1 August 2024
ESMA50-43599798-9913

ESMA Working Paper No. 3, 2024

Decentralised Finance: A categorisation of smart contracts

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Financial Innovation

Decentralised Finance: A categorisation of smart contracts♦

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Abstract

First introduced on the Ethereum blockchain in 2015, smart contracts have become the backbone of Decentralised Finance (DeFi). Smart contracts are computer programmes stored on the blockchain and run when predetermined conditions are met. They are designed to facilitate financial transactions among blockchain users, without the need for trusted intermediaries that characterises traditional finance. Owing to their open-source nature, smart contracts have been claimed to be a major source of financial innovation. Nonetheless, they bring enormous technological complexity. Regulators and supervisors need to understand and monitor this complexity to systematically evaluate the risks to investors and financial stability stemming from DeFi. By discerning different categories of smart contracts, this article represents a first step in this direction. Building on on-chain data and using the topic model proposed by Ibba et al. (2021), we implement a categorisation of smart contracts on the Ethereum blockchain, define five major smart contract categories, and monitor their relative incidence over time. We note a major difference in terms of smart contracts heterogeneity between the first and the second surge in smart contract deployment (occurring in 2017-2018 and in 2021-2023, respectively), reflecting the increased complexity of smart contracts and the adoption of more sophisticated protocols that came to characterise DeFi.

JEL Classifications: E42, E49, K24, K29, D18, O3

Keywords: Decentralised finance, DeFi, smart contracts, Ethereum, blockchain

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♦ The views expressed are those of the authors and do not necessarily reflect the views of the European Securities and Markets Authority. Any error or omissions are the responsibility of the authors. The authors would like to thank referee Olena Havrylchyk, Professor of Economics at University Paris 1 Panthéon-Sorbonne and member of ESMA's Investor Trend and Research Working Group, for her feedback on earlier versions of the work. They are also grateful to Claudia Guagliano and Steffen Kern for their valuable feedback and input.

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Non-technical summary

Owing to their open-source nature, smart contracts have been claimed to be a major source of financial innovation. Nonetheless, they bring enormous technological complexity. Regulators and supervisors need to understand and monitor this complexity to systematically evaluate the risks to investors and financial stability stemming from DeFi. This analysis seeks to contribute to ESMA's mission of promoting investor protection and financial stability by proposing a methodology to categorise smart contracts, so to better understand their functionalities and features.

After providing a non-technical overview of the phenomenon of smart contracts, explaining their role in decentralised finance, this paper leverages natural language processing and topic modelling to cluster smart contracts into homogeneous groups. Being this an unsupervised task, said groups are thus investigated 'manually' in order to infer information on the functionalities and characteristics of the smart contracts comprised therein, allowing to assign a label to each category. Lastly, comparing the categories' incidences over time, this paper discusses the drivers that might explain these trends.

The methodology presented in this paper serves to provide a closer, more nuanced look at the underlying dynamics and trends that characterise DeFi. As such, it aims to answer regulators' calls for a closer, consistent monitoring of DeFi and its underlying protocols. Moreover, as discussed below, this methodology can also provide a solid basis for further analysis aimed at investigating specific types of smart contracts or the interconnectedness between different categories of smart contracts.

1 DeFi and smart contracts

1.1 DeFi as a new form of market organisation

Financial systems typically consist of three components: (i) institutions, (ii) instruments, and (iii) markets (Viney and Phillips, 2012). In traditional finance, financial institutions are intermediaries (banks, securities companies, insurance companies, fund management companies, etc.) who provide financial services (such as banking, securities trading, insurance, trusts, fund investment, etc.).[1] Financial instruments are contracts, that is, legal agreements involving monetary value such as stocks, bonds, or derivatives.[2] Lastly, financial markets refer broadly to any marketplace where the trading of financial instruments occurs (Qin et al., 2021).

Within DeFi, institutions as rule-setters and arbitrators are replaced by smart contracts and protocols.[3] Indeed, the latter set the rules and agreements governing the financial interactions between the users of a blockchain, effectively acting as 'trustless'[4] financial intermediaries within the blockchain system. Similarly, in DeFi financial instruments are represented as tokens or digital assets built on blockchain networks, such as stablecoins,[5] governance tokens,[6] synthetic assets,[7] insurance tokens,[8] etc. Lastly, in DeFi markets are facilitated by decentralised exchanges (DEXs), which allow users to trade tokens directly with one another without the need for intermediaries.[9]

As automated clause execution tools whose transparency and immutability replace the trust between parties that characterises centralised finance, smart contracts represent the underlying infrastructure of DeFi. As such, since their introduction on the Ethereum blockchain in 2015, smart contracts have garnered significant interest by market analysts, academia, the media, and the public at large, who devoted a growing attention to the subject (Chart 1).

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1 In the EU regulatory framework, all institutions that carry out the services or activities listed in Directive 2013/36/EU, Directive 2014/65/EU; Directive 2009/138/EC, Directive 2009/65/EC, Directive 2003/41/EC or Directive 2011/61/EU.

2 In the EU regulatory framework, financial instruments are those comprised under Section C of Annex I of Directive 2014/65/EU (MiFID II).

