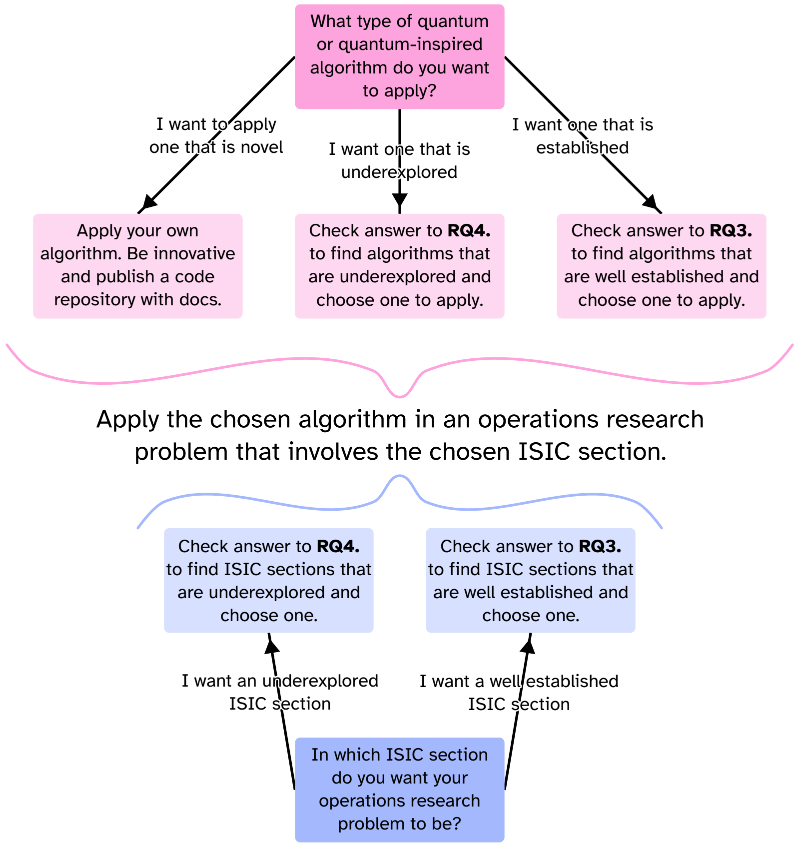

Fig. 2. Decision flowchart to help researchers who are interested in joining the field to find a good research question.

relevant to our research questions. The search and selection steps culminated in 149 studies, the majority coming from journals and conferences of high prestige.

The next step is the quality assessment, which passes each document through two checklists of "yes or no" questions, one related with the quality of the study and the other related with the quality of the reporting. Thanks to this assessment, we gained lots of insights related with the research methods and the structural features of the studies. The quality assessment was partly supported by the SJR Indicators of the journal-sourced studies and the CORE Rankings of the conference-sourced studies. We believe that the quality scores attributed to the studies are representative of their quality, especially when their attributed score is low.

The following step is the data extraction and classification, where a series of data features are extracted from the studies—more concretely, features such as *Type of Approach*, *Algorithm Name*, *Type of Quantum Computer*, *Publication Source*, among others. Moreover, four additional features were inferred from the studies, using the International Standard Industrial Classification of All Economic Activities (ISIC), which enabled us to find to which industry activity each study belongs to. All the features considered, we have extracted a powerful set of data features that enables us to find useful insights not only about the features themselves but also the relationships between the features.

The most significant step in the systematic mapping study is the analysis, which is responsible for exploring the extracted data with the main goal of finding relevant insights that help us address the research questions of the mapping. Our analysis was divided into three parts. First, we focused on the individual features themselves. Next, we focused on the relationship between pairs of features. Last, we performed a non-systematic exploratory data analysis with the goal of finding any insight that was not captured by the other two parts. From a general standpoint, we were able to analyze in an effective way, with lots of useful findings that culminated into a productive discussion and useful answers to the research questions. However, two features were not subject to the same level of analysis as originally specified in the protocol due to lack of evidence. These features are `D030` and `D040`.

In the end, we were able to produce a itemized list of insights, each item corresponding to each data feature. We believe that this lets readers navigate quickly among the synthesized insights. With the convenience of the reader in mind, we also produced a subsection with direct answers to the research questions that were posed. We believe that those outputs are particularly useful for readers who wish to go straight to the point, and also for those that wish to know what are the potential paths for future work.

To add to the two textual outputs, another two non-textual outputs were also produced, a decision flowchart and a website. The decision flowchart aims to help researchers that are interested in finding a research question to be addressed as part of a new research work. The website displays a series of interactive charts, letting users direcly explore the data that was extracted as part of the systematic study and acquire even more insights.

All the outputs considered, we believe that, by taking into account the convenience of the reader, we are maximizing the effectiveness of the systematic mapping study. That is, we believe that we have met our goal of providing a map of what has already been explored and a list of potential paths for further exploration in a way that is effective and easy to digest to readers who are interested in joining the research effort.

Considering the findings themselves, it was exciting for us to see that most of the applications focus on essential economy activities such as electricity supply, transportation, and manufacturing. However, we also would like to see more effort in other activities such as agriculture, forestry, and fishing, as well as construction, art, and mining. We believe that more applications in such sectors would be very valuable and impactful for the field. We also challenge newcomers to apply quantum algorithms in activities such as education, accommodation and food service, finance and insurance, and real estate. These activities, despite not being as explored as the others, are equally important and prevalent, and improvements in algorithms would still be very significant. Plus, we would learn about potential advantages that quantum or quantum-inspired algorithms may specifically bring to these activities. We also challenge newcomers who want to research in an already explored ISIC section to explore applications on ISIC divisions, groups, or classes that were not explored as much.

Now, shifting our view to the coming years, we expect to witness quick progress on the field, as quantum computers become more available and capable of larger problems. This means that we expect our systematic mapping study to become obsolete before the year 2030. However, we believe that our protocol can easily be replicated and modified for any future work that wishes to produce a new systematic mapping study or even a systematic literature review. Until then, we are open to submissions from authors who wish to add their primary studies to our website, to keep our insights up-to-date.

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A FOR ELECTRONIC PUBLICATION—SUPPLEMENTARY MATERIAL: DETAILED SEARCH AND STUDY SELECTION

In this supplementary material, we present a detailed description of the search and study selection steps of the systematic mapping study. The search step is detailed in subsection A.1 and the study selection step is detailed in A.2.

A.1 Search

A systematic mapping study should strive for a selection of papers that constitute a good representation of the population. Hence, more papers is not necessarily better, as it may induce a distorted view of the overall research extant in the area. Nonetheless, if very few papers have been published so far in the area, it may be adequate to search for the maximum amount of papers possible [110].

In our case, a simple and quick search in electronic databases suggests that very few papers apply quantum or quantum-inspired algorithms in the context of OR (e.g., by searching in IEEE Xplore for the keywords "`Quantum`" and "`Operations Research`"). Hence, during our search step, we will be targeting the maximum amount of studies while still keeping the number of studies feasible. Particularly, we should avoid steps in our search strategy that lead to an explosion in the number of findings.

For our SMS, three search strategies are used: electronic database search, reverse snowball sampling, and forward snowball sampling. In the following subsubsections, each search strategy is described in the order they are performed. We call the reader to take into account that those strategies are used while doing study selection between them, a step that is described in the next subsection. Figure 3 illustrates the order of these search and study selection steps during the SMS, which resulted in a list of 149 primary studies [176, 15, 79, 162, 109, 131, 34, 33, 84, 107, 106, 119, 147, 14, 164, 42, 81, 123, 172, 45, 158, 35, 99, 103, 36, 137, 132, 133, 122, 77, 125, 67, 136, 31, 143, 161, 58, 25, 39, 17, 8, 154, 155, 160, 85, 47, 89, 128, 113, 149, 44, 12, 60, 59, 26, 55, 118, 121, 101, 16, 32, 50, 46, 90, 139, 43, 24, 78, 82, 142, 68, 53, 135, 171, 170, 23, 150, 178, 169, 62, 22, 75, 92, 80, 87, 86, 108, 145, 159, 129, 140, 97, 13, 37, 173, 179, 146, 124, 51, 74, 49, 61, 157, 168, 1, 167, 71, 175, 156, 153, 52, 76, 152, 102, 116, 134, 144, 66, 126, 127, 112, 115, 114, 117, 27, 130, 148, 163, 2, 6, 10, 11, 65, 105, 19, 54, 18, 20, 29, 100, 165, 174, 3, 4, 5, 48, 91, 69, 70].

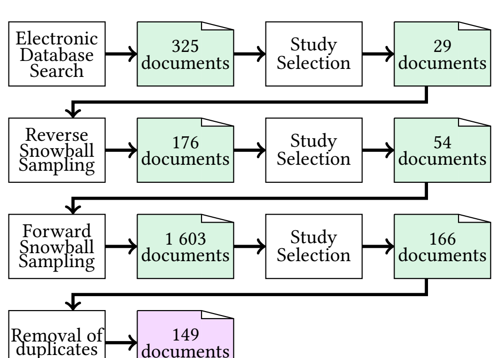

Fig. 3. Illustration of the steps taken while searching and selecting studies and the number of selected documents after each step.

A.1.1 Electronic Database Search. First, a set of papers is identified using electronic database search. For this purpose, the PICOC criteria is used to develop search strings that are accepted by different electronic databases [64, 110]:

Population. Operations Research
Intervention. Quantum Algorithms OR Quantum-inspired Algorithms
Comparison. Not applicable.
Outcomes. Not applicable.
Context. Not applicable.

The *Comparison*, *Outcomes*, and *Context* criteria were not used because we believe that by including these criteria the search would get too restricted [110]. In the same way, special caution was taken with the Population criterion, since Operations Research may be used interchangeably with other terms, such as Operational Research, Operations Management, Operational Management, Operations Strategy, Operational Strategy, Operations Strategies, and Operational Strategies. All these variations were incorporated into the search strings.

Regarding the Intervention criterion, we opted for a more general search term, "quantum". The reasoning is that studies which contain "Quantum Algorithm" or "Quantum-inspired Algorithm" will hit that term, while some more specific studies that contain "Quantum-behaved Particle Swarm Optimization Algorithm" will also hit that term, but not "Quantum Algorithms", unless we developed very specific and complicated rules for these search strings.

We identified a set of electronic databases that we believe to be relevant and extensive, while providing useful tools such as exporting the search results: Scopus, IEEE Xplore, ACM Digital Library, Inspec, Compendex & Knovel, and ScienceDirect. With respect to other well-known electronic databases, we explain why these were excluded: Google Scholar does not provide a tool to export the search results; ArXiv is a database of mainly preprints, which do not undergo full peer review; and SpringerLink's publications are also indexed in Scopus.

Taking into account the chosen PICOC criteria, the goal of our search, the special caution with the Population criterion, the option for a more general search term instead of the Intervention criterion, and the electronic databases that we identified, we developed the search strings listed in table 6.

Once the search in electronic databases is finished, we advance to the study selection step, as mentioned before. After that, we go back to the search step to perform the reverse snowball sampling technique, as described next.

A.1.2 Reverse Snowball Sampling. In this part of the search, we perform reverse snowball sampling in each of the identified studies, except those that were identified in the study selection step as being too old. Reverse snowball sampling is a technique to find more studies that are related to those that were already found [57, 63, 110]. In our case, we go through each reference in a study, and if its title appears to be related in some way to the research questions we have specified, then we add that study to our collection of documents. This technique is repeated for every study identified during the first part of the search step, the search in electronic databases.

In its original form, this technique should also be repeated for any study added while performing it, going back in time until we reach a date of publication that is considered too early, which is a recursive behavior. However, we decided to limit this recursive behavior to the articles identified in the search in electronic databases, as further recursion would lead to an explosion in the number of findings, making the SMS unfeasible.

Once the reverse snowball sampling is performed on each of the identified studies, we advance again to the study selection step. Afterward, we return to the search step, advancing to the next part, in which we perform the forward snowball sampling technique.

Table 6. List of search strings used in the systematic mapping study, grouped by the electronic database they are used for.

Electronic Database	Search String
Scopus	`(TITLE-ABS-KEY("operations research" OR "operational research" OR "operations management" OR "operational management" OR "operations strategy" OR "operational strategy" OR "operations strategies") OR "operational strategies") AND TITLE-ABS-KEY(quantum))`
IEEE Xplore	`("All Metadata":"operations research" OR "All Metadata":"operations management" OR "All Metadata":"operations strategy" OR "All Metadata":"operations strategies" OR "All Metadata":"operational research" OR "All Metadata":"operational management" OR "All Metadata":"operational strategy" OR "All Metadata":"operational strategies") AND ("All Metadata":quantum)`
ACM Digital Library	`"query": AllField:("Operations Research" OR "Operations Management" OR "Operations Strategy" OR "Operations Strategies" OR "Operational Research" OR "Operational Management" OR "Operational Strategy" OR "Operational Strategies") AND AllField:(quantum) "filter": Article Type: Research Article,ACM Content: DL`
Inspec, Compendex & Knovel	`((("operations research" OR "operations management" OR "operations strategy" OR "operations strategies" OR "operational research" OR "operational management" OR "operational strategy" OR "operational strategies") WN KY) AND ((quantum) WN KY)) + (ja OR ca) WN DT`
ScienceDirect	`(("operations research" OR "operations management" OR "operations strategy" OR "operations strategies" OR "operational research" OR "operational management" OR "operational strategy" OR "operational strategies") AND (quantum))` in title, abstract or author-specified keywords

A.1.3 Forward Snowball Sampling. In the final part of the search, we perform forward snowball sampling in each of the studies that were included during the study selection step. This is another technique to find more studies that are related to those that were already found [57, 63, 110]. In this snowball sampling technique, instead of going through the references of a study, we use electronic databases to find studies that cite that study, going forward in time. We add every study we find that cites any of the included studies.

Not all electronic databases support finding studies that cite a target study. Therefore, the choice of electronic databases for this technique is important, since it determines the number of studies that we are able to find. We identified a set of electronic databases that we believe to be relevant and extensive, while providing the option to export the search results: Scopus and Dimensions. We also identified Google Scholar as a relevant and extensive electronic database, but it lacks the option to export the search results.

Considering the electronic databases we have identified, we developed a protocol for finding studies that cite a study. First, we use the tools available at the study's publisher website to find citing studies. Second, we use Scopus to find citing studies. Next, we use Dimensions to find citing studies. Last, we use Google Scholar to find citing studies, but only if its search results contain fewer than 50 studies, since we are unable to export the search results in this electronic database.

As with the reverse variant, the forward snowball sampling also has a recursive behavior in its original form. However, for the same reasons as before, we decided to limit this recursive behavior to the included studies, as further recursion would cause an explosion in the number of findings, making the SMS unfeasible.

Once the forward snowball sampling is applied on each of the included studies, we discard any duplicates we may have. After that, the search step is finished and we advance to the next step, study selection, which will be executed once again, for the last time.

A.2 Study Selection

In this step, the collected studies pass through a selection process that decides which studies are candidates for answering some or all of the specified research questions. For this step, we read the title and abstract of each study.

The selection process consists of checking each study against a set of inclusion and exclusion criteria. This means that, by default, a study is excluded. To be included, the study needs to meet all the inclusion criteria. However, once the study meets any of the exclusion criteria, it is immediately excluded.

In order to validate the study selection, for each study, we find its ranking based on the SCImago Journal & Country Rank (SJCR) or on the conference rankings from the Computing Research and Education Association of Australasia (CORE), depending on whether the study is part of a journal or of a conference. For studies that belong to journals, we chose to use the SJR Indicator, as it is a good measure of the influence of the journal, enabling us to compare each study in terms of its journal’s influence [88]. We also take into account the SJR Best Quartile for the same purposes. For studies that belong to conferences, we chose to use the CORE rankings, since their method assigns each conference to a specific category with an associated prestige and impact [21]. However, we note that those indicators are limited and cannot be taken at face value.

Once we have determined the rankings associated with each of the studies, we validate the selection process by analyzing the distribution of selected studies among the rankings, since it provides an evidence on whether our process generally selects studies associated with journals and conferences with a higher prestige.

A.2.1 Inclusion Criteria. The inclusion criteria are a set of conditions that a study must verify in order to be included. To maintain the feasibility of the study, we accept only peer-reviewed studies written in English and published during or after 2011. We chose 2011 because it was in this year that the first commercially available quantum computer was released—D-Wave One, from D-Wave Systems, Inc. Moreover, a quick search in electronic databases also suggests that research on real-world applications with quantum and quantum-inspired algorithms only started to become significant during the years after 2011.

Regarding the specified research questions, we have an inclusion criterion which requires the study to present an application of a quantum or quantum-inspired algorithm in an OR context. The following list details the inclusion criteria that a study must meet.

- Studies written in English.
- Studies whose publication type corresponds to Peer-reviewed Scientific Articles in a classification derived by the Ministry of Education of Finland based on publication activities of universities (publication types A and C)[2].
- Studies published during or after 2011.
- Studies that present an application of a quantum or quantum-inspired algorithm in an Operations Research context.

To clear any ambiguity and to aid the reproducibility of this work, we specify “Operations Research context” as follows:

- Any application in a real-world scenario that is part of a program that improves the operation of a system.
- Any application in a simulated scenario, simplified or not, that is part of a program that improves the operation of a system.
- Any theoretical application that was mainly designed to improve the operation of a system.

[2]Details about the classification are available in a website from the Finnish Ministry of Education and Culture.

