A Systematic Mapping Study on Quantum Circuits Design Patterns

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Abstract: *Introduction.* In order to study quantum software's quality, the use of patterns for designing quantum circuits is quite an unexplored field whereas a promising one too. *Method.* This work aims to discover the current state of the art of quantum circuits design patterns by searching the literature via a Systematic Mapping Study. *Results.* The search space was formed by 1327 studies in three different databases for a final result of 15 primary studies. *Conclusions.* These studies include a taxonomy for different design patterns over quantum circuits.

1 INTRODUCTION

A quantum circuit is normally defined as a set of quantum gates to be applied to a set of qubits. According to (Ozols and Walter, 2021) a quantum circuit has three main parts:

1. An initial state, usually starting with every qubit in state $|0\rangle$.
2. A sequence of quantum gates acting over a set of qubits (normally from one qubit up to three or even more).
3. A set of measurements to extract the information after applying all the quantum gates.

Design patterns (DP) have traditionally been used at the design phase of the development of classic software systems (Budgen, 2013)(Gray, 1996)(Rosal, 2014). The use of DP in classic computing has meant a huge advance in the design phase of every software development life cycle, as it helps leading to better designs so that higher quality software solutions can be achieved. DP allow us to focus on an specific Object-Oriented challenge by naming, abstracting and identifying the main aspects of the class design used for solving that problem. For that, DP identify the different classes designed and gives each class a role for solving the problem (Gamma et al., 1994).

Considering the rise of Quantum Computing (QC), we consider that there is a gap in QC finding and using DP when designing quantum circuits, so that the quality of these is improved. This is certainly a relevant subject to be taken into account in order to follow many of the principles of the *Talavera Manifesto for quantum software engineering and programming* (Piattini et al., 2020) and thus, it might be helpful for improving different quality aspects of quantum circuits which will affect the quality of the quantum software programmed from them, including several well-known quality characteristics such as the understandability (Cruz-Lemus et al., 2021) or even the maintenance of quantum/hybrid software systems (Piattini et al., 2021).

In this Manifesto, several principles and commitments are exposed for the sake of reaching a correct and formal growth of the Quantum Software Engineering (QSE) so that a high quality quantum software development process can be achieved. Keeping this in mind, we consider that DP may contribute to increase the quality of quantum circuits, as they have traditionally done with models in classic software (Budgen, 2013)(Gray, 1996)(Rosal, 2014).

Within this context, we have performed a Systematic Mapping Study (SMS) based on the methodology by Petersen *et al.* (Petersen et al., 2008). A SMS is a secondary study with a wide scope aiming to provide a global view about certain topic (design patterns for quantum circuits in our case) and identify the amount and kind of research already performed. A total of 1327 studies were analyzed, resulting in 41 potential candidates, leading to a primary studies list (PSL) with 15 items. We think that the obtained re-

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sults could benefit: (i) future researchers studying the quantum DP field and (ii) quantum software development companies interested in improving the quality of their systems by means of QSE principles.

The remainder of the paper is organized as follows: Section 2 defines the methodology followed for developing the SMS. The answers to the research questions expressed in the previous section are detailed in Section 3. Also, the different potential threats to validity are explained in Section 4. To conclude, in Section 5 some ideas for future works and some conclusion are proposed.

2 SMS METHODOLOGY

2.1 Planning the Review

As aforementioned, we performed a SMS based on the proposed process by Petersen *et al.* (Petersen et al., 2008) combined with the backward snowballing technique[1]. The mapping was performed by the first author and was constantly supervised by the other two authors. The methodology and its stages are explained throughout this section.

2.1.1 Protocol Definition

Three different stages were performed (see Figure 1):

1. Planning the Review: Define the protocol, the selection criteria and the research questions among other items.
2. Performing the Review: Process all the search space and obtain the PSL as well as classifying all the studies found.
3. Reporting the Review: Answer the research questions and obtain the conclusions.

2.1.2 Research Questions

Bearing the goal of the study in mind, the following research questions have been defined:

- **RQ1:** Which kind of publications have been done about DP in QC?
- **RQ2:** Which are the core research topics about DP in QC?
- **RQ3:** Which are the main advances regarding the definition and/or detection of DP in quantum circuits?

[1]Process consisting on performing the selection strategy over each study in the references section from an article and, if applicable, add it to the PSL (Wohlin, 2014).