3 Protocols refer to the software systems or platforms that facilitate services and transactions, building on a set of smart contracts to automate and enforce the activities they support.

4 In this context, 'trustless' refers to the ability of a system to function and reach consensus without relying on a central authority or trusting the participants or third parties involved.

5 Stablecoins are crypto-assets pegged to a fiat currency, a crypto-asset, or a basket of those.

6 Governance tokens are used for voting and decision-making within a protocol.

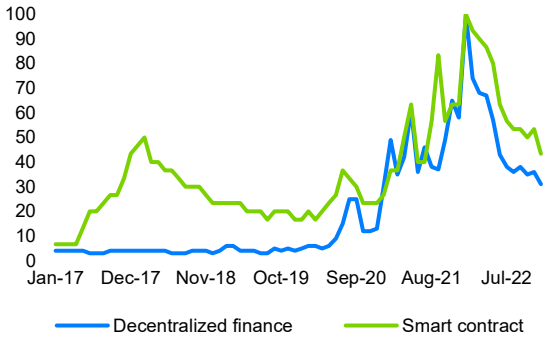
7 Synthetic assets are digital representations of real-world assets.

8 Insurance tokens represent ownership or participation in an insurance protocol or platform.

9 Examples of popular DEXs in DeFi include Uniswap (www.uniswap.org), SushiSwap (www.sushi.com), and Balancer (www.balancer.fi).

Chart 1

Google searches for the terms 'decentralized finance' and 'smart contract'



Note: Interest for 'smart contract' and 'decentralized finance' over time, measured by the number of Google searches. Note that a value of 100 represents the peak in popularity for the given term.
Sources: Google, ESMA

DeFi advocates argue that the 'trustless' nature of smart contracts is set to alter the financial environment. By eliminating the need for intermediaries such as banks and brokers, they argue, smart contracts grant individuals complete autonomy over their finances, lessening their reliance on centralised agencies and making central institutions, including supervisors and standard setters, obsolete. However, whether this should be seen as a positive or negative development is yet to be seen. Indeed, the regulation of market participants ensures that their financial position is sound and accurately represented and meets prudential standards, and that governance and management of risks meet regulatory requirements (He et al., 2017). The absence of central institutions and supervisors would then raise concerns as to who would be in a position to identify, monitor, and mitigate risks pertaining to both financial stability and investor protection.

In order to assess potential threats to investor protection and to financial stability posed by DeFi, it is important to understand the latter's dynamics. These, to a large extent, are determined by smart contracts. This article shows that natural language processing and topic modelling allow for the categorisation of smart contracts into different groups. The latter are clusters of smart contracts that are homogeneous in terms of features and functionalities. Therefore, tracking the prevalence of these clusters can shed light over the evolving dynamics that characterise DeFi and is a first step to decipher the latter's complexity.

This article is organised as follows. The next section delves into the role of smart contracts in the blockchain environment. The subsequent one will provide an overview of the risks to users and financial stability stemming from smart contracts. Then, the article will present the methodology used to categorise smart contracts. First, it will discuss the data used and the data retrieval process. Secondly, it will present the topic model being employed, and thus the results. Some considerations on the usefulness of the model as a tool to monitor DeFi, enhancing investor protection and financial stability, will conclude the article.

We should note that, being primarily concerned with a methodology for the clustering of smart contracts, this article does not delve into the underlying motives that lead entities to create and deploy smart contracts on the blockchain. Nor does it make any effort to discern the nature of said entities (whether they are individuals, institutions, or software). Indeed, inferring said motives, as well as the nature of those entities, would require other research methods, which we do not implement in this analysis. We do think, however, that the method presented here can provide a useful tool to complement analysis primarily concerned with investigating the underlying motives for the deployment of smart contracts.

1.2 The role of smart contracts in the blockchain system

A blockchain can be represented as a network of nodes and edges, where nodes are the blockchain 'accounts' and edges are the transactions amongst those accounts. Accounts are entities with a cryptocurrency balance that can transact with each other. On the Ethereum network, which is the focus of our analysis, there exist two types of accounts, externally-owned accounts (EOAs) and smart contract accounts. Both have the ability to hold and send Ether (ETH, Ethereum's currency) and tokens,[10] that is to say, to transact with the rest of nodes in the network. Yet they do so in very different ways: EOAs are controlled by someone who ultimately decides which other accounts to send ETH/tokens to; conversely, smart contracts are, once deployed on the network, controlled by their underlying code, which determines how they interact with other nodes.[11] Indeed, the actions performed by a smart contract (such as transferring tokens/ETH or creating new contracts) are defined by the code in which it is written and which is triggered by the incoming transactions (tokens/ETH that the smart contract may receive from other accounts).

Smart contracts can thus be defined as immutable computer programs that run deterministically on the blockchain and execute automatically, interacting with other accounts on the blockchain (be they EOAs or other smart contracts) according to the code that defines their actions (Antonopolous, 2018). Antonopoulos (ibid.) derives the following properties from this definition:

- **Computer programs***:* Smart contracts are simply computer programmes. The word 'contract' refers the fact that they are designed to carry-out rule-based operations, as opposed to carrying a legal meaning.