- Any theoretical application that was mainly designed to solve an optimization problem that is sufficiently complex to be understood as easily translatable to an Operations Research problem, such as the tail assignment problem.
- **Not** a theoretical application that was mainly designed to solve a simple optimization problem that can be extended to operations research problem, such as the knapsack problem.

If doubt exists on whether a study meets an inclusion criterion, we check if the study meets the other inclusion criteria. If it does, we check the exclusion criteria. If it was not excluded, then we read its full-text. If doubt persists, then we assume that the study meets that criterion.

A.2.2 Exclusion Criteria. The exclusion criteria are another set of conditions that a study must **not** verify in order to maintain its inclusion. In this regard, we only want primary studies, since our goal is to find any evidence that has been produced about the application of quantum or quantum-inspired algorithms in the context of OR. We also avoid including studies whose full-text is unavailable to us. The following list details in depth the exclusion criteria on which a study will be excluded if it meets any of the criteria.

- Studies that are not a primary study, such as reviews that analyze a set of different quantum algorithms presented in primary studies.
- Books, compilations of proceedings, and gray literature.
- Studies whose full-text is not accessible.

If there exists doubt on whether a study meets an exclusion criterion, we check the other exclusion criterion. If it was not excluded, then we read its full-text. If doubt persists, then we assume that it does not meet that criterion. The SMS should include the number of articles that are excluded due to the lack of access to their full-text, as well as the reason for the lack of access.

B FOR ELECTRONIC PUBLICATION—SUPPLEMENTARY MATERIAL: RESULTS OF THE SYSTEMATIC MAPPING STUDY

In this supplementary material, we present the outcomes of the systematic mapping study, following the structure of the research method: first, the search and selection results are shown in subsection B.1; second, the results of the quality assessment step and its validation are shown in subsection B.2; then, in subsection B.3, the results from the data extraction and classification step are presented; finally, subsection B.4 shows the outcomes of the analysis.

B.1 Search and Study Selection

As mentioned in section 3, each of the three search substeps is followed by a selection step. All in all, more than 2 000 studies were considered, including duplicates. Ultimately, a total of 149 studies were selected, as shown in figure 3. We note that, among the excluded articles, 6 articles were excluded due to the lack of institutional access to their full-text. Although we have tried our best to include these papers, we should clarify that, while our institutions regularly update their subscriptions to account for all representative databases from the most relevant publishers, including taking into account suggestions from affiliated researchers, their corresponding venues were not encountered.

Table 7 shows the number of documents added by each search method and the number of documents selected from them, as well as their respective hit rates. Considering the hit rates, reverse snowball sampling stands out because of its very good hit rate, albeit starting from a low number of documents. Nonetheless, considering the number of documents simultaneously added and selected, forward snowball sampling was the most significant search method; it led to the inclusion of more documents than the other two search methods combined.

Table 7. Number of documents added by each search method and selected from them, together with their hit rate.

Search method	# docs. added	# docs. selected	Hit rate
Electronic database search	325	29	$\approx 8.92\%$
Reverse snowball sampling	147	25	$\approx 17.01\%$
Forward snowball sampling	1 549	112	$\approx 7.23\%$

As detailed in the research method, as part of the validation of the study search and selection steps, we used the ranking of each study based on the SCImago Journal & Country Rank (SJCR) or on the conference rankings from the Computing Research and Education Association of Australasia (CORE), whenever possible.

As shown in figure 4, among the 149 selected studies, 111 correspond to publications from journals, 36 correspond to publications from conferences, and two correspond to publications from workshops. The proportions are, respectively, 74.5%, 24.2%, and 1.3%.

Considering the publications sourced from journals, figure 5 shows the violin plot of the distribution of their SJR Indicator. Figure 6 presents the distribution of these publications in respect of their SJR Best Quartile. We note that an SJR Indicator of 1 corresponds to a journal with average prestige and influence, while higher (respectively lower) values correspond to journals with higher (respectively lower) influence.

Considering these distributions, out of the 111 journal-sourced publications, 60 correspond to an SJR Best Quartile of Q1, while 24 correspond to the SJR Best Quartile of Q2. In other words, just over

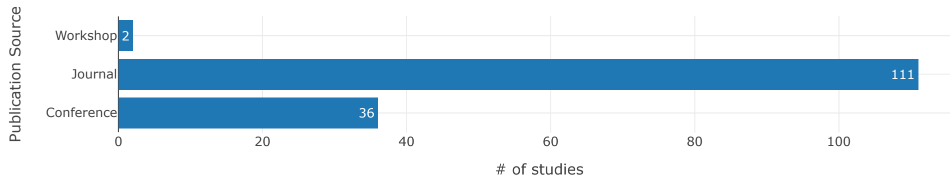

Fig. 4. Distribution of selected studies according to their publication source.

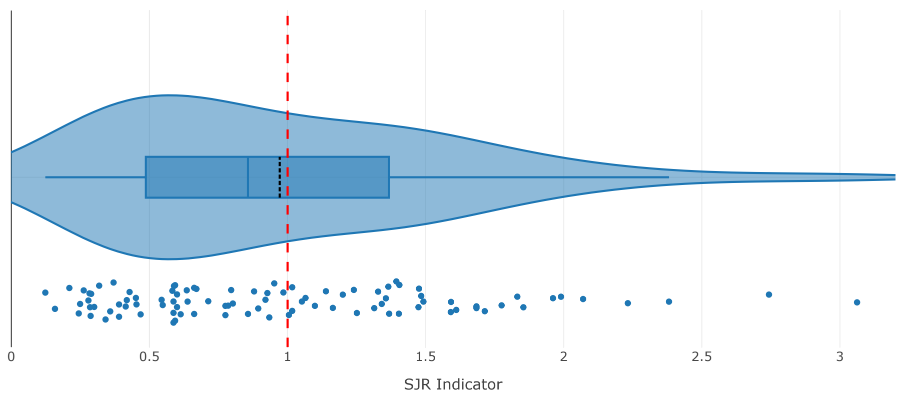

Fig. 5. Violin plot of the distribution of the SJR Indicator of the selected studies that were published in journals. The SJR Indicator of 1 is marked in a vertical red dashed line. The median is marked in a vertical black dashed line inside the box plot.

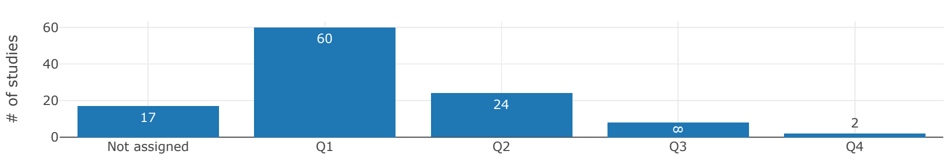

Fig. 6. Bar plot of the distribution of the SJR Best Quartiles of the selected studies that were published in journals.

three-quarters of these publications (≈ 76%) correspond to studies published in better-than-average journals in terms of their SJR Best Quartile.

Considering the publications sourced from conferences, figure 7 shows the distribution of the CORE Rankings among the 36 selected studies. Twenty-four of these studies were not assigned to any CORE Ranking, which may suggest that the studies are being published in recent and/or less-known conferences. Five of the remaining studies were assigned an A ranking, and another 5 were assigned a B ranking. A ranking of A corresponds to a study published in an "excellent conference, and highly respected in a discipline area," whereas a ranking of B corresponds to a study published in a "good to very good conference, and well regarded in a discipline area." Finally, considering the two remaining studies, one was assigned a ranking of C—"conference venues that meet basic standards for peer reviewed venues"—and the other was not assigned to any ranking, as it corresponds to a "conference which is run primarily in a single country, usually with Chairs from that country, and which is not sufficiently well known to be ranked."

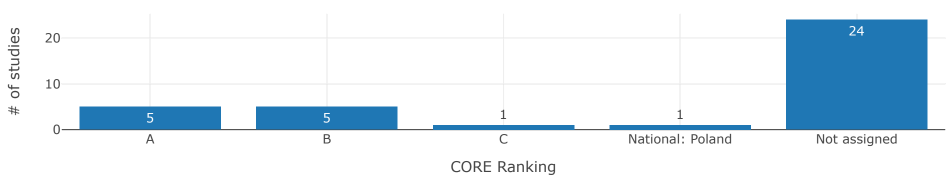

Fig. 7. Bar plot of the distribution of the CORE Rankings of the selected studies published in conferences.

These results suggest that our search and selection process was effective, since it found a set of studies that are relevant and have sufficient quality according to the considered indicators. The large amount of studies considered suggests that the set of selected studies is a good representation of the universe of primary studies that are relevant to answer our research questions.

B.2 Quality Assessment

In this step, the studies have been assessed concerning their measured quality according to our developed criteria. Figure 8 shows the distribution of the values of S_S and S_R of the selected studies.

To validate this step, we look for the correlations between S_S, S_R, the SJR Indicator, and the CORE Rankings. We expect higher rankings to be associated with higher quality scores, which would serve as evidence that our quality assessment is still representative of the quality of the studies, although focused on our research questions.

First, the correlation between S_S and S_R is evident when we look at figure 9. This correlation is accepted by the nonparametric statistical test Spearman rank-order correlation coefficient, which rejected the null-hypothesis that the correlation between both scores is non-positive, with a p-value of $p < 0.001$. We note that the p-value should be interpreted while taking into account the size of the sample set for the statistical test.

Second, for the correlations between the quality scores and the SJR Indicator, we present figures 10 and 11, which show two scatter plots illustrating the correlations. In this situation, the correlation is not as obvious, but it appears that, as we move from the left part of the chart to the right part, the SJR Indicators have a larger range of values, which also increases in terms of maximum value. In other words, studies that we assessed with a low quality score are associated with below-average SJR Indicators, whereas studies that we assessed with a high quality score are associated with any SJR Indicator. We expected this pattern, as we contend that journals with high SJR Indicators produce high-quality studies, while journals with low SJR Indicators may produce both high-

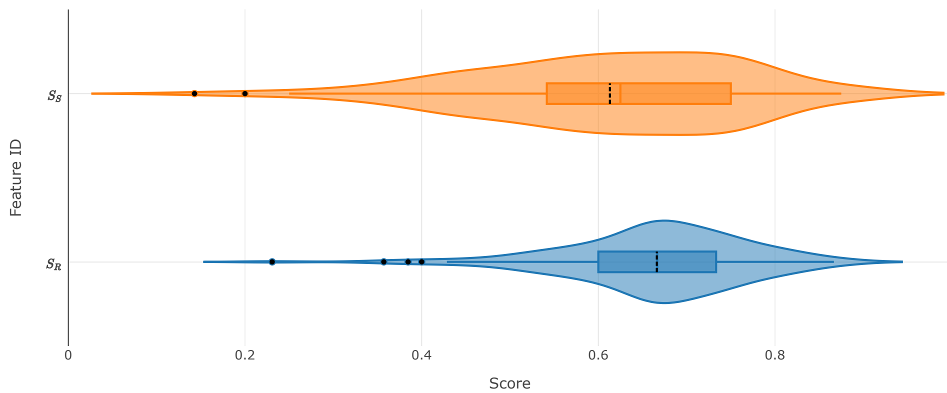

Fig. 8. Violin plots of the S_S and S_R values of the selected studies. Black dots represent the outliers. The black dashed line represents the median.

and low-quality studies. We used the Spearman's rank-order correlation coefficient to check the statistical confidence between the quality scores and the SJR Indicator. The results are shown in table 8 and suggest the existence of a significant positive correlation between S_R and the SJR Indicator for a significance level of $\alpha = 0.05$, whereas the correlation between S_S and the SJR Indicator is not strongly significant under the same significance level.

Table 8. p-values obtained when computing the Spearman rank-order correlation coefficient between the S_S and S_R scores and the SJR Indicator and CORE rankings of the selected studies. Bold values reject the null hypothesis that there is no correlation for a significance level of $\alpha = 0.05$.

	S_S	S_R
SJR Indicator	$p \approx 0.122$	**$p \approx 0.011$**
CORE Ranking	**$p \approx 0.012$**	**$p \approx 0.007$**

For further detail, we also present box plots illustrating the distribution of the quality scores of the selected studies grouped by their SJR Best Quartile in figures 12 and 13. The relationship between these values becomes more noticeable when we also look at these box plots, particularly for S_S.

Next, for the correlations between the quality scores and the CORE Rankings, we show box plots illustrating the distribution of the quality scores of the selected studies grouped by their CORE Rankings in figures 14 and 15. The box plots suggest that the studies that have an assigned CORE Ranking are part of the studies with the highest quality scores, while studies without an assigned CORE Ranking are much more sparse, with scores between 0.14 and 0.8. We also performed the same statistical test as with the journal-sourced studies, the Spearman's rank-order correlation coefficient. The results are shown in 8 and suggest a significant correlation between our assessed quality scores and the CORE Rankings, for a significance level of $\alpha = 0.05$. However, we call readers'

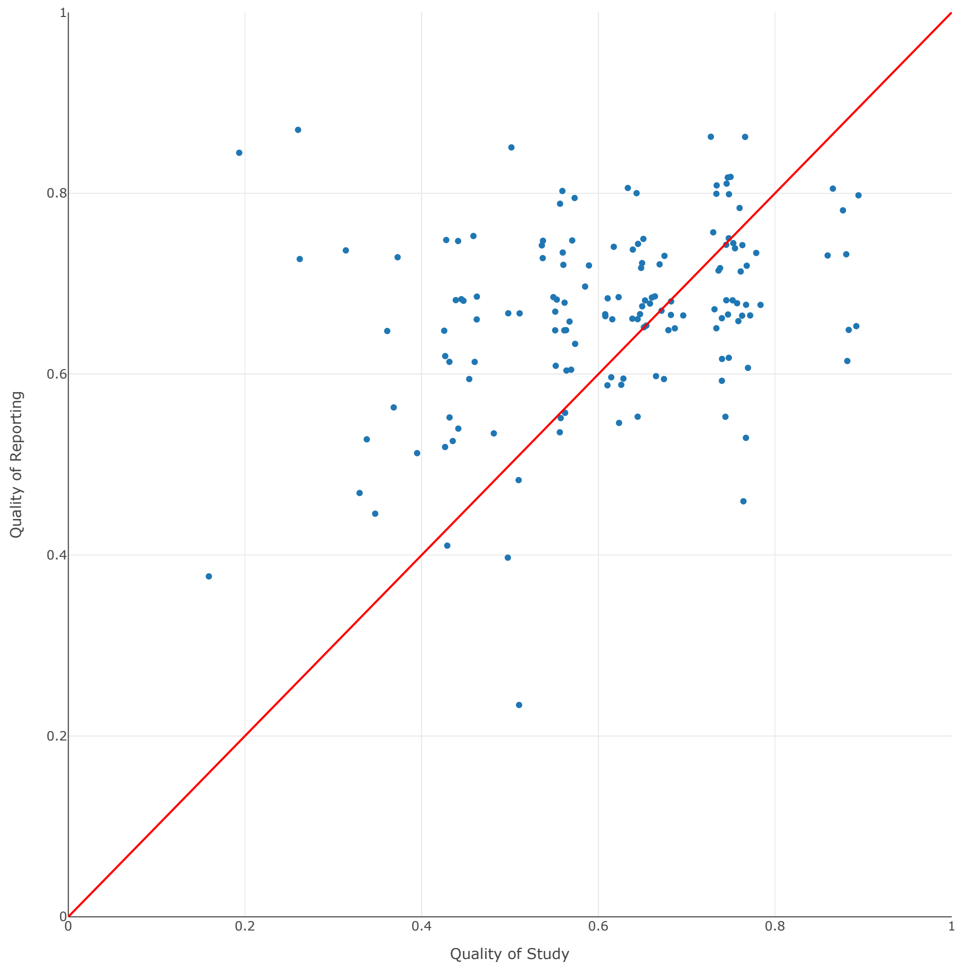

Fig. 9. Scatter plot of the S_S and S_R values of each of the selected studies. Blue dots represent the selected studies, and the red line is a visual aid to mark the diagonal of the chart. All the dots in a perfect positive correlation between both scores would overlap the line.

attention to the fact that these tests use a very small sample of 32 studies, a size that makes the statistical test unreliable when considered by itself.

All in all, our search and selection procedures reunited a set of studies that are both relevant to our research questions and sufficiently good according to our expectations. Moreover, these procedures enabled us to collect additional insight regarding the selected studies, which will be considered in subsection B.4.

B.3 Data Extraction and Classification

For the data extraction and classification step, each of the 149 selected studies was analyzed and read in order to fill the extraction form shown in table 3. The overall process was straightforward,

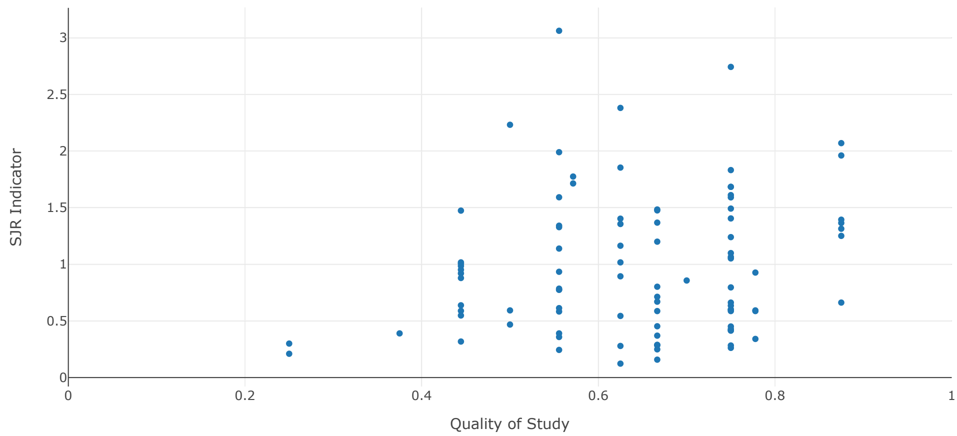

Fig. 10. Scatter plot of the S_S value and SJR Indicator of each of the selected studies. Blue dots represent the selected studies.