2.1.3 Selection Criteria

In order to minimize the threats to validity of the study, a set of inclusion and exclusion criteria (IC_i and EC_i) were defined. The inclusion criteria (IC_i) used were:

- IC_1: Studies expressing explicitly its aim of contributing in the DP in quantum circuits in the abstract and/or title.
- IC_2: Studies dated between 1980 and 2022.
- IC_3: Studies labeled in any of these fields: Computer Science, Mathematics, and Engineering.

The start date was 1980 since that is the year when Paul Benioff proposed his "Quantum Model of the Turing Machine" (Benioff, 1980), which was considered as a seminal work.

On the other hand, the applied exclusion criteria were:

- EC_1: Studies not written in English.
- EC_2: Studies mentioning patterns but not being proper DP (e.g., light patterns, encoding-based patterns, etcetera).
- EC_3: Studies related to Quantum Annealing (QA). QA presents a series of differences with respect to quantum circuits such as:
  1. Atomic information level is considered differently, in other words, a qubit in a gate-based circuit behaves differently to a qubit within a QA algorithm, and so, the way of manipulating the information is not the same.
  2. The types of problems to be solved within each model are different. More specifically, QA focuses on optimization problems while gate-based has a wider problems scope.

For this purpose, in the second phase of the SMS, the appropriate queries were launched to three scientific databases: *SCOPUS*, *arXiv*, and *Google Scholar*. Consequently, all the resulting studies passed through two filtering stages by applying all the aforementioned exclusion and inclusion criteria. All those articles passing the first filtering stage were considered as *potential candidates*. Finally, all the potential candidates went through the last riddling stage. Those studies (*primary studies*) passing this stage became part of the PSL and were classified and processed for answering the research questions.

2.1.4 Search String

The search string used, bearing in mind the selection criteria was:

(design pattern) AND
(quantum AND (circuit OR computing))

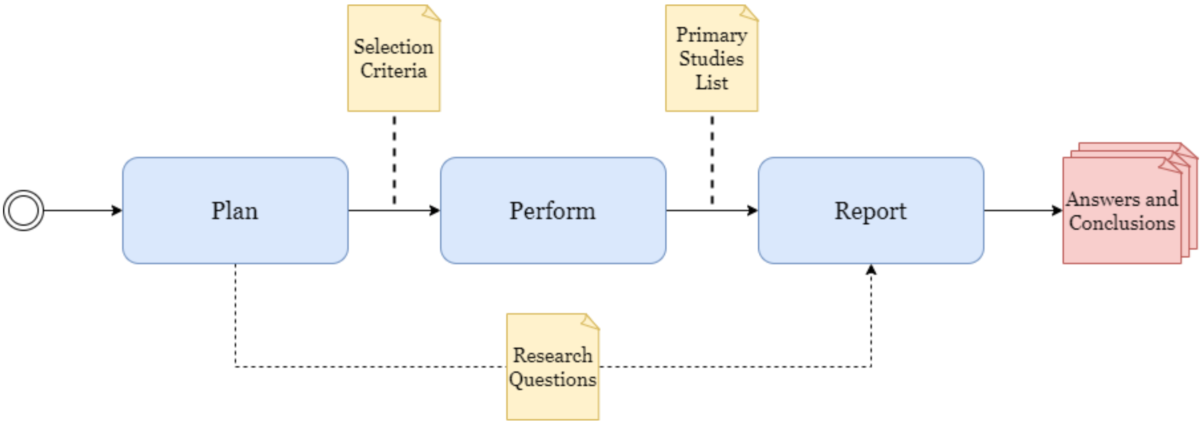

Figure 1: SMS methodology steps.

2.2 Data Extraction

To acquire quantitative and qualitative information for answering our research questions, the following data were extracted from each primary study:

1. Document title.
2. Authors.
3. Publication date/year.
4. Type of publication (RQ1).
5. Research subject (RQ2 & RQ3).

3 RESULTS

After applying the explained strategy, we found 904 articles matching the search string on *SCOPUS*. From those, 30 were considered possible candidates but only eight of them were selected as primary studies.

In *arXiv*, 122 publications were initially found plus one more due to snowballing. From them, seven were considered possible candidates and three of them were finally included as a primary studies.

For *Google Scholar*, we analyzed the first 300 results that appeared in the search result. The vast majority of the results were far from matching the selection criteria or had already been found in *SCOPUS* or *arXiv*. Also one more citation was obtained from Scholar proposed in later reviews. However, four more publications were tagged as potential candidates and later as primary studies.

This way, the final PSL contained 15 primary studies. The complete list with the references can be found in an Appendix at the end of the document. Figure 2 graphically summarizes all this process.