[10] As their name suggests, tokens are value counters stored in smart contracts, that is to say a mapping of addresses to numbers storing the balance of each address. For simplicity we can think of tokens as cryptocurrencies within Ethereum (yet we should note that, strictly speaking, Ether is a token itself). For an overview of the different kinds of tokens, we direct the interested reader to Coutts (2019).

[11] For a more thorough explanation on the difference between EOAs and smart contract accounts, see https://ethereum.org/en/developers/docs/accounts/

- **Immutable**: Once deployed, the code of a smart contract cannot change. Unlike is the case with traditional software, the only way to modify a smart contract is to deploy a new instance of it.[12]
- **Deterministic**: The outcome of the execution of a smart contract is solely determined by the state of the blockchain at the moment of execution.[13]

By a similar token, the Proposal on harmonised rules on fair access to and use of data (known as 'Data Act') defines a smart contract as a "computer program stored in an electronic ledger system wherein the outcome of the execution of the program is recorded on the electronic ledger."

The literature has devoted significant attention to assessing the legal status of smart contracts. Yet, as explained by Dell'Erba (2018), in the absence of a jurisdiction of reference smart contracts carry no inherent legal meaning. Indeed, he argues "smart contracts shall be considered as legal contracts when they represent the implementation of a contractual agreement, characterised by legal provisions in the form of a code. In other circumstances, a smart contract may merely consist of a digital instruction designed to give execution to an agreed sequence of events. In this latter case, although smart contracts enable the creation of new codified relationships defined and enforced by code, there is no relationship with an underlying contractual right or obligation, and the chain of codified events does not turn in the creation of any new contractual relationship" (ibid.).

1.3 Risks to investors and financial stability

Smart contracts hold a potential for financial innovation. In this regard, it is important to note their composability feature, which is linked to their open-source nature and refers to their ability to seamlessly integrate and interact with each other, allowing for the creation of complex and interconnected decentralised applications (dApps).[14] Yet, as is the case with other forms of financial innovation, they come with risks, among which we should note the inability to modify or terminate smart contracts, the transaction-ordering dependency vulnerability, the timestamp dependency vulnerability, the mishandled exception vulnerability, and the

[12] Whereas there is no doubt as of whether the execution of a smart contract is, from a formal point of view, immutable, we can note the ongoing debate on the influence that on the one hand a specific function, namely the 'selfdestruct' function, and on the other Article 30 of the proposed Data Act (available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A68%3AFIN), have on the immutability and the trustless nature of smart contracts. We thus direct the interested reader to Chen et al. (2021), the thread available at https://ethereum.stackexchange.com/questions/315/why-are-selfdestructs-used-in-contract-programming; Adams (2023), Hitchens (2019), and the open letter by Polygon Labs to Representatives of the European Parliament, the Council of the European Union, and the (An Open Letter to Representatives of the European Parliament, the Council of the European Union, and the European Commission, 2023).

[13] This implies that, should a smart contract need to rely on information external to the blockchain (for instance, weather information), said information must necessarily be transposed on-chain. This is done by the so-called 'oracles', which is to say entities that record real-world information and store it on-chain. Further information on oracles can be found at https://ethereum.org/en/developers/docs/oracles/

[14] dApps are application built on a decentralised network that combine a smart contract (or a set of smart contracts) and a frontend user interface.

trustworthiness of data feed 'Oracles'.[15] Moreover, smart contracts remain an unregulated phenomenon,[16] where the accepted principle is exemplified by the notion that "code is law", meaning that that whatever is achieved via the code (and, consequently, via a smart contract) merits acceptance by the community, regardless of any moral or legal consideration. This principle, coupled with the pseudonymity of the developers who deploy smart contracts and their unaccountability,[17] favoured the rise of 'illicit' smart contracts,[18] such as ponzi schemes.[19] These risks to users are exacerbated by significant information asymmetries[20] and by the fact that participation into certain smart contracts, especially 'illicit' ones, is sometimes aggressively advertised.[21]

In terms of financial stability, through streamlining transactions and expediting settlement time, smart contracts and dApps might contribute to a more efficient price discovery or, conversely, to greater volatility and instability due to higher asset price correlations. Besides, as noted by the European Commission (2022), the composability feature of smart contracts, which allows for DeFi protocols to build on top of each other, enabling a variety of services to users, also creates dependencies among protocols, leading to a risk of contagion. Indeed, combining modular elements adds to the complexity and increases operational risks (Fliche et al., 2023), while the fact that several smart contracts rely, either directly or indirectly (that is to say, via other smart contracts), on few ones in order to perform a set of actions leads to concentration risk on key contracts (He et al., 2017). In this respect, we should also note that composability enables rehypothecation, in which assets "staked" (i.e. deposited) on one protocol can be pledged as collateral (or liquidity) in another protocol (Hermans et al., 2022). As noted by ESMA (2022), since this process does not envisage any intermediary who can monitor

[15] For the transaction-ordering dependency vulnerability, see, for the timestamp dependency, mishandled exception, and transaction-ordering vulnerabilities, see Luu et al. (2016). For a discussion on the trustworthiness of data feeds 'Oracles', see Zhang et al. (2016).