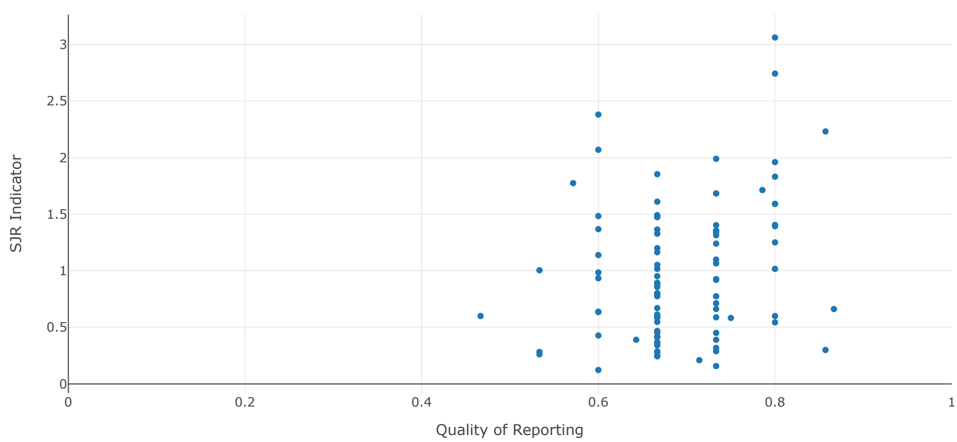

Fig. 11. Scatter plot of the S_R value and SJR Indicator of each of the selected studies. Blue dots represent the selected studies.

as the majority of the data was unequivocal to extract. Nonetheless, there existed some doubt when attributing ISIC sections, divisions, groups or classes. Fortunately, the doubt was cleared by following the instructions from the protocol, as the information from subgroups could be used to discriminate the most appropriate group. The extracted data is shown in subsection B.4, where it is analyzed.

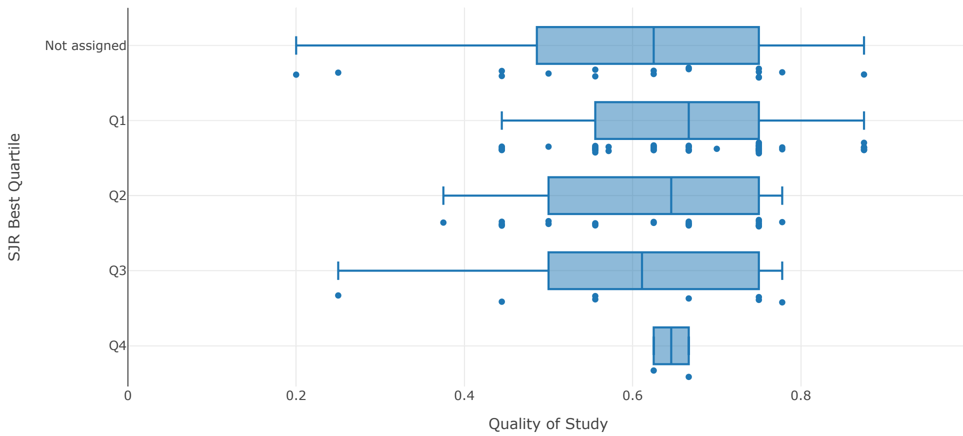

Fig. 12. Box plots of the S_S value of the selected studies, grouped by their SJR Best Quartile. Blue dots represent the selected studies.

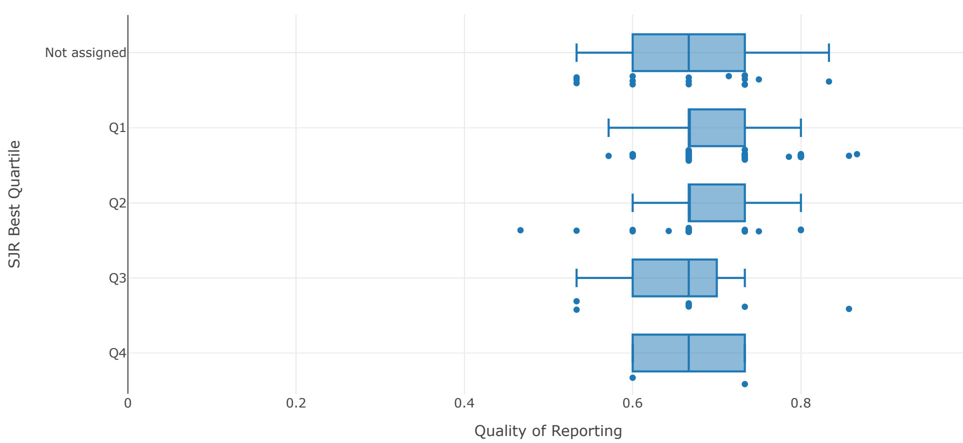

Fig. 13. Box plots of the S_R value of the selected studies, grouped by their SJR Best Quartile. Blue dots represent the selected studies.

We have published all of the collected data on a website that has interactive charts, which enables users to directly explore the collected data.
We have also published our code and data in a GitHub repository, so that readers can download it and use their own methods to extract more insights.

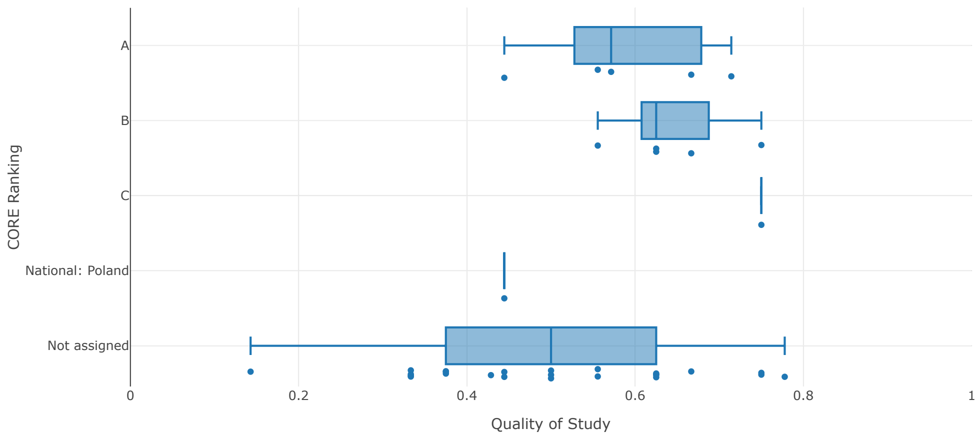

Fig. 14. Box plots of the S_S value of the selected studies, grouped by their CORE Ranking. Blue dots represent the selected studies.

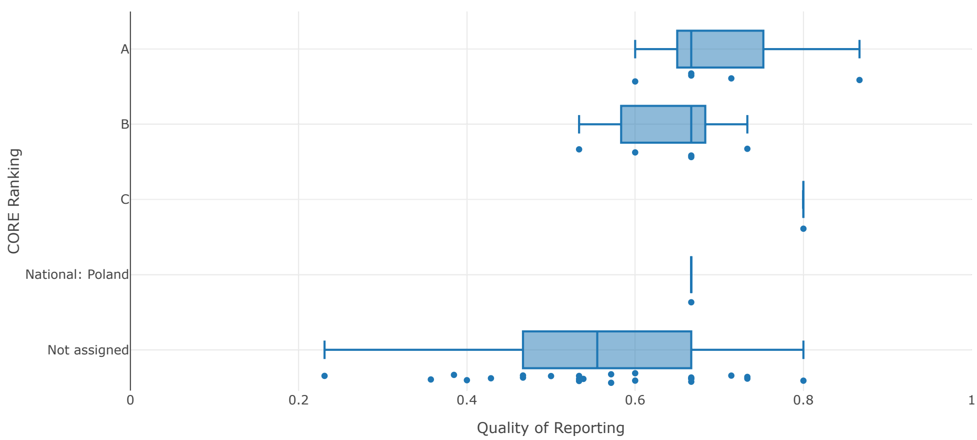

Fig. 15. Box plots of the S_R value of the selected studies, grouped by their CORE Ranking. Blue dots represent the selected studies.

B.4 Analysis

In this subsection, we present the data that was collected along with our analysis on that data. The analysis will be presented in a segmented fashion, with each segment dedicated to a group of features. For a more holistic interpretation of the results, we refer the reader to section 4, which contains the discussion of the study.

B.4.1 Analysis of Individual Features. The first analysis focuses on each feature listed in table 4. As mentioned above, the analysis is done in a segmented fashion. More concretely, we present paragraphs headed with the feature IDs that are the main subject of each paragraph.

SS00 *and* SR00*—Quality Scores.* The data is presented in figure 16, which shows the distribution of the S_S and S_R values. Looking at the violin plots, it appears that there is much more sparsity associated with the S_S values compared to the S_R values.

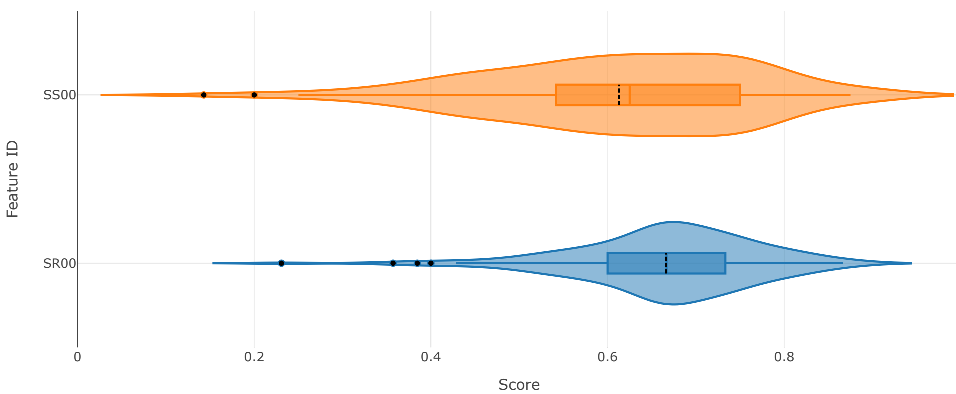

Fig. 16. Violin plots of the S_S and S_R values of the selected studies. Black dots represent the outliers. The black dashed line represents the median.

SS01 *to* SS10*—Checklist to Assess the Quality of the Study.* Figure 17 illustrates the proportions of the different responses collected as part of the checklist to assess the quality of the study. First, when looking at features SS01 and SS02, we understand that a great majority (≈ 88.6%) of the selected studies compare their proposed application with an existing application, and the remaining few do not make any sort of comparison. Plus, a large part of the aforementioned majority compares both algorithms across multiple scenarios. Second, focusing on features SS03 and SS04, we notice that close to half (≈ 47.0%) of the studies use a real-world scenario or case study for their application. However, the majority of the selected studies use benchmarks that are not based on real-world scenarios (≈ 51.7%). Then, looking at the bars of the feature SS05, it appears that very few studies use random values when defining their variables and/or scenarios. Moreover, among the studies that do use random values, just over half of these (≈ 53.8%) explain the reasoning behind the source of randomization that is used. As already implicit, when considering feature SS06, it appears that a great majority (≈ 92.6%) of the studies do use arbitrary definitions of their variables and/or scenarios, of which a large part (≈ 76.8%) explains the reasoning behind their arbitrary definitions. Moving on to features SS07 and SS08, we know that a great majority of the studies use statistical analysis (≈ 95.3%), but very few use statistical tests (≈ 16.1%). Next, looking at the bar of feature SS09, we observe that none of the studies addressed their reliability and validity threats. Finally, examining the last bar, SS10, we observe that a bit over half (≈ 60.4%) of the selected studies present considerations for their future work.

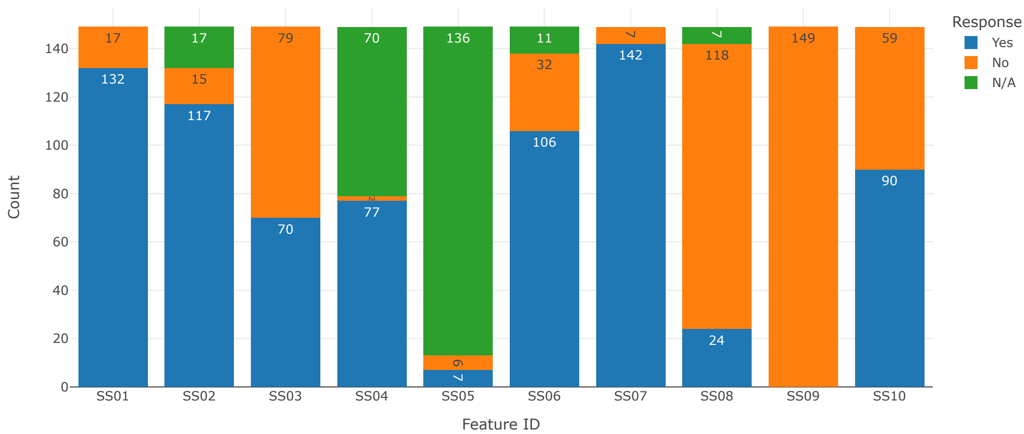

Fig. 17. Stacked bar charts with the proportions of the different responses (SS01 to SS10) collected for the checklist to assess the quality of the study.

SR01 *to* SR16—*Checklist to Assess the Quality of the Reporting.* Figure 18 illustrates the proportions of the different responses collected as part of the checklist to assess the quality of the reporting. First, looking at the bar of feature SR01, most of the selected studies (≈ 62.4%) present their overall structure. Second, looking at features SR02 to SR05, which are related to the structure of the studies, we observe that a great majority of the studies do present the motivation behind their application, as well as their research goals. However, a great majority of the studies lack a summary of their methodology and their conclusions. Third, considering features SR06 to SR10, we learn that a great majority of the studies (≈ 96.0%) present their methodology in a way that can be reproduced. Moreover, almost all of the studies from that majority also show a reproducible specification of their implementation (≈ 98.6%). However, very few of the selected studies that use a comparison algorithm present a reproducible specification for the comparison algorithm (≈ 16.7%). Moreover, a great majority of the studies present a reproducible specification of their scenarios (≈ 85.8%), as well as for their statistical analysis (≈ 99.3%). Moving on to features SR11 and SR12, we notice that all the studies use images or tables to present their results, and the great majority refer to and explain them in the text (≈ 88.6%). Afterwards, considering the bar of feature SR13, we observe that a great majority of the articles do use all their references in the text, with very few failing to cite or use some references (≈ 7.4%). Next, considering features SR14 and SR15, we observe that only three of the selected studies have a publicly available code repository with their application implementation. Fortunately, all three studies have documented their code. Finally, considering feature SR16, we observe that a significant majority of the studies do not list their contributions (≈ 67.1%).

D010—*Type of Approach.* The data in figure 19 shows the proportions of the different approaches of the selected studies. We observe that a significant majority of the studies (≈ 80.5%) use a purely classical application, while the remaining studies use a hybrid application. No studies use a purely quantum approach.

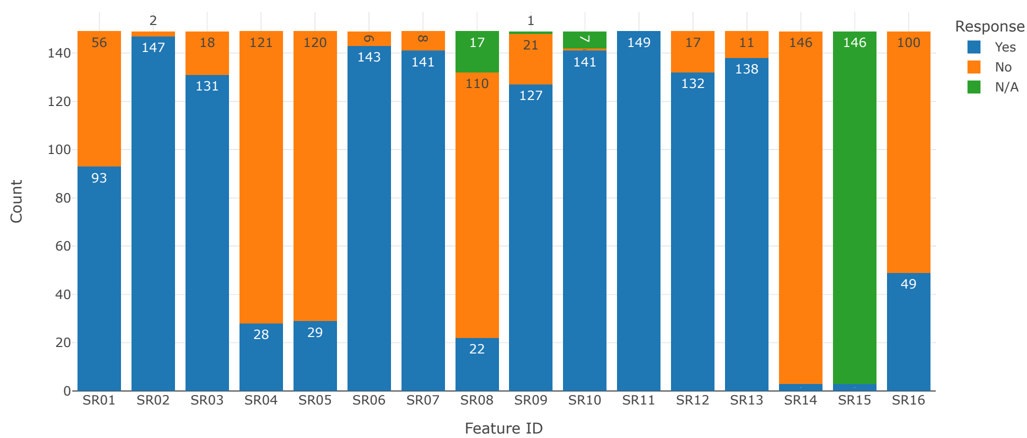

Fig. 18. Stacked bar charts with the proportions of the different responses (SR01 to SR16) collected for the checklist to assess the quality of the reporting.

