Towards a Comprehensive Catalog of Architectural and Design Patterns for Blockchain-Based Applications: A Literature Review

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Abstract. *Well structured software architectures usually contain a lot of patterns representing abstract solutions to recurring problems. We performed a preliminary literature review to identify existing catalogs of architectural and design patterns which are applicable in blockchain-based applications. The main contributions of this paper are a summary of 12 existing catalogs and our catalog proposal. Because the blockchain domain lacks a clear categorization of patterns, as well as precise descriptions and corresponding evaluations, we plan to continue working on those issues. Our final goal is to simplify the search for useful blockchain patterns.*

Keywords. Blockchain, smart contracts, software engineering, patterns, design, architecture

1 Introduction

The popularity of blockchain technology and the lack of guidelines on how to design blockchain-based software attracted researchers to explore possibilities for helping practitioners in their engineering endeavors (Destefanis et al., 2018; Porru et al., 2017; Wan, Xia & Hassan, 2019; Xu et al., 2016). In our work, we are focusing on architectural and design patterns that can be used in blockchain-based applications. We are following the definition of Xu et al., who defined blockchain-based applications as applications that make significant use of blockchain, including distributed applications, but not limited to them (Xu, Weber & Staples, 2019).

A blockchain platform is the technology needed to operate a blockchain; it consists of client software for processing nodes, local data storage, and any other clients needed to access the network. The platform can be used as an architectural, storage, or computational element, or as a communication, asset management, or control mechanism (Xu, Weber & Staples, 2019).

Smart contracts are programs that are deployed or executed as a part of a blockchain transaction, and they normally encode agreements between non trusting participants (Alharby, Aldweesh & Moorsel, 2018). If we were to consider a blockchain as a new database type, smart contracts behave similarly to stored procedures, in Structured Query Language (SQL), or classes in Object-Oriented (OO) programming (Rocha & Ducasse, 2018). Like the data, smart contracts become immutable after they are included in a public or private blockchain ledger (Xu, Weber & Staples, 2019). Consequently, blockchains can provide a decentralized secure storage that does not require trust accumulation (Zhang et al, 2020).

Well structured software architectures usually contain a lot of patterns that make them more flexible, reusable and understandable; these patterns represent abstract solutions to recurring problems that can be observed and applied in different settings (Gamma, 1995). Blockchain platforms are fundamental building blocks of the blockchain-based applications' architectures (Xu, Weber & Staples, 2019). They can be integrated with other components, or they can be the only components. Hence, it is worth learning about relevant patterns, to be able to apply them properly, in order to improve the quality of the software development process and product. We aim to simplify the discovery of relevant patterns with a new extensive catalog.

We performed a preliminary review, including white, i.e., peer reviewed, and gray, i.e., non peer reviewed, literature, on architectural and design patterns for blockchain-based systems. We identified 97 patterns.

The remainder of the paper is structured as follows: in Sec. 2, we present the related work; in Sec. 3, we present the research protocol that was pursued in our study; in Sec. 4, we present the results of the study; and in Sec. 5, we present our plans for the future.

2 Related Work

Several literature reviews have been performed in the blockchain domain, but we are not aware of any review that would focus on architectural or design patterns. Existing reviews focus on different topics: Yli-Huumo et al. tried to learn what is the state of the blockchain research, and discovered that the majority

of the papers focus on technical challenges, such as, throughput, latency, and security (Yli-Huumo et al., 2016); Sankar et al. and Zheng et al. surveyed consensus protocols (Sankar, Sindhu & Sethumadhavan, 2017; Zheng et al., 2017); Alharby et al. performed a systematic mapping study of academic research on smart contracts and found 188 relevant papers, out of which almost two-thirds were exploring different applications of smart contracts (Alharby, Aldweesh & Moorsel, 2018); Casino et al. and Zhang et al. performed literature reviews of blockchain-based applications (Casino, Dasaklis & Patsakis, 2019; Zhang et al, 2020). We note that Casino et al. included gray literature in their review, as is the case in our study.

In addition to survey papers, Xu et al. presented a taxonomy that highlights the impact and trade-offs arising from decisions related to blockchain platforms, particularly in respect to performance and quality attributes (Xu et al., 2017). Verdonck demonstrated how unique blockchain characteristics, such as, immutability and visibility, alter the way in which smart contracts are developed, compared to traditional development (Verdonck, 2019).