The first remarkable fact to highlight is the low number of publications found (see Figure 3). Despite the quick evolution experienced in the recent years, QC is an area still in it infancy, especially in some specific fields such the use of design patterns for quantum circuits. Anyhow, in the recent years it seems to be a increasing interest in the topic.

Additionally, Table 1 shows a ranking of the most contributing authors in DP for quantum circuits.

Table 1: Most contributing authors ranking.

Name	# publications
Houshmand, M.	4
Sedighi M.	4
Zamani, M.S.	4
Eslamy, M.	2
Leymann, F.	2
Samavatian, M.H.	2

3.1 RQ1: Types of Publications

According to the results found in Table 2, there is not a predominant type of publication related to DP in QC. The number of works published in journals (5), conferences (5) and pre-prints included in *arXiv* (5) -labelled as *Other* in Table 2- is quite similar. It is interesting to highlight that there are no books published about this topic yet. Once again, we consider that the topic is still in its early development stages and these numbers will grow in the future.

Table 2: RQ1 results.

Category	# publications	Percentage
Journal	5	33.33%
Conferences	5	33.33%
Books	0	0.00%
Other	5	33.33%

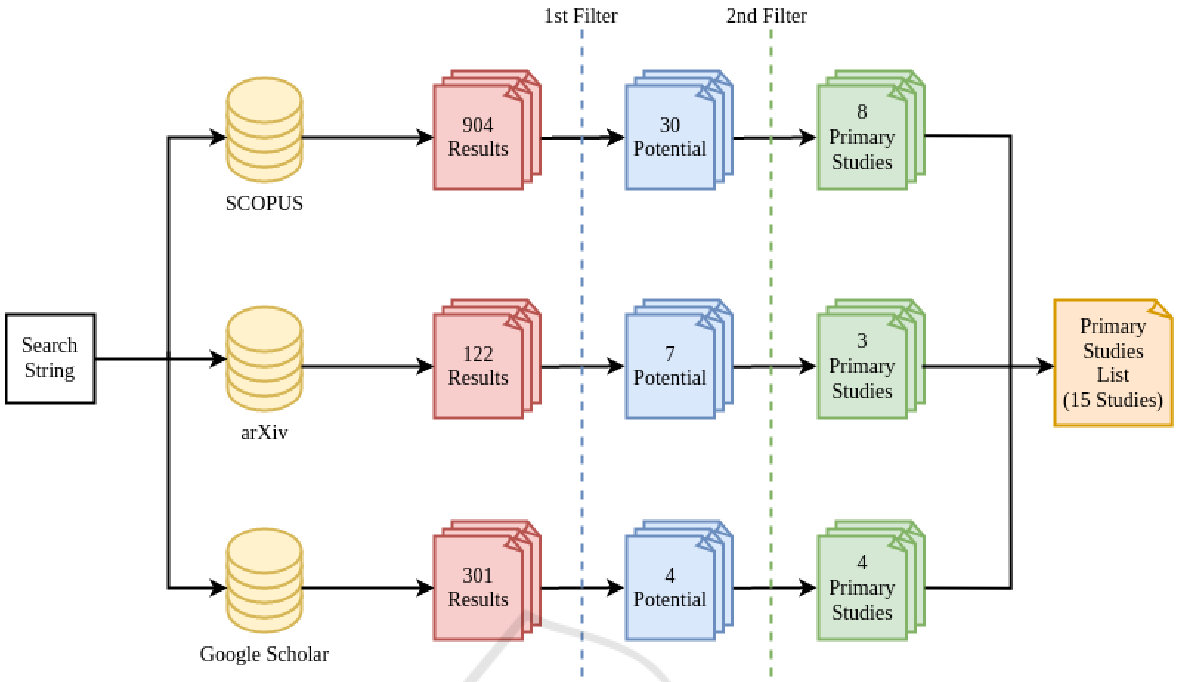

Figure 2: Search protocol summary.

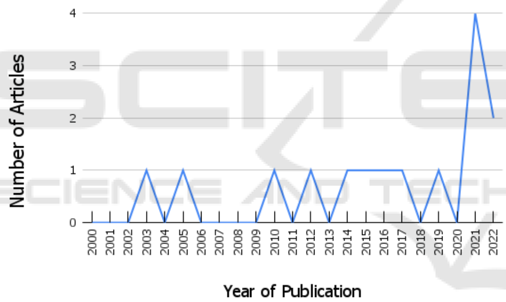

Figure 3: Publications per year.

3.2 RQ2: Core Research Topics

Table 3 provides information about the different topics on which the works in the PSL were based. Most of them (8 out of 15) were focused on *1WQC*[2] measurement patterns. This approach uses only measurements as operational units applied over a set of qubits by establishing "measurement patterns". Besides, three publications are focused on pattern languages and models for quantum circuits, two are focused on pattern matching and, finally, two on patterns in hybrid quantum/classic algorithms.