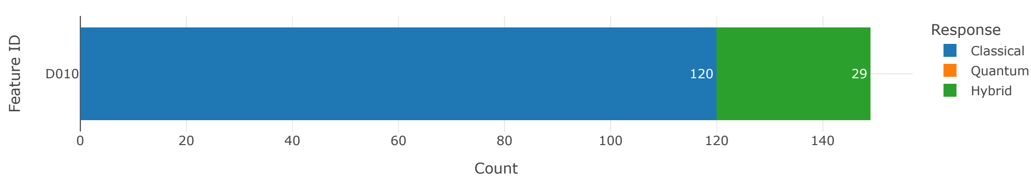

Fig. 19. Stacked bar chart with the proportions of the different responses collected for feature D010.

D030—*Does the study use a simulator or a real quantum computer?* Figure 20 presents the proportions of the different responses collected for feature D030. Out of the selected studies that use a hybrid approach, the great majority use a real quantum computer as part of their methodology (≈ 82.8%), and one study uses a simulator.

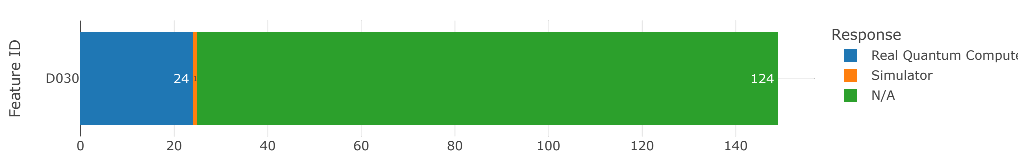

Fig. 20. Stacked bar chart with the proportions of the different responses collected for feature D030.

`D040`—*Type of Quantum Computer.* The proportions of the different responses collected for feature `D040` are shown in figure 21. Considering the studies that use a real quantum computer or a simulator, the great majority targeted quantum annealers (92%), while the remaining two studies targeted gate-based quantum computers.

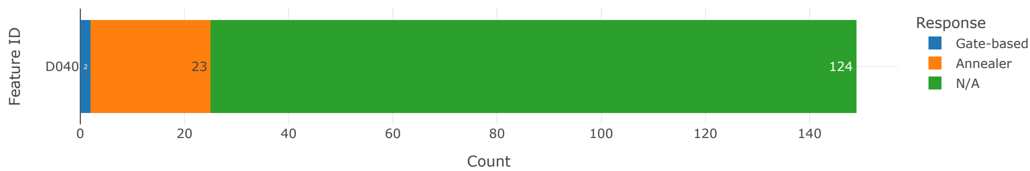

Fig. 21. Stacked bar chart with the proportions of the different responses collected for feature `D040`.

`D070`—*Publication Source.* Figure 22 presents the proportions of the publication sources of the selected studies. The large majority of the selected studies were published in journals (≈ 74.5%), while a significant part of were published in conferences (≈ 24.2%). Two articles were published in workshops.

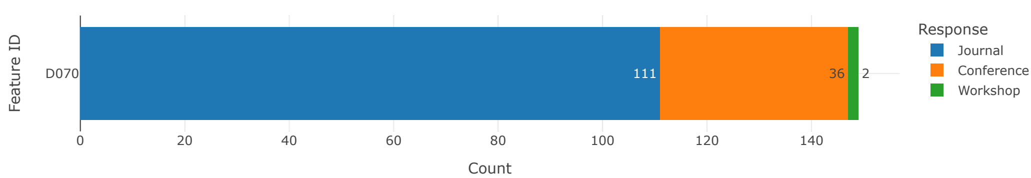

Fig. 22. Stacked bar chart with the proportions of the different responses collected for feature `D070`.

`D020`—*Algorithm Name.* Considering the algorithms used as part of the applications of the selected studies, figure 23 presents the distribution of such algorithms. We observe that a significant portion of the applied algorithms correspond to variants of the quantum particle swarm optimization (≈ 43.0%). Next, we have a significant portion of applications that are based on solving the formulation of their problem as a quadratic unconstrained binary optimization model (≈ 16.8%). Another significant portion involves quantum-inspired genetic and evolutionary algorithms (≈ 11.4% and ≈ 6.7%). All in all, 26 different types of algorithms have been applied to OR problems. A significant majority of these algorithms are applied only once or twice.

`D060`—*Publication Year.* Figure 24 shows the number of selected studies per publication year. A noticeable trend is toward more and more publications over time. The three years with the highest number of studies were 2020, 2021, and 2019, in order.

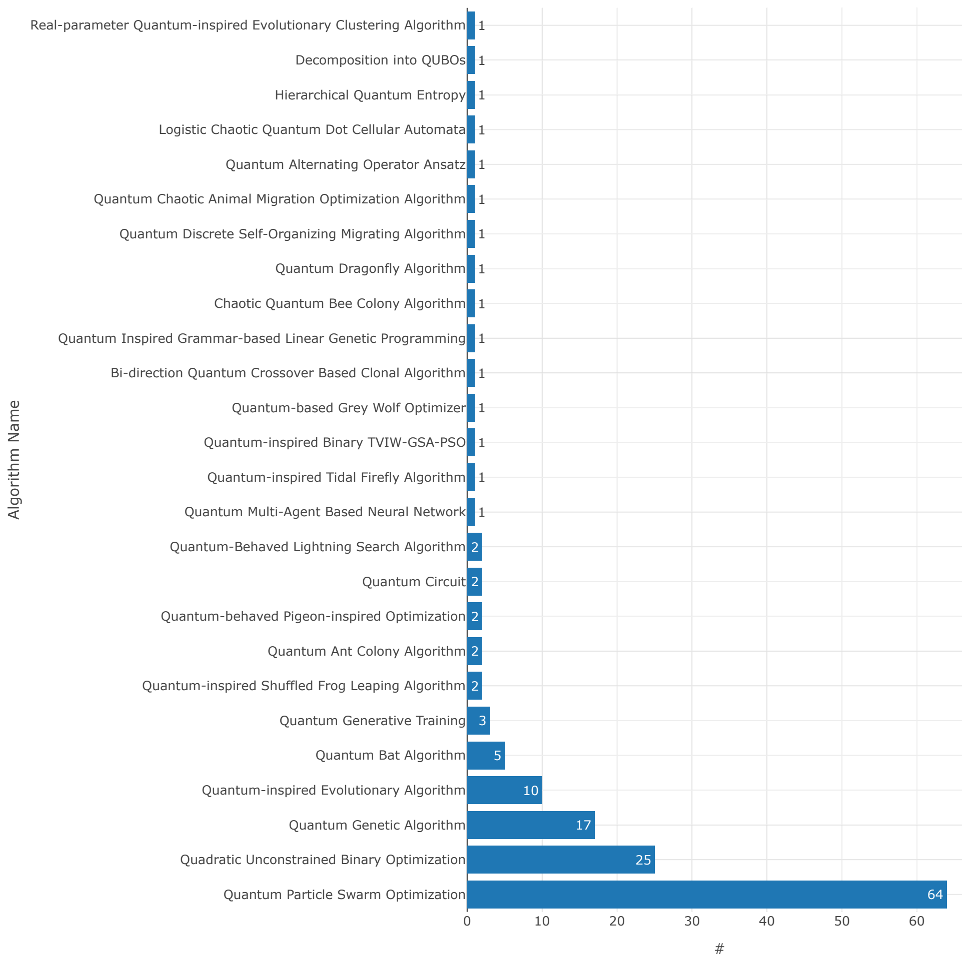

Fig. 23. Bar chart with the distribution of the different responses collected for feature `D020`.

`D050` *to* `D053`—*ISIC*. Figure 25 shows a bar chart with the distribution of the selected studies according to their ISIC section. We notice that the two most frequent ISIC sections are related to "electricity, gas, steam and air conditioning supply", and to "transportation and storage". Combined, these sections correspond to $\approx 48.3\%$ of the studies. The next two most frequent ISIC sections are related to "manufacturing" and to "professional, scientific and technical activities", with a combined share of $\approx 28.9\%$. Among all ISIC sections, seven have a significant amount of corresponding studies, another seven have only one or two corresponding studies, and another seven have no corresponding studies. Focusing on the seven ISIC sections that have a significant amount of corresponding studies, figure 26 shows the distribution of the studies belonging to these ISIC sections according to their ISIC division. This figure gives us a good idea of where the applications are being made. Concretely, lot of effort is seen in ISIC section D and in ISIC division "Warehousing

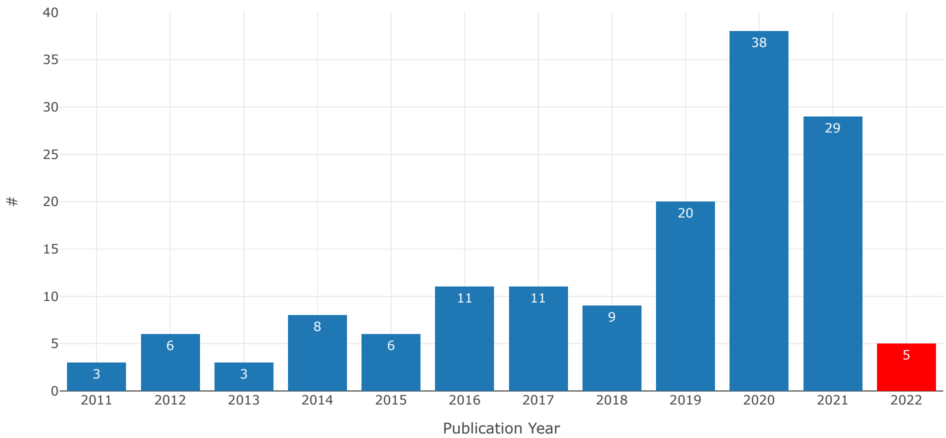

Fig. 24. Bar chart with the distribution of the different responses collected for feature D060. **Note that the bar for year 2022 only contains publications made in the first four months.**

and support activities for transportation". In other words, it appears that there is a significant effort to apply quantum or quantum-inspired algorithms in OR problems related to energy supply as well as transportation. Significant but sparse effort is visible in the remaining ISIC divisions. We note the amount of divisions that have corresponding studies under the ISIC section "Manufacturing"—it appears that there is an effort regarding applications in many different manufacturing activities, ranging from basic metals to computer products. We decided to go further in depth, by creating figure 27, which focuses on the studies corresponding to ISIC section "transportation and storage". This figure shows the distribution of these studies according to their ISIC group. We observe that almost all applications are concerned with "support activities for transportation", yet few are related to transport activities by themselves. For this reason, we decided to go once again further in depth with another figure. Figure 27 shows the distribution of the same studies according to their ISIC class. Here, we notice that some of the studies are concerned with "service activities incidental to air transportation", while others are concerned with "service activities incidental to land transportation". However, the majority of these are associated with "other transportation support activities". In other words, a significant share of the selected studies focus on applications in transportation support activities that are not directly related with air, land, or water transportation, nor with cargo handling.

We refer the reader to the webpage to explore an interactive treemap chart similar to the one shown in figure 29, as well as an interactive icicle chart.

B.4.2 Analysis of Relationships between Pairs Features. The second part of the analysis focuses on the relationships between the pairs of features listed in table 5. As in the first part, we present the analysis in a segmented fashion, heading paragraphs with the numbers of the pairs that are analyzed.

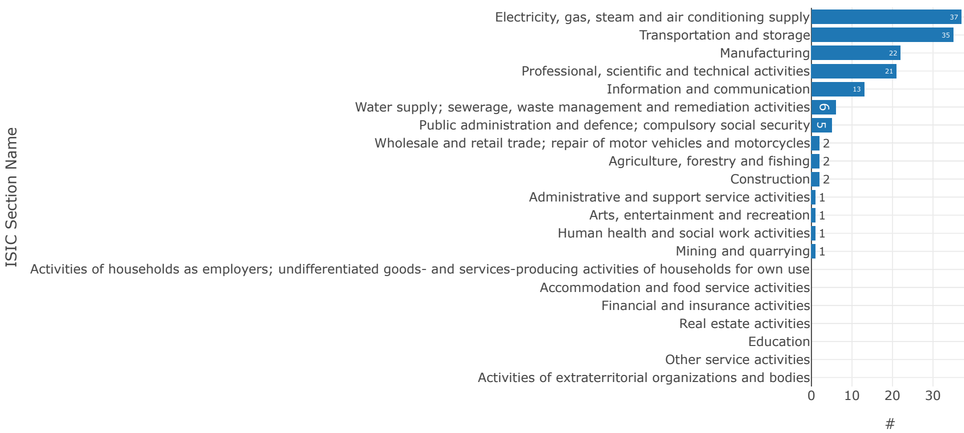

Fig. 25. Bar chart with the distribution of the selected studies according to their ISIC Section.

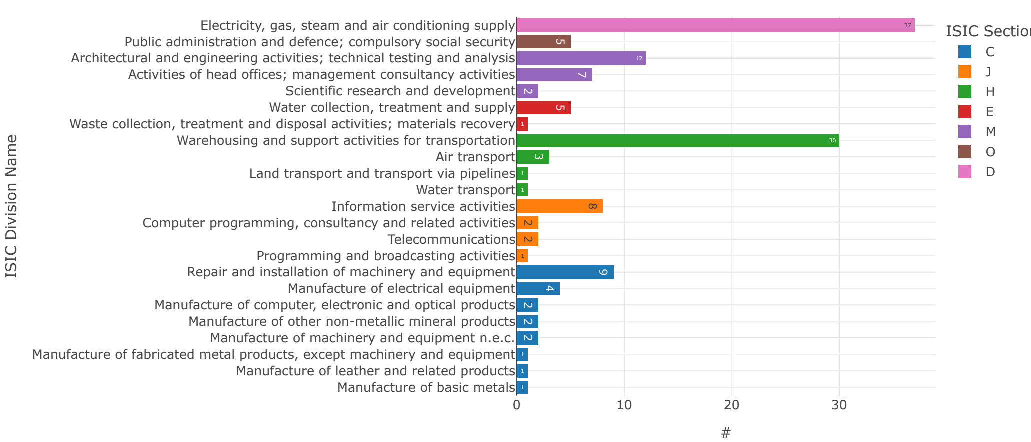

Fig. 26. Bar chart with the distribution of the studies belonging to ISIC sections C, D, E, H, J, M, and O, according to their ISIC Division.

Pair 1—`SS00` *and* `D010`. We begin by analyzing the relationship between features `SS00` and `D010`. Figure 30 shows the violin plots of the distributions of the S_S of the selected studies, grouped by their type of approach. At first glance, it appears that no significant difference exists between both distributions. Indeed, the Mann–Whitney U test does not reject the null hypothesis that the distributions are identical. The test returned p-value ≈ 0.231, given an alternative hypothesis that the median of the distribution of the *Classical* population is greater than the median of the distribution of the *Hybrid* population.

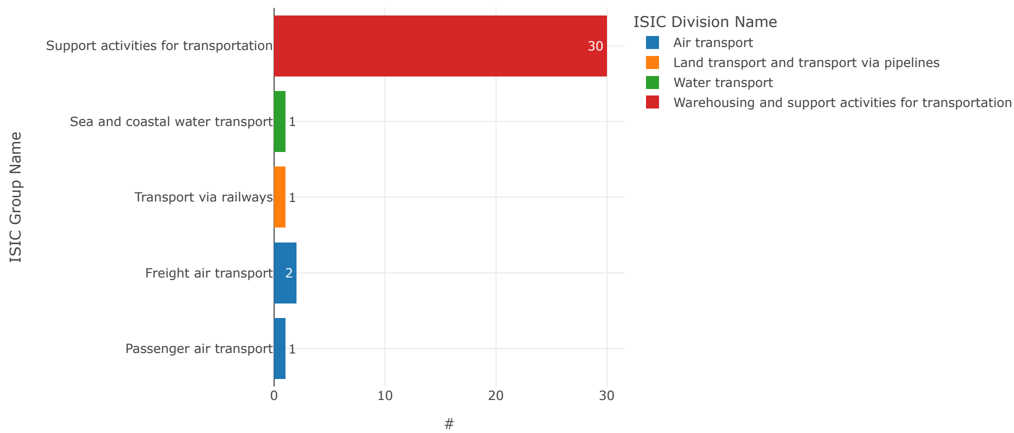

Fig. 27. Bar chart with the distribution of the studies belonging to ISIC section H according to their ISIC Group, colored by their ISIC Division.

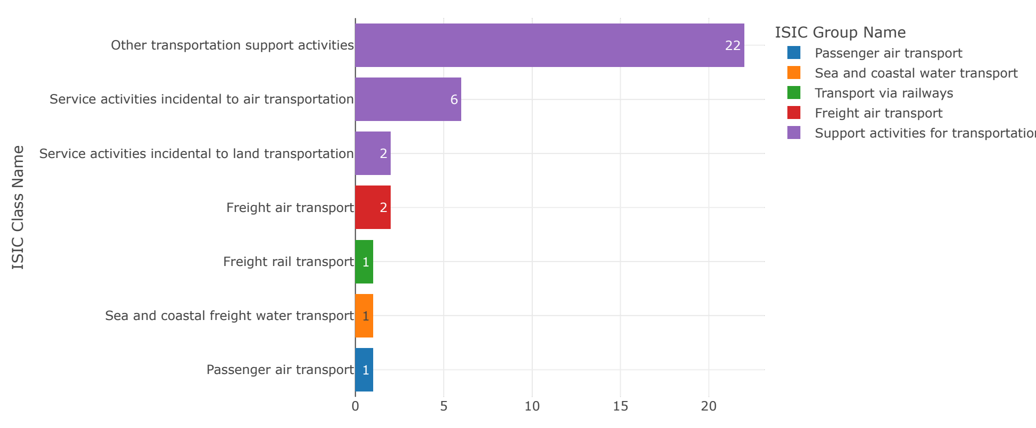

Fig. 28. Bar chart with the distribution of the studies belonging to ISIC section H according to their ISIC Class, colored by their ISIC Group.