(Liu et al., 2020) and ("Blockchain Patterns, Mechanisms, Models and Metrics", 2020) represent gray literature that includes pattern catalogs. Liu et al. published their catalog after we performed our search. It contains 12 patterns for blockchain-based self-sovereign identity, which are split into 3 categories, namely, *key management*, *DID management*, and *credential design* patterns. Each pattern is presented in compliance with the standard guidelines suggested in (Meszaros & Doble, 1997), thus, the presentation includes the pattern name, summary, context, problem, forces, solution, consequences, including benefits and drawbacks, related patterns, and known uses.

In our study, we identified one pattern from the Arcitura, the author of ("Blockchain Patterns, Mechanisms, Models and Metrics", 2020). Hence, the entire catalog would have been included if we performed at least one cycle of backward snowballing (Wohlin, 2014), as a part of the protocol. ("Blockchain Patterns, Mechanisms, Models and Metrics", 2020) contains 13 patterns, split into 4 categories, namely, *integrity and validation*, *scalability and reliability*, *security and privacy*, and *utility* patterns. The patterns are presented in a uniform manner, which is not consistent with the standard guidelines. The presentation includes the pattern name, problem, solution, application, and mechanisms.

3 Research Method

In this paper, we focus on the catalogs containing blockchain patterns. We formulated the following research question: *Which architectural and design pattern catalogs for blockchain-based applications exist, and what are their characteristics?*

In software engineering, survey studies often follow the Systematic Literature Review (Kitchenham & Charters, 2007) or Systematic Mapping Study (Petersen, Vakkalanka & Kuzniarz, 2015) protocol. However, these protocols were designed to guide analysis of white literature, and do not provide instructions on how to incorporate gray literature. Thus, we adopted the guidelines for the Multivocal Literature Review, suggested by (Garousi, Felderer & Mantyla, 2019).

Examples of gray literature include reports, theses, specifications, official documents, discussion boards, and blogs (Yasin et al., 2020). Our reasons for including gray literature match the following criteria (Garousi, Felderer & Mantyla, 2019):

- The subject is not solvable by considering only the formal literature (Criterion 1);
- The formal literature lacks volume (Criterion 2);
- Synthesis of insights and evidence from the industrial and academic community would be useful to both communities (Criterion 6); and
- There is a large volume of practitioner sources indicating high interest in the topic (Criterion 7).

It is common to search for gray literature using Google Search and Google Scholar. This is a preliminary study, thus, we used only Google Search. Nevertheless, our results include also white literature content.

Instead of formulating a single search string which could later be validated with a validation set, we used five different strings, namely: "blockchain" "pattern", "blockchain patterns", "blockchain" "design patterns", "blockchain" "security patterns", and "blockchain" "architectural patterns". The reason for our decision is based on the fact that the "blockchain" term limited the results to the investigated topic, while not excluding the results focusing on more specific aspects, such as, smart contracts or patterns for different technologies. On the other hand, "pattern" seems to be too vague, since the number of relevant hits was too low, and additional terms improved the results.

We inspected the first 5 pages of the results returned for each search string, which was either 48 or 49 links per string, and 243 overall. Our stopping criterion was "effort bounded" (Garousi, Felderer & Mantyla, 2019). We detected 31 duplicates with the exact same link.

We performed the search on 6^{th} May 2020, using a clean installation of the Google Chrome browser, via the IP address of the University of Maribor VPN. Relevant sources included white literature and all other publications, including any web-page content that is the main topic of the web-page, such as, blogs, documentation, slides, white-papers, wiki-pages, YouTube videos, and the like. We used nine exclusion criteria:

- Main content is missing,
- Main content is not in English,

- Content is not related to blockchain technology,
- Content is not related to software engineering,
- Content is not *presenting* any architectural or design patterns, i.e., diagrams or pattern name lists are not sufficient without (at least) a description of an issue they are addressing,
- Content is a comment or a Q/A post,
- Content is payable and not included in journal subscriptions, such as, online course,
- Blockchain itself is presented as the only pattern,
- Patterns are presented implicitly, and would need to be extracted, e.g., from a reference architecture or source code.