[16] In this regard, we should note that the Markets in Crypto-assets Regulation (MiCA), which entered into force in June 2023 and is available at eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1114, does not regulate smart contracts. Arguably, the most direct attempt to regulate smart contracts within the EU stems from Article 30 of the proposed Data Act. Curiously, Belarus has been the first country to regulate the use of smart contracts (through Decree No. 8 of 21 December 2017, available at president.gov.by/ru/documents/dekret-8-ot-21-dekabrja-2017-g-17716). We should note that the open-source nature of smart contracts and blockchain in general prevents any regulation to be directly enforceable on smart contracts.

[17] In this regard, we should note the exception provided by Spain, who has dedicated new powers to regulators to address crypto promotions (Dombey et al., 2022).

[18] For an overview of 'illicit' smart contract activities, see Juels et al. (2016). Note that in this context, which is characterised by the absence of a reference jurisdiction, the adjective 'illicit' merely reflects a normative judgement, as opposed to any legal consideration.

[19] Possibilities of (early) detection of ponzi schemes via NLP and supervised learning have been discussed widely by the recent literature. See, for instance, Chen et al. (2018), Wang et al. (2021), Ibba et al. (2021), Fan et al. (2020), Jung et al. (2019) and Shen et al. (2021).

[20] In this regard, we should note the work of Bartoletti and Pompianu (2017), who document a case of a smart contract that claimed to have a constant fee of 3% was actually retaining a fee starting at 3%, but in fact increased by 3 percentage points at each interaction, (thus 3% for the first interaction, 6% for the second, 9% for the third and so on). This (huge) difference in collected fees arises from a single "+" in the source code ("fees += 100/33", as opposed to "fees = 100/33"), which can easily go unnoticed by the user who sends money to this contract. This 'bug' was also noted in some internet fora, such as Reddit.com (https://www.reddit.com/r/ethereum/comments/4br0za/piggybank_earn_eth_forever/) and Bitcointalk.org (https://bitcointalk.org/index.php?topic=1410587.80)

[21] See, for instance, ESAs' public warning of 17 March 2022, available at www.esma.europa.eu/press-news/esma-news/eu-financial-regulators-warn-consumers-risks-crypto-assets

potential collateral dependencies, it can exacerbate concentration risk, given that the default of one actor can quickly propagate through the system.

These risks are yet to receive adequate attention by supervisors and regulators. This is arguably due to a variety of reasons, ranging from the borderless, decentralised nature of smart contracts and the consequent inability, to enforce any regulation on them, to the limited capacity of institutions to effectively analyse them. However, especially as DeFi grows and its linkages with traditional finance broaden, it is becoming increasingly important for authorities to assess these risks. To do so, it is necessary to understand the different features and functionalities of smart contracts. The model presented in this paper can provide useful insight in this regard.

1.4 Growing interest in the literature

In recent years, smart contracts have been the subject of a growing body of literature. Within the latter we can discern four main themes, namely (i) smart contract design, (ii) (potential) applications, (iii) legal aspects and implications, (iv) smart contract categorisation using on-chain data. (i) focuses on topics such as their underlying infrastructure,[22] the different programming languages used to write smart contracts,[23] their security,[24] and their functioning.[25] (ii) covers use cases in industries such as insurance,[26] auctions,[27] healthcare management,[28] smart grids,[29] and the notary field.[30] (iii) investigates smart contracts' legal status under specific regulatory frameworks, their regulation and governance, potential dispute resolution, intellectual property, and the implications in terms of privacy and data protection (especially with regard to the GDPR).[31] An active topic of debate in the field is the "code is law" principle,[32] [33] defining what it means[34] and examining its significance for the rule

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22 See, for instance, Szabo (1997) and Cai et al. (2018). The latter provide an overview of decentralized applications (dApps) and the role of smart contracts in building them.

23 See Varela-Vaca and Reina Quintero (2021), who identify 101 smart contract languages.

24 See Tsankov et al. (2018).

25 See Palanisamy and Xu (2019).

26 See Gatteschi et al. (2018).

27 See Braghin et al. (2019).

28 See Khatoon (2020).

29 See Lombardi et al. (2018).

30 See Ulloa and Gallegos (2022).

31 See Corrales et al. (2019) and Finck (2019).

32 According to the Law Firm Quinn Emanuel Urquhart & Sullivan, LLP (2022), Lawrence Lessig (2000) is credited with coining the phrase "Code Is Law," which is the title for his 2000 Harvard Magazine article (Lessig, 2000) (see also Lessig [1999]). Yet, one may argue that when Lessig first used the phrase, he didn't have in mind its contemporary usage (Mack, Abovethelaw.com, 2019).