Pair 2—`SS00` *and* `D020`. For the relationship between features `SS00` and `D020`, we decided to generate violin plots of the distributions of the S_S of the studies corresponding to the four most frequent algorithm names, as shown in figure 31. The remaining algorithm names were not considered, as they have a very low number of samples (≤ 5). A quick look suggests that the studies corresponding to the *Quantum Genetic Algorithm* have a significantly lower S_S compared to the ones corresponding to the *Quantum-inspired Evolutionary Algorithm* and to the *Quadratic Unconstrained Binary Optimization*. This suggestion is also supported by the results of the Mann–Whitney U test

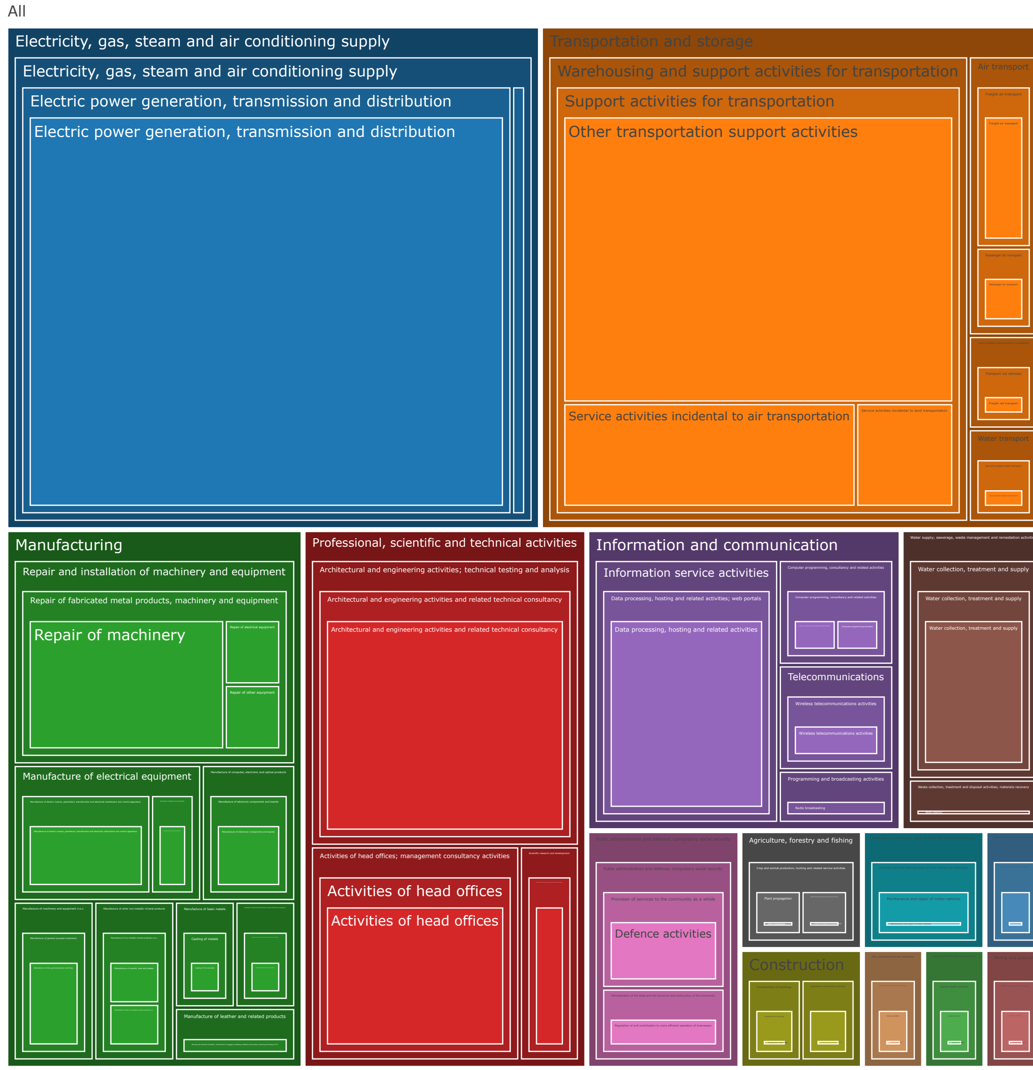

Fig. 29. Treemap of the selected studies according to their ISIC Section, Division, Group, and Class.

between all distributions, shown in table 9, which rejects the null hypothesis for a significance level of 5% between QUBO and QGA, as well as between QEA and QGA.

Pair 3—`SS00` *and* `D030`. We decided not to perform any analysis on the third pair, due to the lack of samples for one group. More concretely, only one of the selected studies uses a simulator, which prevents us from making any reasonable conclusion regarding this pair.

Pair 4—`SS00` *and* `D040`. The fourth pair is also affected by the lack of samples, since only two of the selected studies use gate-based quantum computers. Nonetheless, a great disparity in quality of the study is easy to see, as shown in figure 32, and supported by a Mann–Whitney U test that rejects the null hypothesis that the distributions are identical. The test returned p-value ≈ 0.032, given an alternative hypothesis that the median of the distribution of the *Annealer* population is

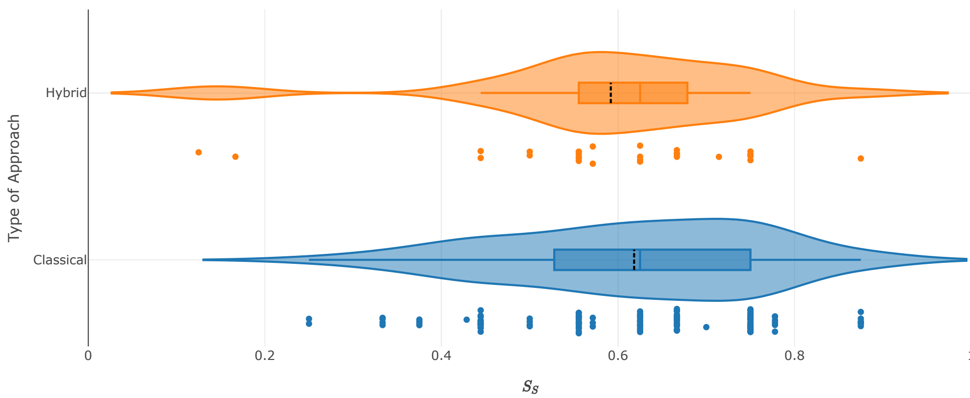

Fig. 30. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by their type of approach (`D010`).

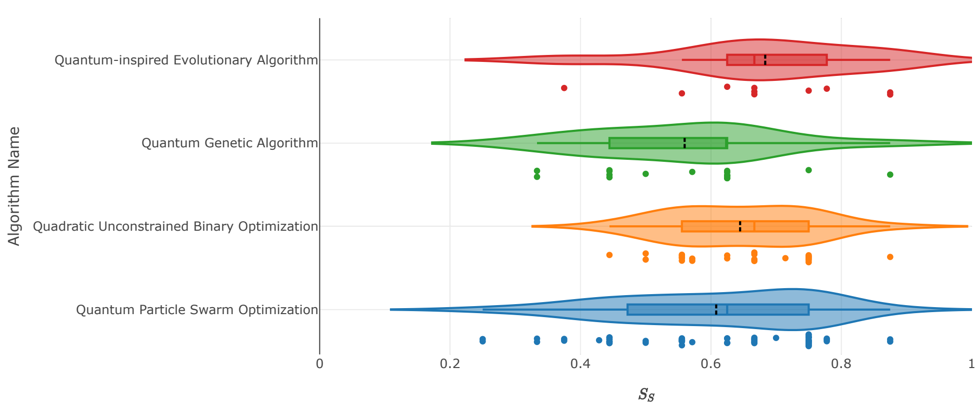

Fig. 31. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by the four most frequent algorithm names (`D020`).

greater than the median of the distribution of the *Gate-based* population. Still, we remind the reader that this test is taken with only two samples for one of the populations.

Pair 5—`SS00` *and* `D050`*.* Considering the relationship between features `SS00` and `D050`, we selected only the studies corresponding to the seven most frequent ISIC sections (C, D, E, H, J, M, and O). The remaining ISIC sections were disregarded due to their low number of samples (≤ 2). Figure 33 shows the violin plots of the distributions of the S_S of these studies, grouped by these ISIC sections.

Table 9. p-values returned by the Mann–Whitney U test between the distributions identified in pair 2 (SS00 and D020). Each value corresponds to an alternative hypothesis that the median of the distribution of the row population is greater than the median of the distribution of the column population. Values in bold reject the null hypothesis for a significance level of 5%.

—	QPSO	QUBO	QGA	QEA
QPSO	—	0.771	0.087	0.915
QUBO	0.232	—	**0.023**	0.846
QGA	0.915	0.978	—	0.990
QEA	0.088	0.163	**0.012**	—

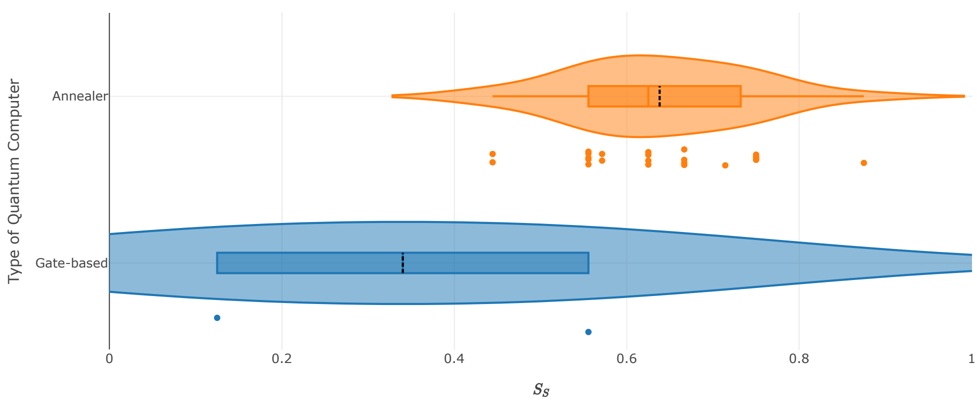

Fig. 32. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by the type of quantum computer (D040).

We do not notice any distribution that appears to be significantly different from any of the others. As shown in table 10, the Mann–Whitney U test did not reject the null hypothesis between any two distributions.

Pair 6—SS00 and D060. We analyzed the evolution of SS00 along the years, as illustrated by the violin plots in figure 34. The distributions shown in the figure appear to be sparse and inconsistent during the earlier years (2011 to 2015), which is expected, given the very low number of samples. As the number of samples increases with time, the distributions become more consistent and similar year over year. We do not observe any significant difference among years 2016 to 2021. We do not consider 2022 in this analysis, since it has a very low number of samples because it only contains publications made in the initial months. We also do not foresee any increasing or decreasing trend for the coming years with respect to the evolution of S_S.

Pair 7—SS00 and D070. For the last pair involving SS00, we analyze the relationship between this feature and D070. Figure 35 shows the violin plots of the the distributions of the S_S of the selected studies, grouped by their publication source. It becomes clear that the distribution of the studies

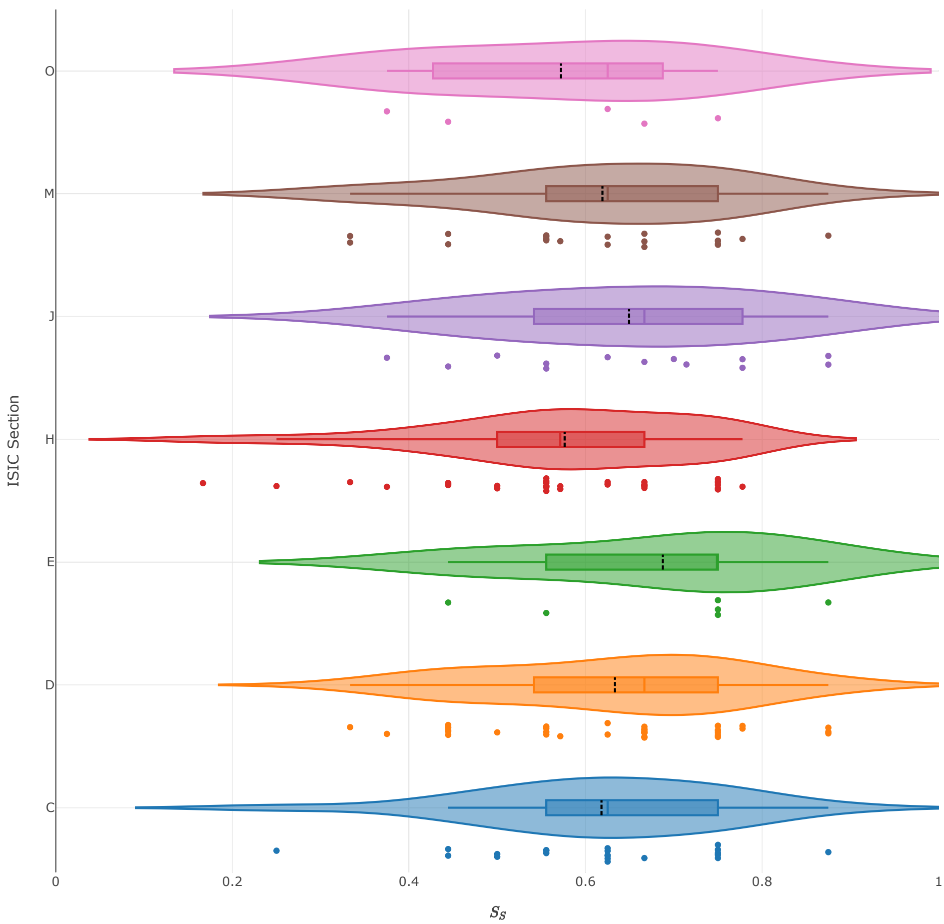

Fig. 33. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by the seven most frequent ISIC sections (D050).

published in journals has a greater median S_S compared to the studies published in conferences. This is supported by the Mann–Whitney U test between these distributions, which rejects the null hypothesis with a p-value of < 0.001, given an alternative hypothesis that the median of the distribution corresponding to *Journal* is greater than the median of the distribution corresponding to *Conference*. No analysis can be done regarding the studies published in workshops, due to the very low number of samples (2).

*Pair 8—*SR00 *and* D010*.* Advancing to the next pair, we analyze the relationship between features SR00 and D010. Figure 36 shows the violin plots of the distributions of the S_R of the selected studies, grouped by their type of approach. At first glance, it appears that no significant difference exists between both distributions. Indeed, the Mann–Whitney U test does not reject the null hypothesis

Table 10. p-values returned by the Mann–Whitney U test between the distributions identified in pair 5 (SS00 and D050). Each value corresponds to an alternative hypothesis that the median of the distribution of the row population is greater than the median of the distribution of the column population. Values in bold reject the null hypothesis for a significance level of 5%.

—	C	D	E	H	J	M	O
C	—	0.705	0.856	0.194	0.732	0.573	0.305
D	0.300	—	0.813	0.069	0.648	0.365	0.188
E	0.158	0.197	—	0.065	0.330	0.179	0.112
H	0.810	0.932	0.940	—	0.907	0.842	0.467
J	0.279	0.361	0.702	0.097	—	0.303	0.187
M	0.436	0.641	0.836	0.163	0.710	—	0.299
O	0.717	0.822	0.920	0.549	0.839	0.723	—

that the distributions are identical. The test returned p-value ≈ 0.403, given an alternative hypothesis that the median of the distribution of the *Classical* population is greater than the median of the distribution of the *Hybrid* population.

*Pair 9—*SR00 *and* D020*.* For the relationship between features SR00 and D020, we decided to generate violin plots of the distributions of the S_R of the studies corresponding to the four most frequent algorithm names, as shown in figure 37. As in pair 2, we did not consider the remaining algorithm names, as they have a very low number of samples (≤ 5). A quick look suggests that the distribution associated with the *Quantum-inspired Evolutionary Algorithm* has a slightly greater median than the distribution associated with the *Quantum Genetic Algorithm*. However, this difference is not significant, as evidenced by the results of the Mann–Whitney U test between all distributions, shown in table 11, which does not reject the null hypothesis between any two distributions, for a significance level of 5%.

Table 11. p-values returned by the Mann–Whitney U test between the distributions identified in pair 9 (SR00 and D020). Each value corresponds to an alternative hypothesis that the median of the distribution of the row population is greater than the median of the distribution of the column population. Values in bold reject the null hypothesis for a significance level of 5%.

—	QPSO	QUBO	QGA	QEA
QPSO	—	0.441	0.151	0.779
QUBO	0.563	—	0.227	0.765
QGA	0.851	0.781	—	0.943
QEA	0.226	0.246	0.063	—

*Pair 10—*SR00 *and* D030*.* As in the third pair, we decided not to perform any analysis on the tenth pair, due to the lack of samples for a categorical value. More concretely, only one of the selected studies uses a simulator, which prevents us from making any reasonable conclusion regarding the distributions associated with D030.