Based on these criteria, we excluded 154 unique hits, which included 8 duplicates. Hence, exactly one-third of the hits was relevant. However, there was a considerable overlap between the links, pointing to the same content. For example, there were 14 web pages that were referring to (Xu et al., 2018), whether it was an abstract with a link, a preprint version, or an official version. By merging such hits, we reduced the number of unique sources to 35. However, we note that, even in this case, all the lists of patterns are not unique; for example, (Xu et al., 2018) and (Xu, Weber & Staples, 2019) include the same patterns. When one list was the same as another we used the newer source as the reference. When one list contained only a subset of patterns presented in another list, we used the more comprehensive source as the reference. That reduced the number of sources to 28.

We removed 5 sources that contained only one pattern, and an additional 11 sources that did not provide any classification of patterns, i.e., all the patterns were included in one category, nor did they present the patterns in a uniform way, i.e., the authors did not even use a custom template. Ultimately, 12 unique catalogs of patterns remained.

We would also like to stress that, when we found a source that was, in fact, a published peer reviewed publication, we used that as the reference, to allow easier and more reliable tracking of sources. The results are presented in the next section.

4 Results and Discussion

As can be seen in Tab. 1, the types of the sources can be very different, and only five have the form of a research paper. Sources other than blogs, theses, and slides were probably peer reviewed, i.e., we conjecture that they represent white literature. (Chittoda, 2019) and (Xu, Weber & Staples, 2019) were published by prominent international publishers, (Lu et al., 2019) was published in a peer reviewed journal, and another four papers were presented at international conferences.

The number of patterns presented in each catalog is between 2 and 15; the mean average number of patterns in a catalog is 7.5, and the median is 6.5. These numbers are very low compared to the 97 unique patterns identified across 35 relevant sources of patterns obtained in our study. We suspect that the actual number of patterns is even higher, since our study is preliminary, and considerably limited in scope. Consequently, we regard existing catalogs as inadequate. We believe that a comprehensive catalog of patterns would be very useful for practitioners and researchers.

Moreover, ("Getting started with blockchain design patterns", 2020), (Chittoda, 2019), ("Design Patterns for Decentralization", 2020), (Lu et al., 2019), ("Four

Table 1: Summary of catalogs

Source	Type	Group	Nr. patterns	Nr. categories	Template
("Community blockchain interaction patterns", 2019)	thesis	gray	6	2	none
("Design Patterns for Decentralization", 2020)	slides	gray	7	1	custom
("Four architecture pattern candidates for Blockchain-based decentralized applications", 2019)	blog	gray	5	1	short standard
("Getting started with blockchain design patterns", 2020)	blog	gray	3	1	custom
("Solidity Patterns", 2019)	blog	gray	14	4	custom
(Chittoda, 2019)	chapter	white	13	5	custom
(Hibti, Baina & Benatallah, 2019)	paper	white	7	3	custom
(Lin, Liao & Chen, 2020)	paper	white	2	1	long standard
(Liu et al., 2018)	paper	white	8	4	none
(Lu et al., 2019)	paper	white	6	2	short standard
(Xu, Weber & Staples, 2019)	chapter	white	15	4	long standard
(Zhang et al., 2017)	paper	white	4	1	custom

architecture pattern candidates for Blockchain-based decentralized applications", 2019), and (Zhang et al., 2017) do not include any reasoning on why the specific sets of patterns are included in the catalogs, nor do they report on any type of pattern evaluation.

Conversely, Liu et al. report that they implemented five out of eight patterns in a real-life application, which could be considered as some kind of evaluation, but they also do not explain how the catalog was created (Liu et al., 2018). In (Hibti, Baina & Benatallah, 2019) and ("Solidity Patterns", 2019), existing, third-party literature was used to extract the patterns included in the catalogs; the authors also report on known uses of patterns, which could be helpful for assessing whether a specific pattern is indeed a solution to a recurring problem. Similarly, (Lin, Liao & Chen, 2020) and (Xu, Weber & Staples, 2019), the only papers where the patterns were presented according to the standard long template, also report on known uses of patterns, but the inclusion of the patterns is based on the authors' experience only, in the case of Lin et al., while the origins of patterns are unknown in the case of Xu et al. ("Community blockchain interaction patterns", 2019) contains a set of theoretical use cases from which new patterns were derived; they were evaluated by implementation feasibility analysis.