33 See, for instance, Adam (2022).

34 "Code is law" refers to a laissez-faire contract theory that acts as an unofficial governing principle within cryptocurrency and other programming cultures. The theory asserts that if an action can be executed within the confines of the code governing a transaction, then that action should be considered just and fair. Therefore, discovered vulnerabilities may be lawfully exploited, so long as the exploit remains within the parameters of the code (i.e., no additional code is introduced, and the

of law[35] and the judicial system.[36] (iv) leverages on-chain data to feed classification models, either for the purpose of either detecting 'anomalous' contracts or to define 'clusters' of smart contracts with similar features and functionalities. For instance, Chen et al. (2018) propose an innovative method to detect ponzi schemes[37] on the Ethereum blockchain.[38] Said method relies on extracting both transactional and source code features of smart contracts to feed a supervised model[39] aimed at discerning between 'licit' and 'illicit' smart contracts.[40] Sun et al. (2020) and Zhang et al. (2021) adopt a somewhat similar approach, in that they feed on-chain source code data to a classification model or a classification model ensemble. While these authors obtain satisfactory results, it is yet to see whether the methods they put forward can be exploited for similar classification purposes not concerning ponzi schemes. Indeed, the conditions that these authors define for a smart contract to be classified as 'ponzi scheme' are quite strict, and one can expect more lenient conditions to have a non-negligible negative effect on the performance and usefulness of these models. Other authors employ unsupervised topic modelling techniques to cluster smart contracts in different categories. The analysis presented in this paper draws from and contributes to this body of literature.

2 Categorising smart contracts

2.1 The data used

As has been mentioned, once deployed on the blockchain, smart contracts interact with it through carrying-out rule-based operations. The latter are governed by the smart contract's source code, which determines the contract's self-execution (that is to say, its actions) given a state of the blockchain. A smart contract's source code typically includes the contract's functions, variables, calls to libraries or other smart contracts it may rely on, as well as potential developers' comments, which do not affect the smart contract execution. As can be seen in

exploit relies entirely on existing and unmodified code). The underlying idea is that by using certain code, users accept all potential transactions that are possible using that code (Fasken, 2022)

35 For further insight into this concept and its legal implications, we direct the curious reader to the landmark judicial case 'Cicada 137 LLC v. Medjedovic', in which the Judge asserted that "[there] is a theory in some cryptocurrency academic thought, that because blockchain technology is based on publicly available or 'open source' programming code and is based on a laissez-faire contract theory, that 'the code is law'. That means, that if one is able to trade with a blockchain participant within the parameters of the programming code or the notional contract among the voluntary participants, the result is lawful whatever it may be."

36 See, for instance, Filippi and Hassan (2018), who discuss the shift from the traditional notion of "code is law" (i.e. code having the effect of law) to the new conception of "law is code" (i.e. law being defined as code).

37 That is to say, smart contracts which serve as ponzi schemes for participating users (many of whom, it should be noted, are actually aware of the speculative nature of the scheme).

38 See also, Bartoletti et al. (2019) and Jung et al. (2019).

39 We should, at this stage, note the distinction between a supervised and an unsupervised model. The former is a model trained on 'labelled' data, meaning that each observation from the training set is associated with a corresponding target or label. It learns from this labelled data to make predictions or classify new, unseen data accurately. This has implications not only on the training stage, but also on the evaluation stage of the model, since said training data is considered as a 'ground truth', part of which can be set aside so to evaluate the model. An unsupervised model, conversely, is trained on 'unlabelled' data, so its objective consists in finding patterns, structures, or relationships within the data without any prior knowledge of the output. A typical use case for unsupervised learning is that of clustering, which happens to be our use case, too.

40 Here, the 'illicit' class refers to that comprising ponzi schemes, whereas 'licit' refers to that comprising the rest of smart contracts.

Chart 2, source code data is essentially a sequence of strings and can, as such, be fed to a topic model. Besides, being ultimately nodes on the blockchain, smart contracts can send and receive transactions. Said transactions are thus recorded on the blockchain and contribute to determining the latter's state at any given point in time. Whereas in this analysis we rely exclusively on source code data, it would be insightful for future research to combine topic modelling on source code data with analysis on transactional data.

Chart 2

Extract of a smart contract source code

```
// Constructor to assign the initial set of signers.
function ReleaseOracle(address[] signers) {
  // If no signers were specified, assign the creator as the sole signer
  if (signers.length == 0) {
    authorised[msg.sender] = true;
    voters.push(msg.sender);
    return;
  }
  // Otherwise assign the individual signers one by one
  for (uint i = 0; i < signers.length; i++) {
    authorised[signers[i]] = true;
    voters.push(signers[i]);
  }
}

// signers is an accessor method to retrieve all te signers (public accessor
// generates an indexed one, not a retreive-all version).
function signers() constant returns(address[]) {
  return voters;
}

// authProposals retrieves the list of addresses that authorization proposals
// are currently being voted on.
function authProposals() constant returns(address[]) {
  return authPend;
}
```

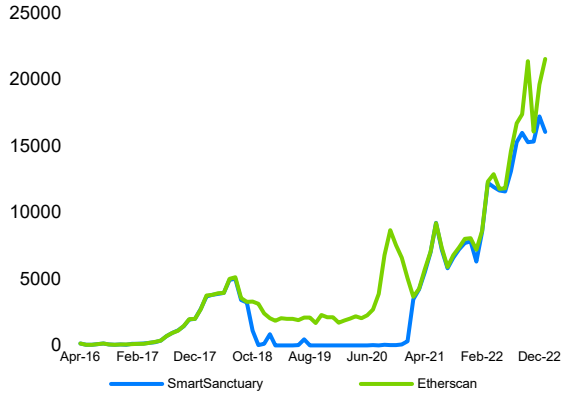
Note: above is an extract of the source code of the smart contract at address 0xFA7B9770Ca4cb04296Cac84F37736d4041251CDF. As we can see, the source code, as any other language, is essentially a sequence of strings, and can therefore be used to feed a topic model.
Source: Etherscan.io