*Pair 11—*SR00 *and* D040*.* The lack of samples is also an issue for the eleventh pair, since only two of the selected studies use gate-based quantum computers. Nonetheless, just like the fourth pair, a great disparity in S_R is easy to notice, as shown in figure 38, and supported by a Mann–Whitney U test that

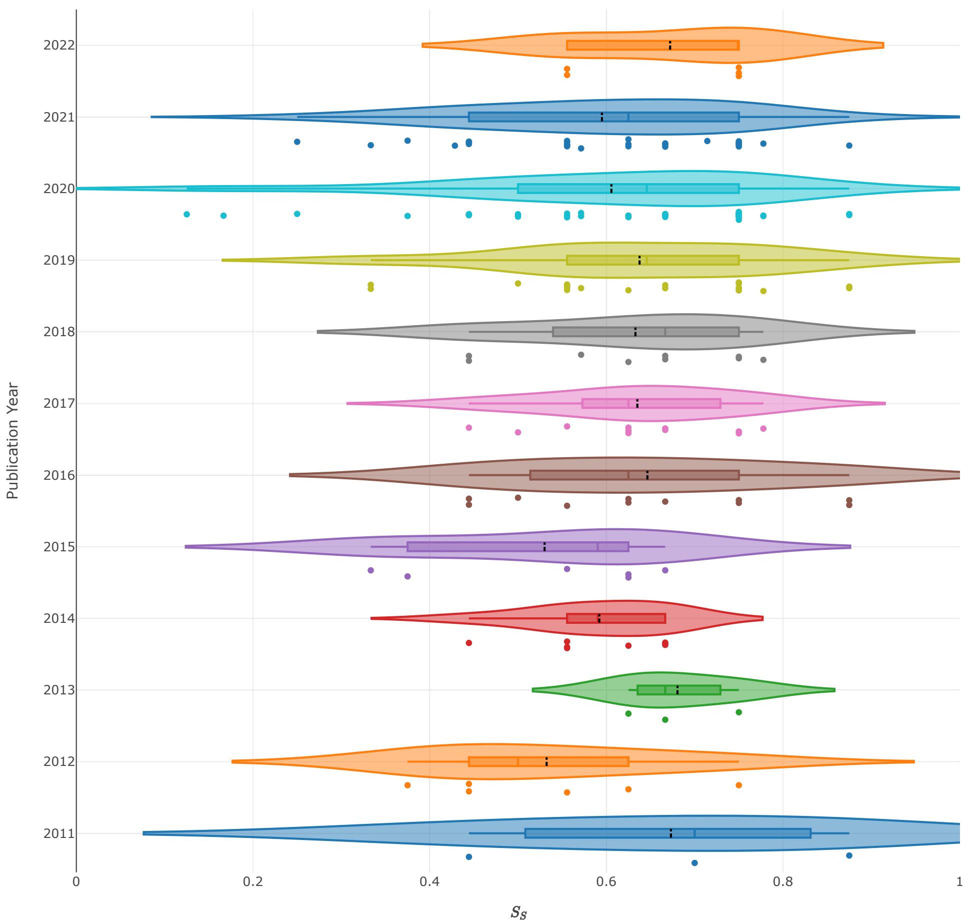

Fig. 34. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by the publication year (D060).

rejects the null hypothesis that the distributions are identical. The test returned p-value ≈ 0.014, given an alternative hypothesis that the median of the distribution of the *Annealer* population is greater than the median of the distribution of the *Gate-based* population. Still, we remind the reader that this test is taken with only two samples for one of the populations.

Pair 12—`SR00` *and* `D050`*.* Features `SR00` and `D050` are considered in this pair. As we did with pair 5, we selected only the studies corresponding to the seven most frequent ISIC sections (C, D, E, H, J, M, and O), since the remaining sections have a low number of samples (≤ 2). Figure 39 shows the violin plots of the distributions of the S_R of these studies, grouped by these ISIC sections. We do not notice any distribution that appears to be significantly different from any of the others. As

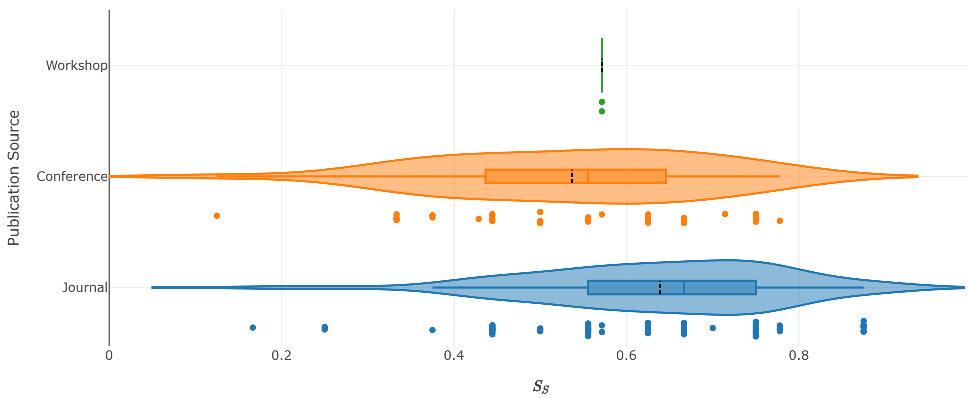

Fig. 35. Violin plots of the distributions of the quality of the study scores (S_S) of the selected studies, grouped by their publication source (D070).

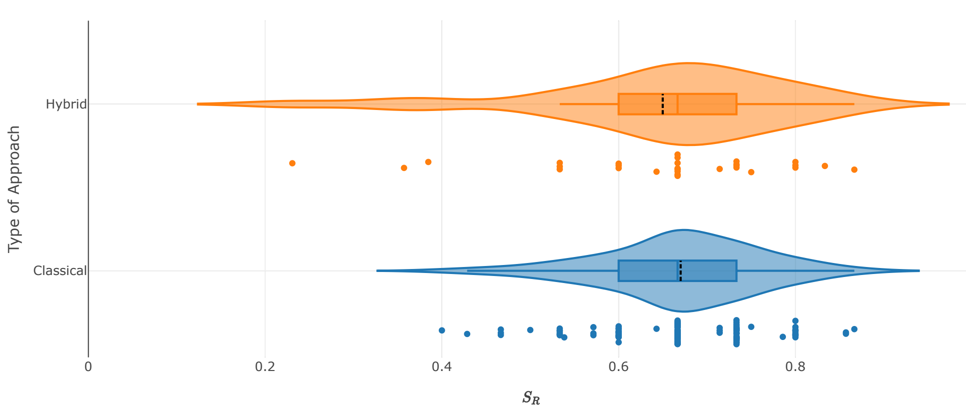

Fig. 36. Violin plots of the distributions of the quality of the reporting scores (S_R) of the selected studies, grouped by their type of approach (D010).

shown in table 12, the Mann–Whitney U test did not reject the null hypothesis between any two distributions.

*Pair 13—*SR00 *and* D060. The evolution of SR00 along the years is illustrated by the violin plots in figure 40. The distributions shown in the figure appear to be very sparse and inconsistent during the earlier years (2011 to 2016), which is expected, given the very low number of samples. As the number of samples increases in with time, the distributions become more consistent and similar

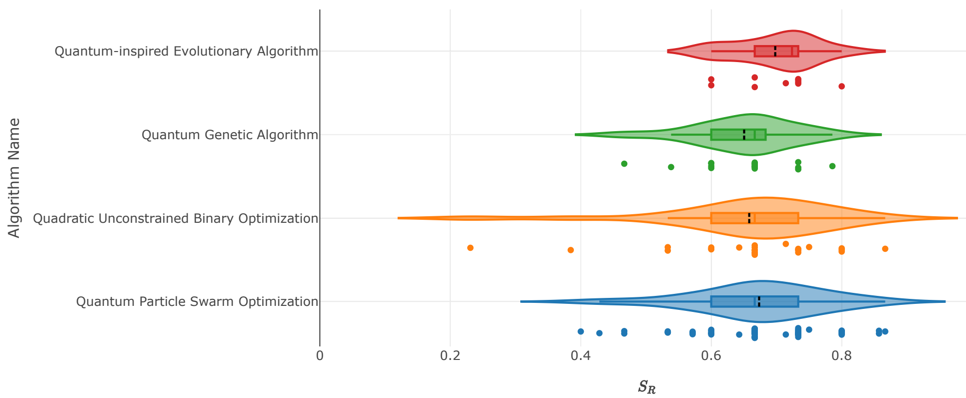

Fig. 37. Violin plots of the distributions of the quality of the reporting scores (S_R) of the selected studies, grouped by the four most frequent algorithm names (`D020`).

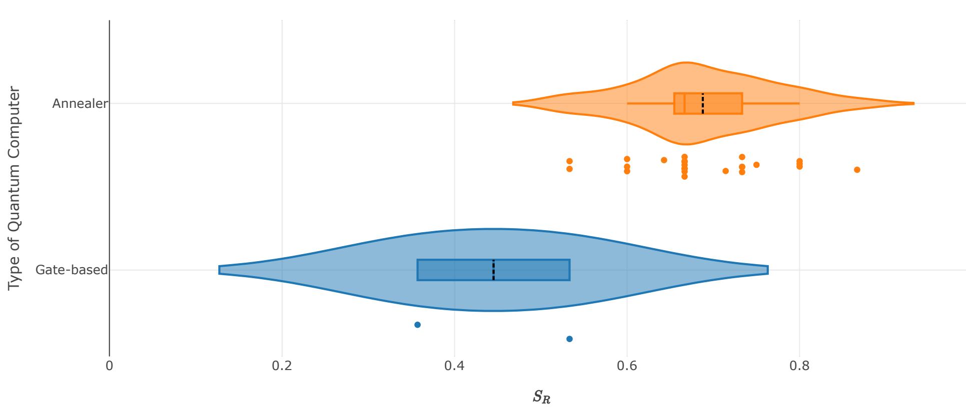

Fig. 38. Violin plots of the distributions of the quality of the reporting scores (S_R) of the selected studies, grouped by the type of quantum computer (`D040`).

year over year. We do not observe any significant difference in the median among years 2017 to 2021. We notice that as years comprise more publications the distributions become more sparser. We do not consider 2022 in this analysis, since it has a very low number of samples because it only contains publications made in the initial months. We also do not foresee any increasing or decreasing trend for the coming years with respect to the evolution of S_R.

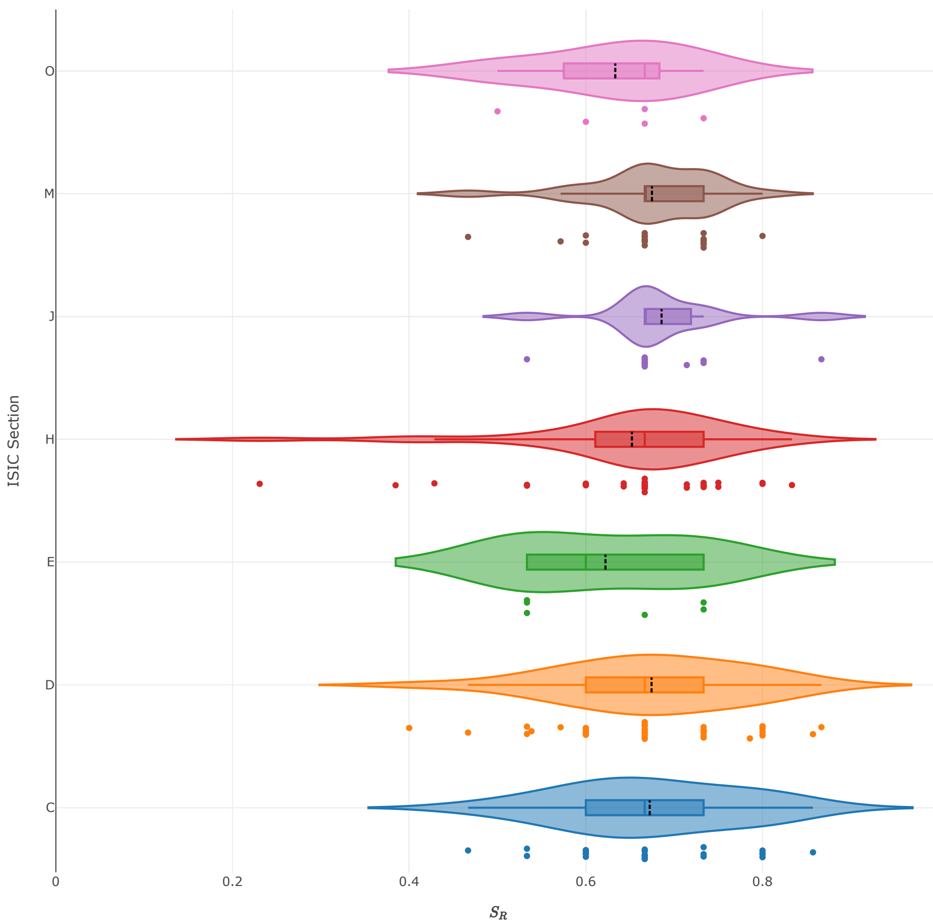

Fig. 39. Violin plots of the distributions of the quality of the study scores (S_R) of the selected studies, grouped by the seven most frequent ISIC sections (D050).

Pair 14—SR00 *and* D070. For the last pair involving SR00, we analyze the relationship between this feature and D070. Figure 41 shows the violin plots of the the distributions of the S_R of the selected studies, grouped by their publication source. It becomes clear that the distribution of the studies published in journals has a greater median S_R compared to the studies published in conferences. This is supported by the Mann–Whitney U test between these distributions, which rejects the null hypothesis with a p-value of < 0.001, given an alternative hypothesis that the median of the distribution corresponding to *Journal* is greater than the median of the distribution corresponding to *Conference*. No analysis can be done regarding the studies published in workshops, due to the very low number of samples (2).

Table 12. p-values returned by the Mann–Whitney U test between the distributions identified in pair 12 (SR00 and D050). Each value corresponds to an alternative hypothesis that the median of the distribution of the row population is greater than the median of the distribution of the column population. Values in bold reject the null hypothesis for a significance level of 5%.

—	C	D	E	H	J	M	O
C	—	0.570	0.159	0.420	0.696	0.604	0.251
D	0.437	—	0.116	0.297	0.577	0.507	0.197
E	0.854	0.890	—	0.791	0.849	0.877	0.537
H	0.586	0.707	0.220	—	0.743	0.721	0.258
J	0.316	0.432	0.175	0.265	—	0.515	0.139
M	0.406	0.500	0.136	0.285	0.500	—	0.159
O	0.768	0.813	0.537	0.755	0.884	0.857	—

Pair 15—`D010` *and* `D050`*.* Moving on to the features `D010` and `D050`, figure 42 shows bar plots of the proportions of the selected studies according to their type of approach, grouped by their ISIC section. It appears that certain sections, such as C, D, and M, have a larger predisposition for studies using purely classical approaches, whereas the other sections have a predisposition to contain more studies that use hybrid approaches.

Pair 16—`D010` *and* `D060`*.* Regarding the time evolution of the type of approach of the selected studies, we present the bar plot of figure 43. This plot shows that studies using a hybrid approach only started existing in recent years (particularly from 2019 onward). We attribute this to the availability of quantum computers in the market.

Pair 17—`D010` *and* `D070`*.* For the last pair, we consider feature `D010` with feature `D070`. Figure 44 shows the proportions of the selected studies according to their type of approach, grouped by their publication source. It appears that studies sourced from conferences have a much more balanced ratio between *Classical* and *Hybrid* (2 for each one, respectively), compared with studies sourced from journals (6.4 for each one). The two workshop articles, however, only concern hybrid approaches.