These numbers seem to show how the *1WQC Measurement Patterns* trend the search space on quantum patterns. Later in Sections 3.3 and 5 some differences between the concepts of DP and measurement patterns will be dealt with.

[2]One Way Quantum Computing

3.3 RQ3: Main Advances in DP for Quantum Circuits

In spite of being such an unexplored subject, several promising results and research topics were found.

In the previous sub-section, we already introduced the 1WQC. It describes a model within the Measurement-Based Quantum Computing (MBQC). The MBQC proposes performing quantum computations using only measurement as computational steps (Jozsa, 2005). Knowing this, 1WQC proposes a quantum computing model that works by only performing a sequence of one-qubit measurements (also known as "measurement patterns") on a particular entangled multi-qubit state, the cluster state (Raussendorf et al., 2002).

Another noteworthy study is (Pérez-Castillo and Piattini, 2022), which proposes a continuous UML flow for designing hybrid systems. Within all the presented UML abstractions, we can highlight a potential pattern presented in subsection 4.3 for designing a hybrid behaviour involving a request from a classical system to the "Quantum Driver", named *Quantum Request*. Nevertheless, we do not consider it as a DP for quantum circuits since it is defining a behaviour in a higher abstraction level (hybrid system).

Moreover, we found quite an interesting piece of work, actually and directly related with DP for quantum circuits (Leymann, 2019). In this article, it is explained what is a DP in classic Software Engi-

Table 3: Core research topics and RQ2 results.

Main Subject	# publications	Percentage
1WQC measurement patterns	8	53.33%
Patterns in hybrid algorithms	2	13.33%
Pattern languages/models	3	20%
Pattern mining over quantum circuits	2	13.33%

neering and its importance when designing software systems. Furthermore, the work states the different points that any pattern description should have and, later, defines a set of patterns for quantum circuits. For the design of those patterns, the same strategy than in classic Software Engineering was followed: first finding recurring problems when designing quantum circuits and then composing an optimal solution for them. The complete description of these patterns can be found in (Leymann, 2019), but in short, they could be stated as:

1. **Initialization:** a set of *state preparation* or *initialization* operations are described.
2. **Uniform Superposition:** an uniform superposition can be achieved by initializing all the n qubits as the unit vector $|0...0\rangle$ and applying a Hadamard gate afterwards.
3. **Creating Entanglement:** it is a commonly used yet powerful mechanism in QC.
4. **Function Table:** used for optimizing computation time.
5. **Oracle:** it is another commonly used concept in quantum algorithms.
6. **Uncompute:** this patterns manages the "undo" computations needed to be performed over auxiliary or *ancillae* qubits.
7. **Phase Shift:** used to encode the fitness of a solution to an algorithm.
8. **Amplitude Amplification:** used to increase the probability of measuring an specific value by amplifying the amplitude of a state.
9. **Speedup Via Verifying:** an approach for reaching different solutions in an algorithm.
10. **Quantum-Classic Split:** used for distributing the computational work between classic and quantum computers in hybrid systems.

It is important to highlight that this list is nor closed neither finished, as it is clarified on the article, but means quite a solid basis to start from in future works. Besides, we think that more than one of these patterns can be found within the same quantum circuit. This work also provides several considerations on the use of DP in classic software engineering and the marriage between the abstract concept of a pattern, i.e., the abstraction technology-agnostic that a pattern proposes and how it is implemented actually in real software systems.

Furthermore, we consider important to highlight the Quantum Computing Patterns[3] web. This website collects the definitions of several patterns, quantum circuit entities and even quantum algorithms. The last category of patterns in this website is based on the previously commented article (Leymann, 2019). We also analyzed the rest of article references in the web page but we believe that the concepts and entities exposed do not exactly fit with the definition of DP explained in Section 1. Due to this reason, neither those articles nor the quantum circuit entities exposed in them were considered for their inclusion as part of the results. These articles are: (Weigold et al., 2020), (Weigold et al., 2021a), and (Weigold et al., 2021b).

In order to check how these DP apply on a Quantum Circuit, Figure 4 presents an example by analysing Grover's Algorithm (Grover, 1996). Basically, this well-known algorithm is capable of finding an element within an unsorted search space with a complexity of $O(\sqrt{N})$, being N the size of the search space.