We are aware of only four catalogs where the authors performed some kind of empirical research to obtain a set of patterns, such as, analyzing existing applications or smart contracts. These catalogs are presented in (Bartoletti & Pompianu, 2017), ("Maintenance of Long-Living Smart Contracts", 2020), ("Decoding Smart Contract Design Patterns", 2018), and (Wessling & Gruhn, 2018). However, in those sources, the patterns are not presented in a uniform manner, and no categorization is provided. The presentation of patterns in all four sources is brief, which makes it hard to implement a pattern. Consequently, they were excluded at the last step, as catalogs of low quality.

Two of the included catalogs did not present patterns in a unified format, and another two used a short version of the standard template. Such presentations are largely inadequate in terms of applicability for practitioners. The same is true for sources using a custom template; however, we would like to stress that some of the custom templates are very informative, even when compared to the long standard template. Hence, we can observe some initiative in the community to help developers apply theoretical knowledge in practice.

Finally, an issue that can easily be overlooked when we are dealing with the catalogs that do not contain large sets of patterns, is the problem of pattern classification. In fact, we even find it hard to agree with some categories presented in the catalogs discussed in this paper. However, as the number of patterns grows and different catalogs are overlapping, it becomes increasingly important to split the patterns into suitable categories. For example, the same pattern can be called *embedded permission*, *access restriction*, *restricting access*, *authorization*, and *access verifier*, and it can be classified as *contract structural* pattern, *smart contract design* pattern, *security* pattern, or *design or coding* pattern. The list of categories used in 12 catalogs is presented in Tab. 2.

When we synthesized the 97 patterns obtained from 35 different sources, by performing "term normalization", we noticed that subcategories could be beneficial as well. Consequently, a useful hierarchy of patterns and categories could be several levels deep. As a part of this preliminary study, based on our intuition and expertise, we drafted our first version of categories for architectural and design patterns used in blockchain-based applications. The suggested categories, subcategories, and patterns are visualized in Fig. 1.

Table 2: List of categories of blockchain patterns included in existing catalogs

Source	Category names
("Community blockchain interaction patterns", 2019)	- Trading - Technology
("Design Patterns for Decentralization", 2020)	- Decentralization
("Four architecture pattern candidates for Blockchain-based decentralized applications", 2019)	- Architecture
("Getting started with blockchain design patterns", 2020)	- Blockchain Design
("Solidity Patterns", 2019)	- Behavioral - Security - Upgradeability - Economic
(Chittoda, 2019)	- Security - Creational - Behavioral - Gas Economic - Life-Cycle
(Hibti, Baina & Benatallah, 2019)	- Organisation - Decision-Making - Learning-Flow
(Lin, Liao & Chen, 2020)	- Design
(Liu et al., 2018)	- Creational - Structural - Inter-Behavioral - Intra-Behavioral
(Lu et al., 2019)	- Data Management - Smart Contract
(Xu, Weber & Staples, 2019)	- Interaction with External World - Data Management - Security - Contract Structural
(Zhang et al., 2017)	- Familiar