Pair 18—`D020` *and* `D050`*.* For pair 18, we analyze the relationship between features `D020` and `D050`. We only consider studies belonging to the four most frequent algorithm names and to the seven most frequent ISIC sections, to guarantee a reasonable number of samples. Figure 45 shows a bar plot of the counts of these studies according to their algorithm name, grouped by their ISIC section. The findings suggest that *Quantum Particle Swarm Optimization* is a widespread algorithm that has been applied in all of the aforementioned ISIC sections, with a particularly large focus on the ISIC section "electricity, gas, steam and air conditioning supply", and with very few applications in the ISIC sections E, J, and O. The next approach, *Quadratic Unconstrained Binary Optimization*, is significantly focused in the ISIC section "transportation and storage", since 65% of the QUBO applications belong to that section, surpassing the number of QPSO applications in the same section. The QUBO representation is minimal in ISIC sections E, J, M, and O and nonexistent in sections C and D. Concerning the *Quantum Genetic Algorithm*, the identified effort is more or less evenly spread among all ISIC sections but E and O. We observe that QGA has a significant number of studies in the ISIC section "electricity, gas, steam and air conditioning supply", being the only algorithm apart from QPSO to also have publications in this section. Finally, the studies using

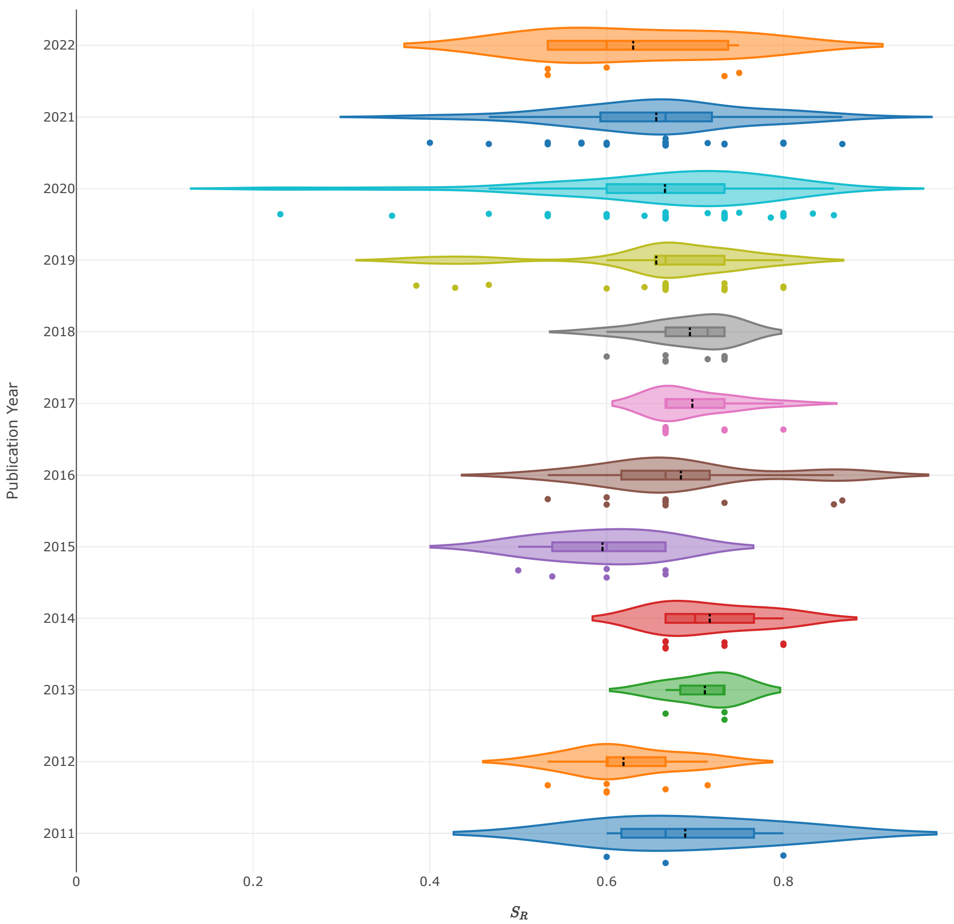

Fig. 40. Violin plots of the distributions of the quality of the reporting scores (S_R) of the selected studies, grouped by the publication year (D060).

the *Quantum-inspired Evolutionary Algorithm* are also more or less evenly spread among all ISIC sections but D, E, and O.

*Pair 19—*D020 *and* D060. Considering the studies belonging to the four most frequent algorithm names and their publication year, we developed the bar plot in figure 46. The results show that *Quantum Particle Swarm Optimization* has at least one associated study in every year from 2011 to 2022. We observe that QPSO has two periods of particularly high publication numbers: 2016 to 2017, and 2020 to 2021. Considering the *Quadratic Unconstrained Binary Optimization*, we notice that it has a very similar trend to the one observed in pair 16, as QUBO applications only started to exist in recent years (particularly from 2019 onward). We believe that this is also aligned with the availability of quantum computers in the market, namely quantum annealers. The other two

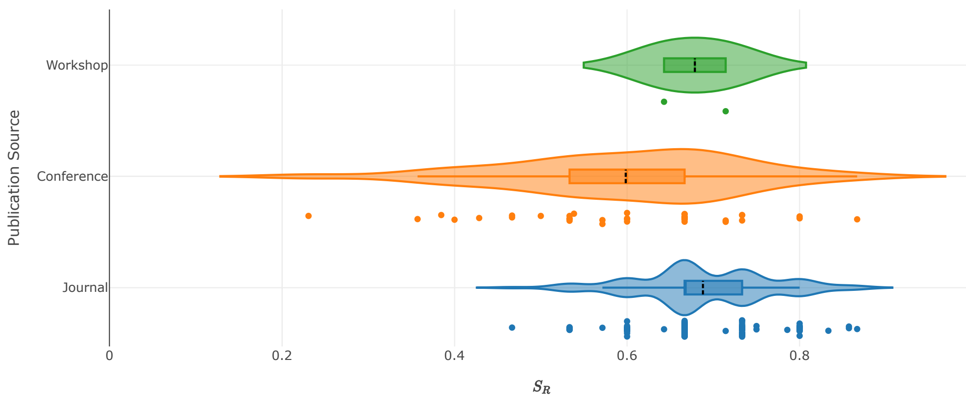

Fig. 41. Violin plots of the distributions of the quality of the reporting scores (S_R) of the selected studies, grouped by their publication source (D070).

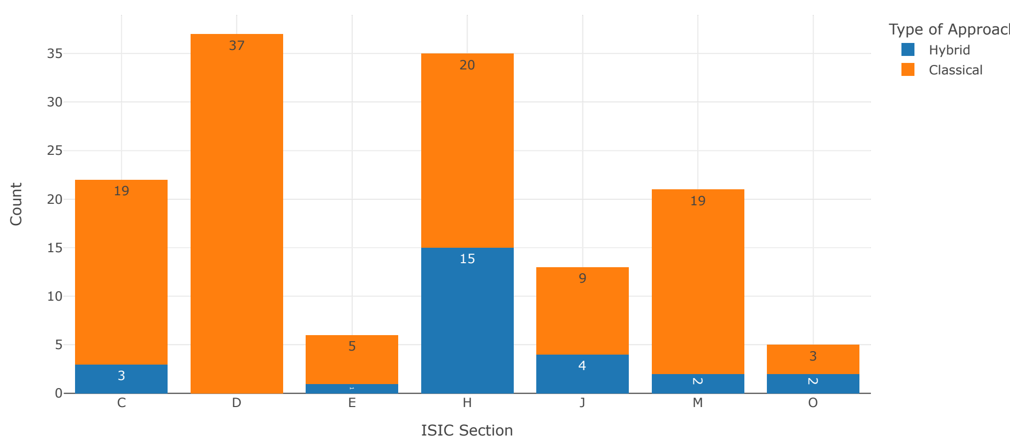

Fig. 42. Bar plot of the proportions of the selected studies according to their type of approach (D010), grouped by their ISIC section (D050).

algorithms, *Quantum Genetic Algorithm* and *Quantum-inspired Evolutionary Algorithm* appear to have a constant trend of only one or two publications per year.

*Pair 20—*D020 *and* D070. For the last pair considering feature D020, we analyze the studies belonging to the four most frequent algorithm names with respect to their publication source. Figure 47 shows the bar plot of the counts of these studies according to their algorithm name, grouped by their publication source. The results show a large disparity between the number of

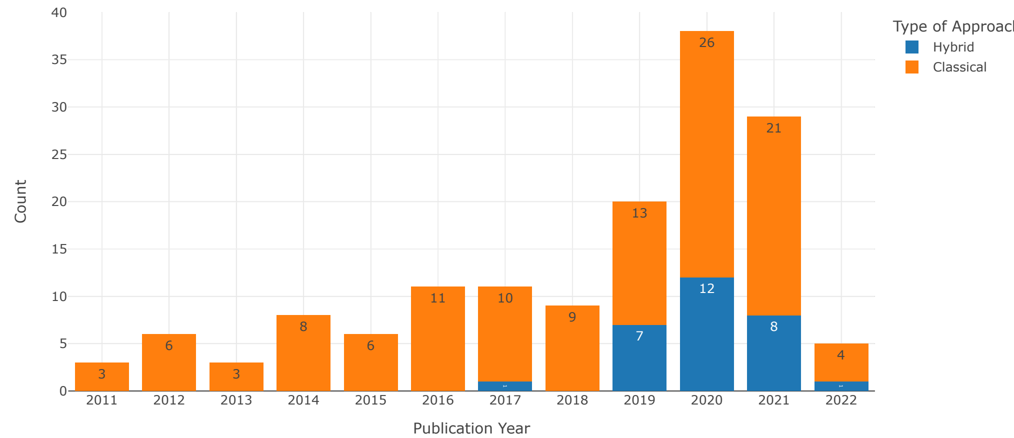

Fig. 43. Bar plot of the proportions of the selected studies according to their type of approach (D010), grouped by their publication year (D060).

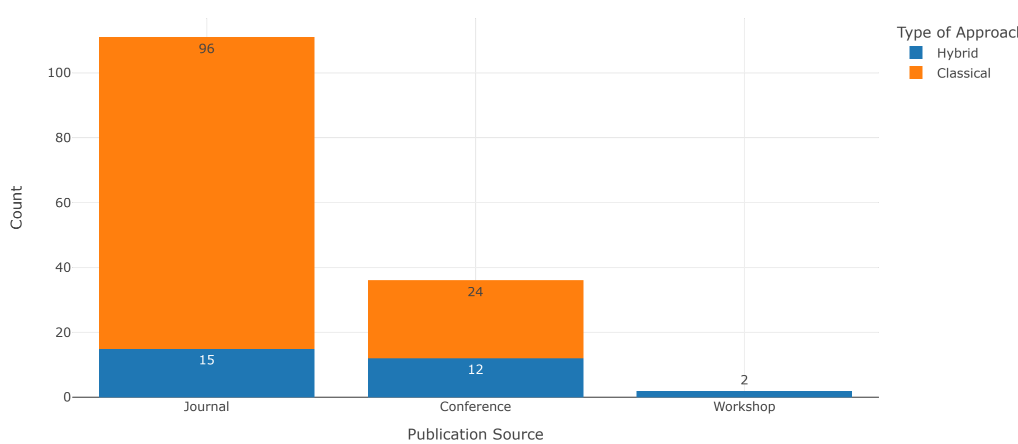

Fig. 44. Bar plot of the proportions of the selected studies according to their type of approach (D010), grouped by their publication source (D070).

Quantum Particle Swarm Optimization studies sourced from journals and sourced from conferences, which was surprising, as we expected the disparity to be similar to the disparity between the number of publications in journals and in conferences. *Quadratic Unconstrained Binary Optimization* stands out from the four algorithms, as it has more publications in conferences than in journals. Plus, the two workshop articles are also concerned with QUBO applications. The other two algorithms, *Quantum Genetic Algorithm* and *Quantum-inspired Evolutionary Algorithm*, have more publications in journals than in conferences, as expected.

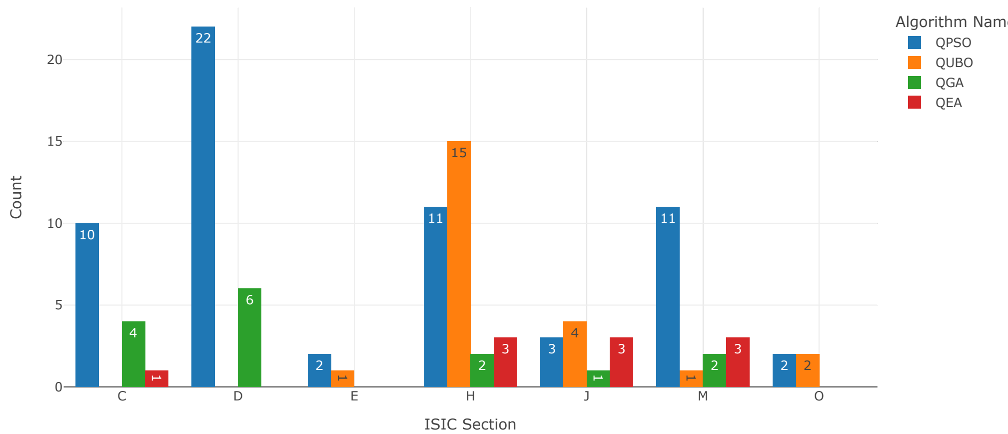

Fig. 45. Bar plot of the counts of the selected studies according to their algorithm name (D020), grouped by their ISIC section (D050). Only studies belonging to the four most frequent algorithm names and to the seven most frequent ISIC sections are considered.

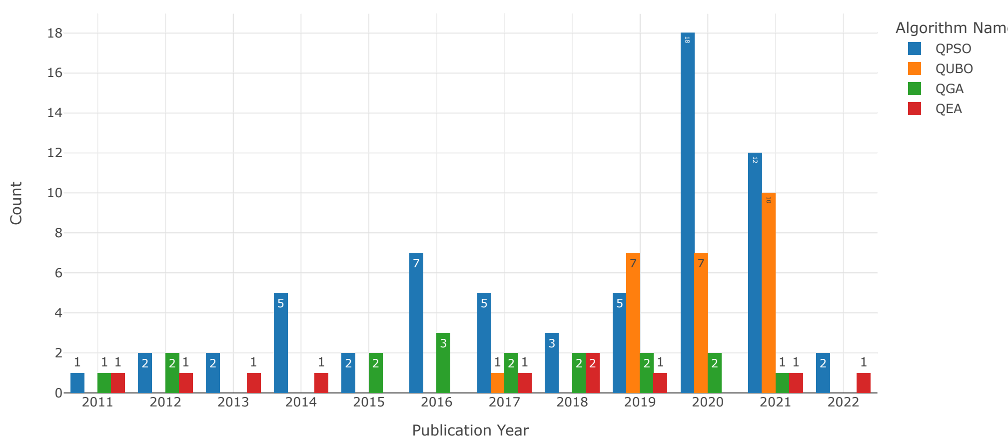

Fig. 46. Bar plot of the counts of the selected studies according to their algorithm name (D020), grouped by their publication year (D060). Only studies belonging to the four most frequent algorithm names are considered.

*Pair 21—*D030 *and* D040*.*

*Pair 22—*D030 *and* D050*.*

*Pair 23—*D030 *and* D060*.*

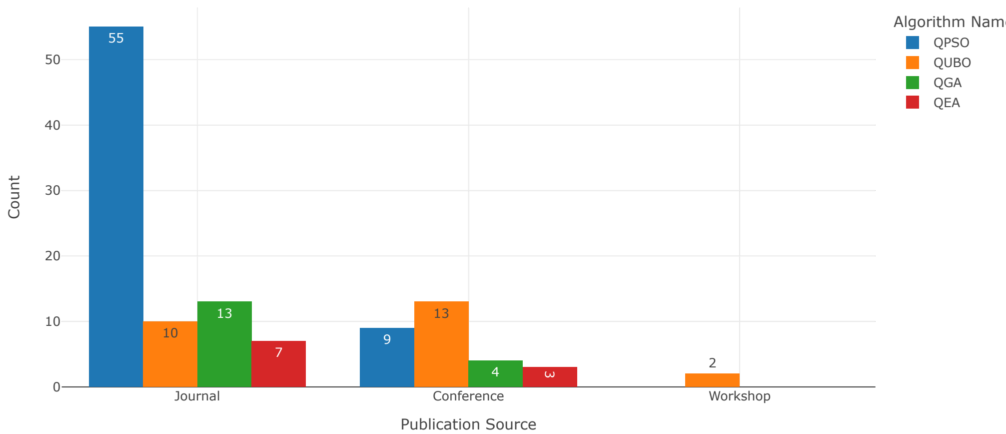

Fig. 47. Bar plot of the counts of the selected studies according to their algorithm name (D020), grouped by their publication source (D070). Only studies belonging to the four most frequent algorithm names are considered.

*Pair 24—*D030 *and* D070*.* We decided to not perform any analysis on pairs 21 to 24, since the feature D030 contains only one sample for one of its two categorical values (*Simulator*). This prevents us from making any reliable conclusion apart from the ones obtained during the first part of the analysis.

*Pair 25—*D040 *and* D050*.*

*Pair 26—*D040 *and* D060*.*

*Pair 27—*D040 *and* D070*.* We also decided not to perform any analysis on pairs 25 to 27, since the feature D040 contains only two samples for one of its two categorical values (*Gate-based*). This prevents us from making any reliable conclusion apart from the ones obtained during the first part of the analysis.

*Pair 28—*D050 *and* D060*.* Moving on to pair 28, which is concerned with the ISIC section and the publication year of the selected studies, we only analyze the studies belonging to the seven most frequent ISIC sections, C, D, E, H, J, M, and O, since the remaining sections have a very low number of samples (≤ 2). Figure 48 shows a bar plot of the counts of the selected studies according to their ISIC section, grouped by their publication year. Regarding the ISIC section "manufacturing", we do not observe any significant increase or decrease in the number of publications, even in the period between 2019 and 2021, which is marked by an overall increase in the number of publications. Next, the ISIC section "electricity, gas, steam and air conditioning supply" follows the overall trend, with an initial period with a low number of publications (2011 to 2019) followed by a period with a very high number of publications (2020 to 2021). Considering the ISIC section "water supply; sewerage, waste management and remediation activities", we observe just one publication in the years 2011 to 2019, and five publications in the years 2020 and 2021, which suggests a renewed interest in this section. The ISIC section "transportation and storage" also follows the overall trend, with an initial period with a low number of publications (2011 to 2018) followed by a period with a very high number of publications (2019 to 2022). Examining the ISIC section "information and communication", its total number of publications is very low. There is also a gap in time where no publications in this section were made (2013 to 2015). Nonetheless, we also observe a significant increase in number of publications in the period 2019 to 2022, in line with the overall trend. Looking at the ISIC section "professional, scientific, and technical activities", which has a low total number of publications compared with the other sections, we also observe a significant increase in number of publications in the period 2019 to 2022, which is aligned with the overall trend. This section also has some years with no publications, namely 2011, 2012, 2013, and 2015. Finally, ISIC section "public administration and defence; compulsory social security" has a very low total number of publications and does not appear to follow the overall trend. In fact, considering the period 2019 to 2021, only two studies belonging to this section were identified in 2020. The remaining three studies were published in 2013, 2015, and 2017.