To compile a dataset for this study, we retrieved all smart contracts available on SmartSanctuary, a repository of verified Ethereum smart contracts.[41] This dataset is understood to draw from various sources and is updated frequently, ensuring that the data used in this study is up-to-date and comprehensive. The dataset comprises just under 300,000 contract addresses, along with their respective deployment date, which ranges from 2017 to 2023. While this dataset appears to be representative of verified[42] smart contracts featuring on Etherscan.io, there is some discrepancy in the number of available contracts in the period between December 2018 and January 2021, which largely coincides with the slump in the valuation of ETH (see Charts 3 and 4).

41 The repository is available at https://github.com/tintinweb/smart-contract-sanctuary (see Ortner and Eskandari [n.d.]).

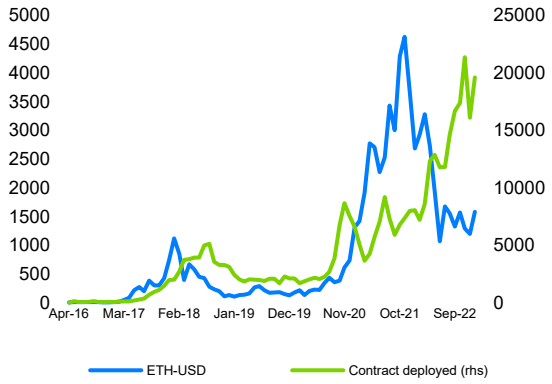
42 It is important to make the distinction between 'source code verification' and 'formal verification'. Source code verification refers to verifying that the given source code of a smart contract in a high-level language (e.g. Solidity) compiles to the same bytecode to be executed by the Ethereum Virtual Machine (EVM, see Glossary [Annex II]) at the contract address. In other words, it is far from representing any sort of audit of the contract. Formal verification, on the other hand, describes verifying the correctness of a smart contract, meaning the contract behaves as expected. In this context, by 'contract verification' we refer to 'source code verification'.

Chart 3
Number of verified smart contracts



Note: Number of smart contracts available on Etherscan.io and on the SmartSanctuary depository between April 2016 and January 2023.
Sources: SmartSanctuary, Etherscan.io, ESMA

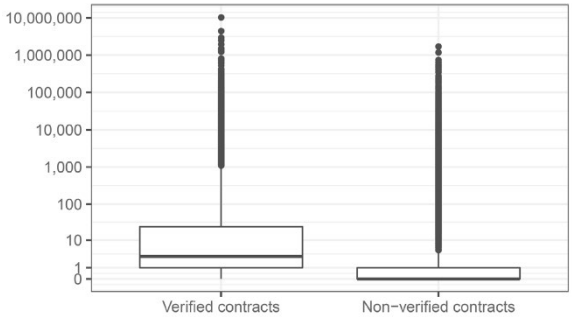
Chart 4
Verified smart contracts deployed vs. ETH-USD price



Note: ETH-USD price (primary y-axis) and number of contracts deployed (secondary y-axis) (April 2016 – December 2022). As we can see, the recent remarkable decrease in the ETH-USD price does not seem to have hindered the steady growth in the number of contracts deployed.
Sources: Etherscan.io, Kaiko, ESMA

Despite this discrepancy, it is sensible to assume that this lack of data does not significantly affect the results of our study, since the latter consists in an ex-post categorisation, rather than in a prediction task. Moreover, we should note that, while representing a small percentage of all smart contracts on Ethereum, verified contracts account for the vast majority of transactions on the blockchain. In this respect, Ansaldi-Oliva and Hassan (2020) estimate that verified smart contracts, a mere 2.2% of all contracts, account for more than 70% of transactions sent to contracts (see Chart 5).[43]

Chart 5
Transactions sent to smart contracts



Note: Number of transactions, reported on a logarithmic scale (log 1+x), for verified and unverified smart contracts. As we can see, verified smart contracts tend to receive a significantly larger number of transactions as compared to unverified ones.
Sources: Ansaldi-Oliva and Hassan (2020)

[43] Therefore, while it should be kept in mind that the taxonomy we propose is based on a (most-likely biased) minority of smart contracts, making its extrapolation onto the rest of contracts problematic, said minority accounts for most of smart contract activity and thus remains a valuable tool to monitor the smart contract system.

2.2 The model

Topic modelling is the task of discovering latent topics (themes) within a given corpus of documents and, possibly, assign the documents to the identified topics.[44] It employs statistical algorithms to identify patterns of co-occurring terms. Based on said patterns, it defines topics, which are characterised by terms that are frequently associated with each other, indicating a shared underlying theme. A smart contract source code is essentially a long string and, as such, can be seen as a document. Therefore, we can employ topic modelling techniques to discern different themes among smart contracts, that is, in order to identify smart contracts with similar features. The unsupervised nature of this task, characterised by the lack of any 'ground truth' both as regards the assignment of documents to predefined categories and as regards the nature of the categories that are to be defined, implies that assigning 'labels' to the smart contracts categories defined by the model is necessarily a 'manual' task.