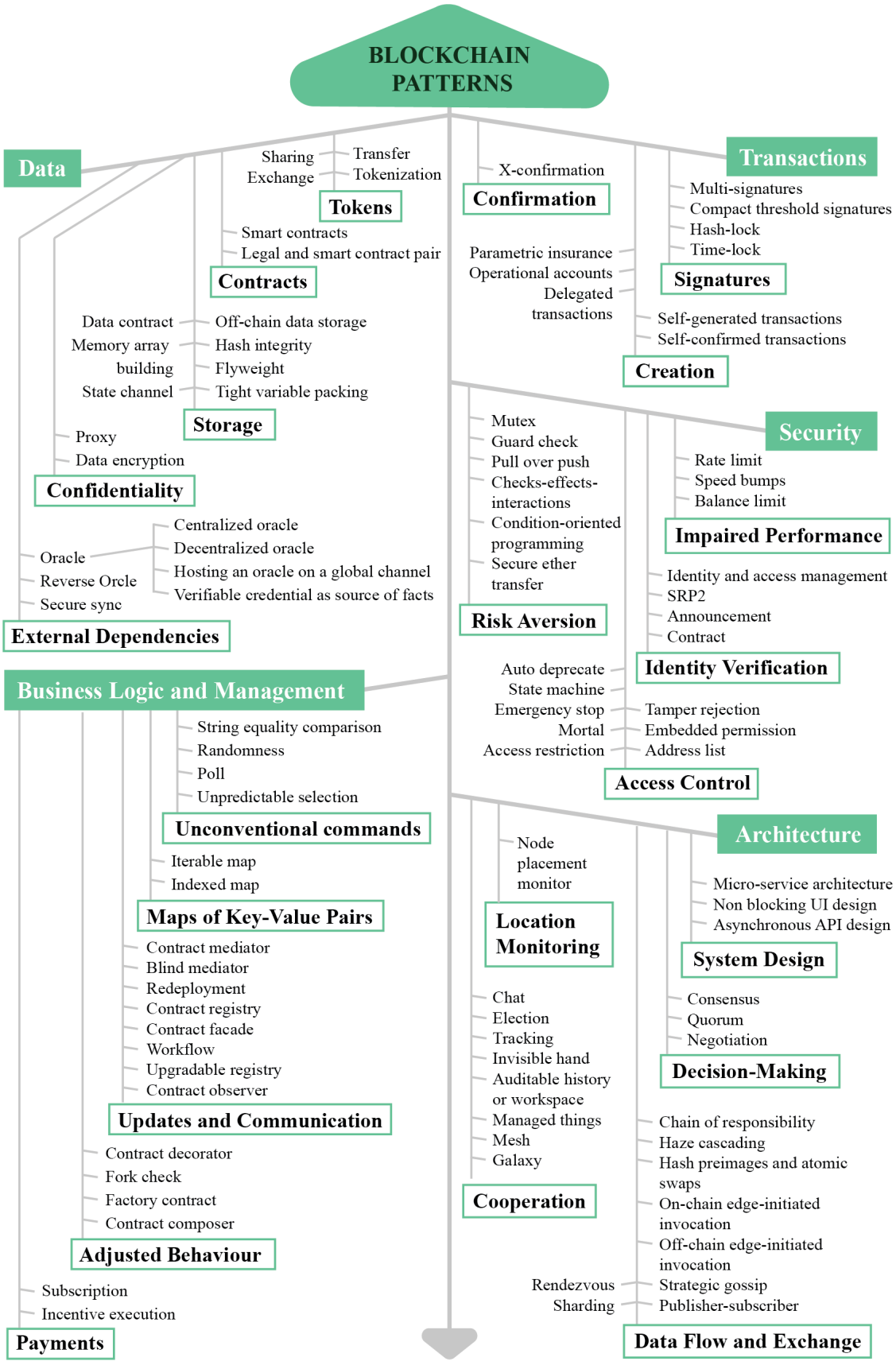

Figure 1: Diagram of categories (marked with green backgrounds), subcategories (marked with green borders), and corresponding patterns (unmarked)

Nevertheless, the categorization of patterns is probably not a unidimensional problem. Thus, we believe that we would need to perform some kind of grounded theory research, such as, open and axial coding (Bryant & Charmaz, 2007), to obtain a comprehensive and sound set of categories.

5 Conclusions and Future Work

In this paper, we present the results of a preliminary study on existing blockchain pattern catalogs. We focus on different characteristics of the catalogs, such as, number of patterns and categories, adopted presentation templates, and research that led to the selection of patterns included in a specific catalog.

We noticed that the catalogs are very limited in size, standard templates are rarely used, and empirical evidence supporting the usage of patterns is almost non existent. This is problematic, because it is not enough that some solution is called a pattern by the authors of the papers and blogs. In practice, it is crucial to understand whether the implementation of the pattern is worthwhile. Additionally, it would be beneficial to collect all the relevant patterns in one place, so that the blockchain developers do not need to go through the same search process as is reported in this paper.

In the future, we plan to perform an exhaustive review, which will provide complete information on existing architectural and design patterns for blockchain-based applications. We expect the list of patterns to grow, because we are already aware of different sets of patterns that are missing in this work.

Acknowledgments

This research was funded by the Slovenian Research Agency under Grant P2-0057.

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