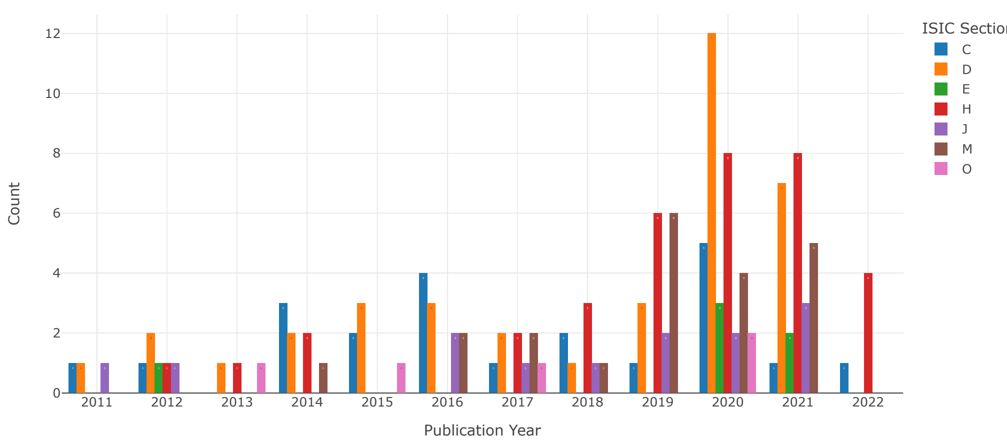

Fig. 48. Bar plot of the counts of the selected studies according to their ISIC section (D050), grouped by their publication year (D060). Only studies belonging to the seven most frequent ISIC sections are considered.

Pair 29—D050 and D070. For the relationship between features D050 and D070, we analyze once again the studies belonging to the seven most frequent ISIC sections, C, D, E, H, J, M, and O, since the remaining sections have a very low number of samples (≤ 2). Figure 49 shows a bar plot of the counts of the selected studies according to their ISIC section, grouped by their publication source. The results show some surprising disparities. First, considering ISIC section "Manufacturing", we observe that more studies were published in journals than in conferences, with a ratio of 3.4 to one, respectively. Next, considering ISIC section "Electricity, gas, steam and air conditioning supply", we observe a surprising disparity, with almost all of the studies belonging to this section sourced from journals, following a ratio of 11.3 journal publications for each conference publication. Considering ISIC section "Water supply; sewerage, waste management and remediation activities", we observe low numbers of studies in both journals and conferences. Still, this section follows a ratio of 2 journal publications for each conference publication. Next, considering ISIC section "Transportation and storage", we also observe a disparity between journal and conference publications, with a ratio of 2.7 to one, respectively. Considering ISIC section "Information and communication", we observe a strikingly similar number of publications among journals and conferences, with a ratio of 1.2 to one, respectively. Moving on to ISIC section "Professional, scientific and technical activities", this section appears to be aligned with the overall trend, with more publications in journals than in conferences, following a ratio of 4.25 to one, respectively. Finally, considering ISIC section "Public administration and defence; compulsory social security", we see a very low number of studies in both journals and conferences, with one more publication in journals. Both workshop studies belong to the ISIC section "Transportation and storage". All in all, the outliers appear to be ISIC section D, which has a remarkably large disparity between the numbers of publications in journals and in conferences; and ISIC section J, which comprises remarkably similar numbers of publications in journals and in conferences.

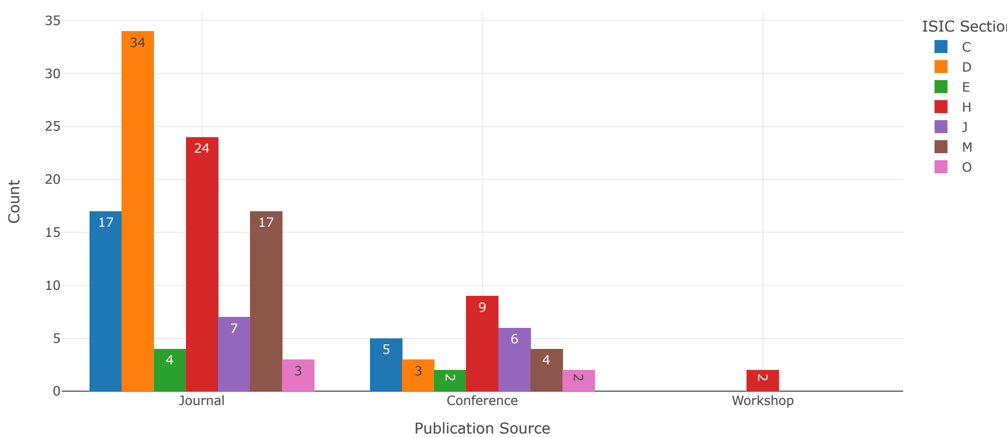

Fig. 49. Bar plot of the counts of the selected studies according to their ISIC section (D050), grouped by their publication source (D070). Only studies belonging to the seven most frequent ISIC sections are considered.

*Pair 30—*D070 *and* D060*.* Examining the relationship between features D070 and D060, we prepared a bar plot that shows the evolution of the source of publication along the years, shown in figure 50. First, considering publications in journals, we observe a trend that is in line with the overall trend: a slow growth between 2011 and 2018 that is followed by a large number of publications from 2019 to 2021. We observe a spike in the year 2020. Next, considering publications in conferences, we observe that the number becomes significant in recent years, particularly from 2018 onward. We also observe a big spike in the number of publications in conferences in 2021. Finally, we observe that the two workshop studies were published in 2019 and 2020, which is in line with the market availability of quantum computers.

*Pair 31—*SS03 *and* D040*.* For the relationship between features SS03 and D040, we only consider the studies that follow a *Hybrid* approach. Figure 51 shows a bar plot with the counts of these studies according to their response to the question "Does the study use a real-world scenario or case study for its application, even if it is simplified?", grouped by the type of quantum computer that is used. On the one hand, we observe that none of the studies that use gate-based quantum computers follow a real-world scenario. On the other hand, we observe that just over half of the studies that use a quantum annealer follow a real-world scenario ($\approx 54.2\%$).

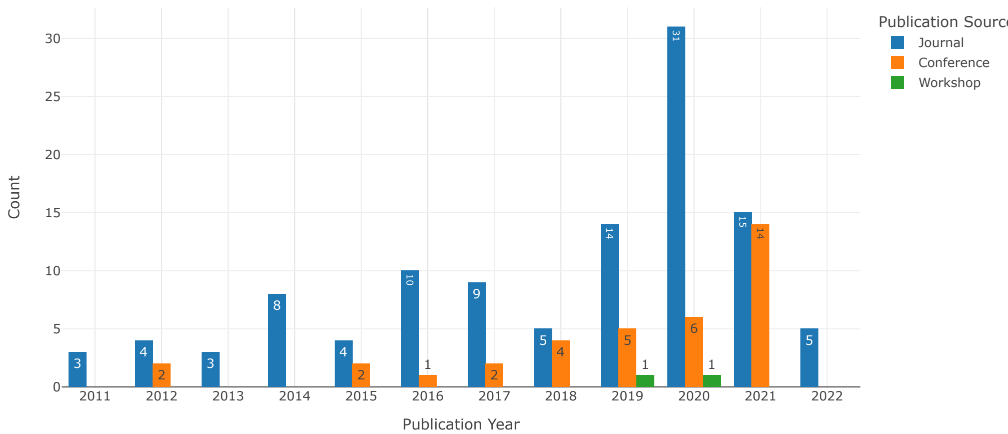

Fig. 50. Bar plot of the counts of the selected studies according to their publication source (D070), grouped by their publication year (D060).

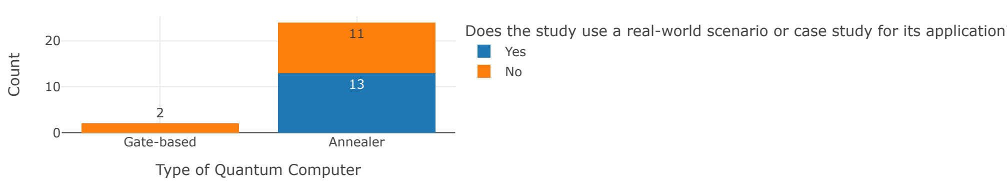

Fig. 51. Bar plot of the counts of the selected studies according to their response to SS03, grouped by their type of quantum computer (D040).

*Pair 32—*SS03 *and* D050. Moving on to pair 32, this time we only consider the studies belonging to the seven most frequent ISIC sections, C, D, E, H, J, M, and O, since the remaining sections have a very low number of samples (≤ 2).

Figure 52 shows a bar plot of the counts of these studies according to their ISIC section, grouped by their response to SS03. First, considering ISIC section "Manufacturing", we observe that a significant majority of the studies use real-world scenarios ($\approx 68.2\%$). Next, considering ISIC section "Electricity, gas, steam and air conditioning supply", the opposite happens, as a significant majority of the studies do not use real-world scenarios ($\approx 59.5\%$). Considering ISIC section "Water supply; sewerage, waste management and remediation activities", we observe that a significant majority of the studies use real-world scenarios ($\approx 66.7\%$). Next, considering ISIC section "Transportation and storage", we observe a ratio similar to the one found in section D, with a significant majority of 60% of the studies not using real-world scenarios. Considering ISIC section "Information and communication", we also observe the same situation: a significant majority of the studies do not use real-world scenarios ($\approx 69.2\%$). Moving on to ISIC section "Professional, scientific and technical activities", this section appears to have a slight majority of studies that do not use real-world scenarios ($\approx 57.1\%$).

Finally, considering ISIC section "Public administration and defence; compulsory social security", we observe that a slight majority of the studies also do not use real-world scenarios (60%).

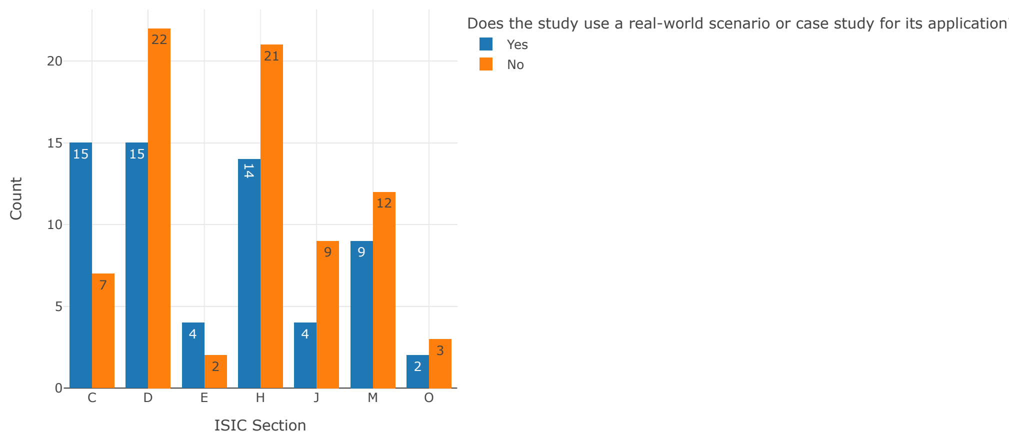

Fig. 52. Bar plot of the counts of the selected studies according to their response to SS03, grouped by their ISIC section (D050).

Pair 33—SS03 and D060. For pair 33, we analyze the evolution of the responses to SS03 along the years. Figure 53 shows a bar plot of the counts of the selected studies according to their response to SS03, grouped by their publication year. However, we do not observe any significant trend other than that roughly half of the studies use a real-world scenario, whereas the other half does not. There is no suggestion that upcoming years will lead to a higher proportion of studies using real-world scenarios.

Pair 34—SS03 and D070. Finally, the last pair concerns features SS03 and D070. Figure 54 shows a bar plot of the counts of the selected studies according to their response to SS03, grouped by their publication source. We arrive at the same observation as in the previous pair: roughly half of the studies use a real-world scenario, whereas the other half does not, whether they were published in journals or in conferences. The workshop articles, however, use real-world scenarios.

B.5 Exploratory Data Analysis

The last part of the analysis is non-systematic and attempts to find insights that were not captured by the systematic analysis so far. We were able to find additional insight into the relationship between features SR01 and D070, as shown in figure 55. We found a big disparity between journal-sourced studies and conference-sourced studies with respect to whether they present their overall structure at the beginning of the text. Objectively, we found that $\approx 65.8\%$ of the journal-sourced studies present their overall structure, whereas only half of the conference-sourced studies present theirs. We speculate that this is due to conference-imposed constraints on the full-text structure and content.

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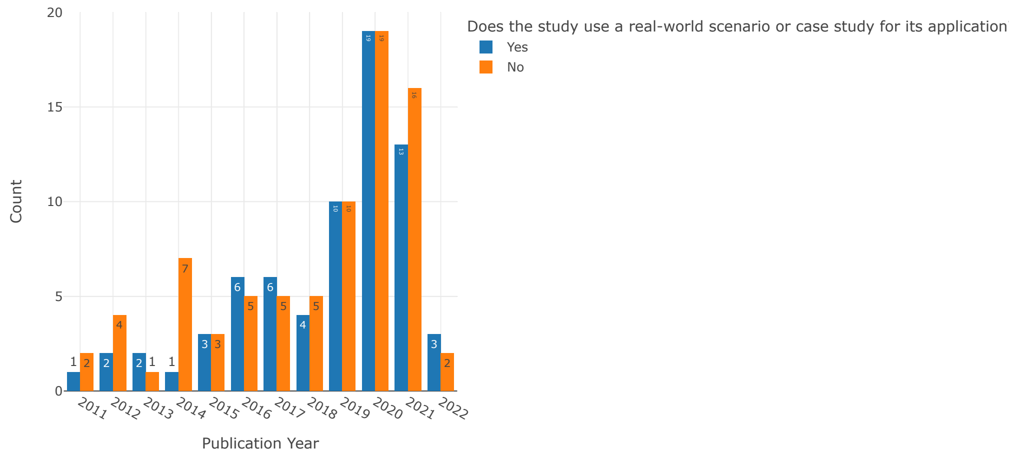

Fig. 53. Bar plot of the counts of the selected studies according to their response to SS03, grouped by their publication year (D060).

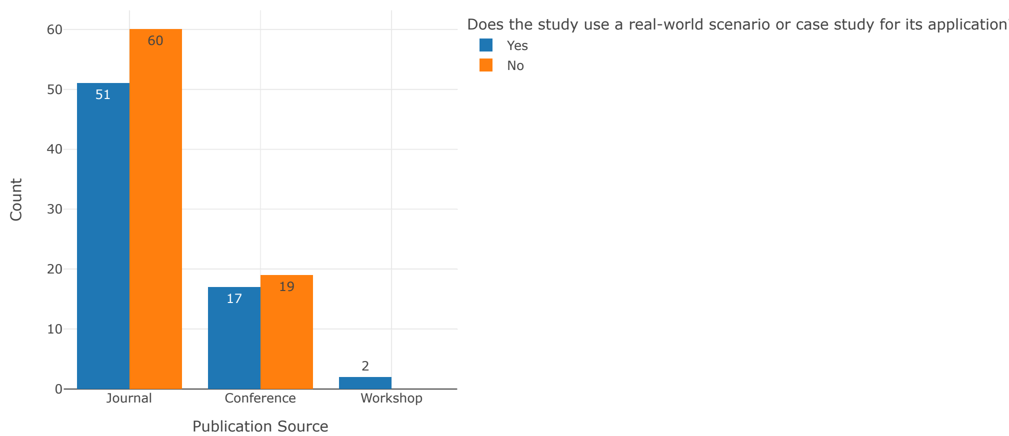

Fig. 54. Bar plot of the counts of the selected studies according to their response to SS03, grouped by their publication source (D070).

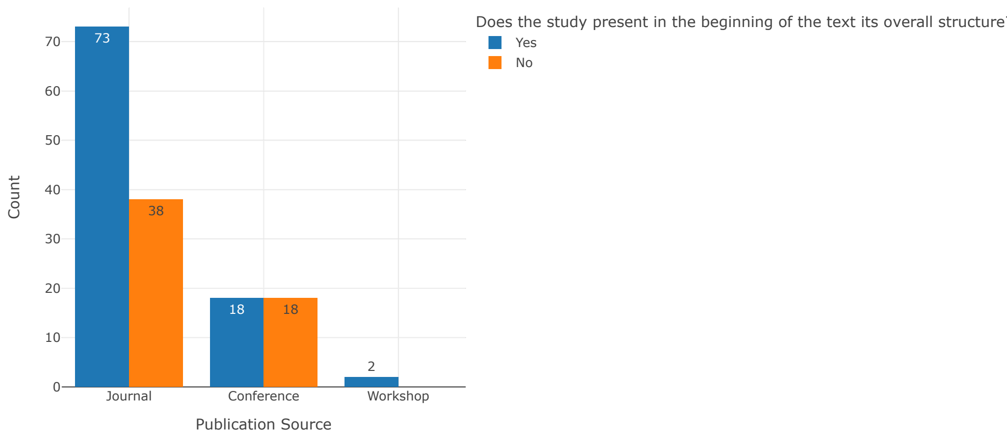

Fig. 55. Bar plot of the counts of the selected studies according to their response to SR01, grouped by their publication source (D070).