To categorise smart contracts, we feed their polished source code to a Latent Dirichlet Allocation (LDA) model, which is arguably the most popular tool in topic modelling. LDA is a generative probabilistic model leveraging Bayesian statistics. It is 'generative' in the sense that it operates under the fundamental assumption that, given a vocabulary (that is, a predefined set of words) and a set of latent distinct topics (each defined as a distribution over the set of words), each document is generated as a composite mixture of k latent topics (k being a discretionary number decided a priori). In more formal jargon, and as explained by Blei et al. (2009), LDA assumes the following generative process for each of the M documents within the corpus:

1. Choose $N \sim \text{Poisson}(\xi)$;
2. Choose $\theta \sim \text{Dir}(k,\alpha)$;
3. For each of the N items i:
   (a) Choose a topic $z_i \sim \text{Multinomial}(\theta)$;
   (b) Choose a word w_i from $p(w_i \mid z_i,\beta)$.

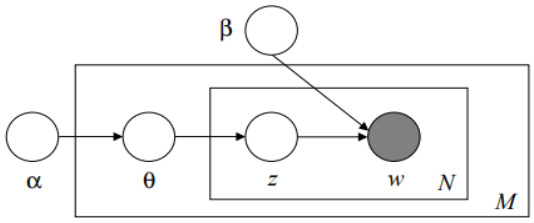
Where: α, ξ are constant parameters given the corpus; N is the number of words for a given document; β is a $k \times V$ random matrix where each row is independently drawn from an exchangeable Dirichlet distribution;[45] θ is the topic mixture for a given document; z_i is the topic mixture for a given word and a given topic mixture θ for the given document; and w_i is the i-th word in the given document. We should note the 'nested' nature of this formulation, which is also represented in Chart 6.

[44] Note that hereinafter, the terms 'category' and 'topic' are used interchangeably.

[45] An exchangeable Dirichlet is simply a Dirichlet distribution with a constant scalar parameter.

Whereas parameter ξ can be estimated, for instance, via maximum likelihood, parameters α, β, θ, and *z* require an iterative empirical Bayes method.[46]

Chart 6
Graphical representation of an LDA model



Note: Graphical model representation of LDA. The LDA relies on a set of assumptions regarding the generation of documents. Paramers α, β, which are constant throughout the corpus, determine, respectively, the topic mixture θ of a given document and, along with z_i, the probability of a given word w_i. On the other hand, parameter θ changes for each given document and determines, in turn, the topic mixture z_i of a given word w_i within the document.
Source: Blei et al. (2003)

Through the estimation of these parameters, we obtain the matrix *β*, where each of the *k* rows corresponds to a topic and each of the *V* columns to a word in the vocabulary. In other words, each topic is identified with an estimated probability distribution over all the words in the vocabulary. This allows us to assess the influence of each word in the definition of a topic (or the importance of a word in discerning among topics).[47] Moreover, representing topics as distributions over words allows for their clustering into macro-topics, for instance via a *k*-means algorithm.[48] The LDA outputs as many topics as are defined through *k*. In this context a topic is a proxy for a category of smart contracts that have similar purposes and functionalities.

The performance of the model is determined by the extent to which said topics are distinct from one another. While in the context of unsupervised learning we cannot rely on any ground truth (such as would be, for instance, a human topic ranking), we can resort to the distributional hypothesis of linguistics, which essentially states that words with similar measing tend to occur in similar contexts, an assumption popularised by Firth (1950) through the maxim “a word is characterized by the company it keeps”.[49]

[46] Describing said method is beyond the scope of this paper, yet we direct the interested reader to Blei et al. (2009), who in section 5 of their paper provide an exhaustive yet clear explanation of the algorithm used for the estimation of these parameters.

[47] This can be done, for instance, though implementing a principal component analysis (PCA) on these dimensions and computing the orthogonality between each original dimension and the first principal component. The original dimension with the lowest orthogonality (corresponding to a specific word in the dictionary) is the one whose ‘contribution’ in discerning among topics is greatest.

[48] For instance, this was investigated by Sievert and Shirley (Sievert & Shirley, 2012) who, after defining a set of topics via LDA, plot them on the first two PCs and thus cluster them via a k-means algorithm.

[49] For further insight on the relationship between the meaning of words and their distributional relations, see Harris (1954).

On this basis, the topics yielded by an LDA model will be considered to be 'coherent' if all or most of the words within a topic are 'related', that is to say, whether their distributional relationship is similar (Syed and Spruit, 2017).There exists multiple coherence metrics that serve as proxy to evaluate the performance of the LDA model. Roder et al. (2015) assessed the correlation that these metrics had with human topic ranking, and propose a coherence score themselves, which they argue has the highest correlation with human topic ranking. The computation of said score is well explained by Syed and Spruit (ibid.). The coherence score ranges from 0 to 1, with larger value reflecting high inter-topic heterogeneity and higher intra-topic homogeneity.[50] One issue when interpreting results, however, is that the coherence score tends to increase with the number of topics yielded by the LDA, even if the additional topics do not increase semantic difference as perceived by a human (intuitively, if the additional topics are irrelevant or not meaningful) (see Chart 7).