We can find four out of the ten patterns provided in the previous list on this example:

- **Initialization**, quantum algorithms usually require the initialization of the qubits involved. In this case, Grover's Algorithm needs to initialize all of them to the $|0\rangle$ state (see the left-most part of the circuit in Figure 4).
- **Uniform Superposition**, highlighted in blue in Figure 4. All the qubits involved in the algorithm are initialized in a $|0...0\rangle$ state and, later, a Hadamard gate is applied to them. This way, the search space created is equiprobable.
- **Oracle**, highlighted in red in Figure 4. In this algorithm, an oracle is used to revert the amplitude of the intended solution.
- **Amplitude Amplification**, highlighted in green in Figure 4. The last step of the algorithm requires to increase the probability of the previously reversed solution.

[3]https://www.quantumcomputingpatterns.org/

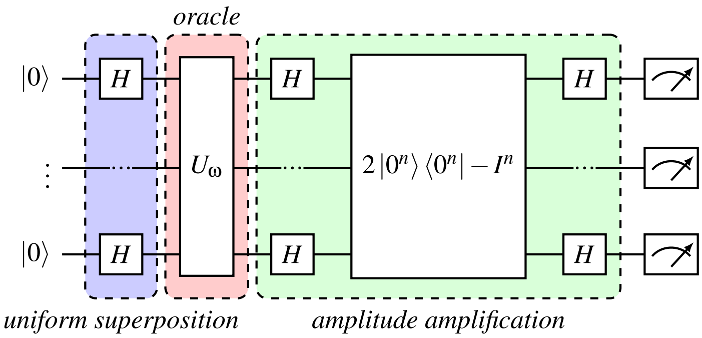

Figure 4: Design patterns in Grover's Algorithm.

4 THREATS TO VALIDITY

The first threat to validity is the power and accuracy of the search string. Prior to starting the review, we familiarized with the field of DP for quantum circuits and used several synonyms and key concepts for the search strategy. After several iterations, all the authors agreed on the final search string. Furthermore, in the literature search strategy, we aimed to retrieve as many relevant studies as possible. To do so, the main scientific databases in QC research with the most extensive coverage were chosen: *SCOPUS*, *arXiv*, and *Google Scholar*. The use of *arXiv* is especially important in the field of Quantum Computing as, being it a novel discipline, there is a certain number of publications in pre-print phase which are shared in the repository.

Regarding the data extraction and selection process, the filtering and classification stages were performed manually by only one researcher to ensure that all studies were reviewed with the same criteria. The inexperience of the first author could be also considered as a thread to validity. Despite this, continuous reviews and corrections have been done throughout the whole process.

5 CONCLUSIONS AND FUTURE WORK

Once we have performed the qualitative and quantitative synthesis of the extracted data, we can present the main conclusions obtained.

The number of primary studies found is small, but in the recent years the number of studies is increasing. This might imply a growing interest in this novel topic, once researchers are becoming aware of the importance of using these kind of elements for establishing the foundations of the QSE (Piattini et al., 2020).

We have discovered that the most published topic in the field are the *One-Way Quantum Computing Measurement Patterns* (Raussendorf et al., 2002). But, as we remarked in Section 3 definition, these measurement patterns are not properly DP as we described them in Section 1.

We have identified a list of authors holding the current knowledge about DP for quantum circuits, especially the main contribution provided by (Leymann, 2019). This works offers an interesting seminal taxonomy for different DP for quantum circuits.

As future work, we believe that there exists several possibilities for research inside this subject, mainly:

- Increase the patterns list proposed in (Leymann, 2019).
- Pondering to start using those patterns in actual quantum software systems.

From a more practical point of view, a strongly viable project implementing all these ideas could be the development of a tool for detecting quantum patterns in quantum circuits. It should be able to detect which (sub-)problems a quantum circuit is solving and so: (i) warn the developer to use the adequate pattern(s) when designing a suitable solution; (ii) match some patterns used in classic software engineering which might show benefits in quantum circuits design; (iii) if needed, register and formalize it as a new pattern establishing a constant line of feedback.

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APPENDIX

The studies in the PSL correspond to the following items in the references section:

- (Duncan and Perdrix, 2010)
- (Eslamy et al., 2016)
- (Eslamy et al., 2018)
- (Gilliam et al., 2019)
- (Houshmand et al., 2012)
- (Houshmand et al., 2015)
- (Iten et al., 2022)
- (Jang et al., 2021)
- (Leymann, 2019)
- (Lomont, 2003)
- (Maslov et al., 2005)
- (Pérez-Castillo and Piattini, 2022)
- (Pius and Silva, 2015)
- (Simmons, 2021)
- (Weigold et al., 2021c)