As we see, the LDA, just as any other topic model, defines categories based on patterns of co-occurring terms. It is thus clear that its performance is hindered by the presence of common, uninformative terms, since the latter decrease the semantic differences among documents. For this reason, prior to feeding smart contract source code to the LDA model, we undertook some steps to 'polish' and remove unnecessary 'noise'. In particular, we removed special characters (such as punctuation marks, symbols, or non-alphanumeric characters), characters related to the formatting of the source code (for example instances such as "\n", indicating a new line of code), and conjunction words (such as "and", "or", "but", etc.). Moreover, given that source code can be written in different programming languages,[51] further steps were taken in order to harmonise said languages. Lastly, to further reduce potential noise in source code, we lemmatised terms, replacing, for instance, 'encode', 'encoding', 'encoded', and the like with 'encod'.

2.3 Smart contract categories

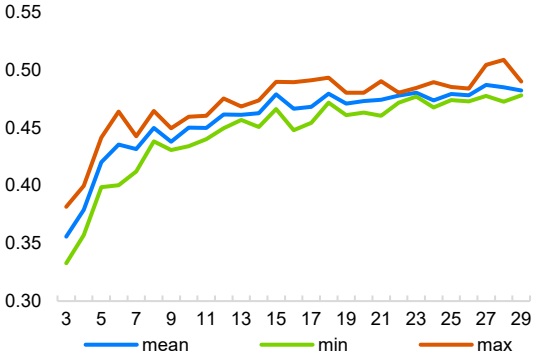
To calibrate the LDA model parameters and evaluate its performance, we relied on a 10-fold cross-validation, which yields the results reflected in Chart 7. As the narrow range between the lower and the upper line suggests, this model proves to be robust to changes in the dataset. Moreover, we note that the coherence score grows steeply until the number of outputted topics is increased to 5, to then gradually reach a plateau oscillating around 0.475. As mentioned, due to the unsupervised nature of the problem, the topics yielded by the model have to be labelled 'manually'. Therefore, it is sensible to choose a number of topics that is relatively low yet which yields a coherence score that, even if not necessarily the highest, is

[50] Note that in this context the terms 'homogeneity' and 'heterogeneity' are meant with regard to the strings contained within the identified topics. Consider a scenario with only two topics, each comprising a number of documents. The more diverse the two sets of words defining, respectively, the two topics, the higher the inter-topic heterogeneity, and the more similar the sets of words featuring in the documents within a given topic, the higher the intra-topic homogeneity. Note that this does not necessarily imply that, given a high coherence score, the topics being considered are discernible. The latter will require a 'human' judgement.

[51] For an overview of said languages, we direct the interested reader to https://ethereum.org/en/developers/docs/smart-contracts/languages/

sufficiently high. Drawing from the literature, and in particular the work of Ibba et al. (2021) and the taxonomy proposed by Bartoletti and Pompianu (2017), we set this number to be five.[52] It should also be noted that, when setting the number of categories to be yielded by the LDA to more than five, the latter became significantly less well defined, meaning that it became harder to define and label them.[53]

Chart 7
Coherence score per number of topics



Note: 10-fold cross-validation coherence scores (y-axis) per number of topics (x-axis). The red line reflects the highest score obtained among the 10 folds, the blue line the mean one, and the green line the lowest one. The coherence score serves as a proxy to evaluate the performance of an LDA model. It ranges from 0 to 1. The closer it is to 1, the higher the inter-topic heterogeneity and the intra-topic homogeneity. In this graph, we should not that in our case it steadily increases prior to reaching a plateau. As suggested by Ibba et al. (2021), picking the number of topics coinciding with the beginning of the plateau (in our case, 5) allows for the identification of easily discernible topics.
Source: ESMA

Considering five topics, we manually analyse a sample of about 200 smart contracts for each topic to infer their purpose and verify whether those belonging to the same category share common features and functionalities. This also allows us to assign a 'label' to each category. Through this analysis, we find five categories of smart contracts. These categories can be labelled as *financial*, *operational*, *tokens*, *wallet*, and *infrastructure*.

– **Financial:** smart contracts belonging to this category serve primarily to gather and redistribute funds, thus enabling basic financial operations. These range from simple borrowing and lending protocols to ICOs and complex DAO project.[54] This category also comprises 'airdrop' smart contracts, that is, contracts whose purpose is to distribute a limited amount of tokens to a set of wallets (usually as a marketing strategy and in the hope that the distributed token will be adopted as a cryptocurrency). Since they are able to store funds and release them upon the fulfilment of predefined conditions, financial smart contracts also serve insurance purposes. We should note

[52] Bartoletti and Pompianu (2017) analysed the application domain of 834 verified smart contracts, and proposed a taxonomy comprising five categories, namely *financial, notary, game, wallet,* and *library*.

[53] The definition of additional categories, rather than yielding loosely homogenous groups, led to a partial reshuffling of existing ones. On the one hand, this supports the decision to set the number of categories to five, in line with the literature. On the other, this dynamic is a reflection of the instability of results that is inherent to topic modelling.

[54] A decentralized autonomous organization (DAO) is an entity structure where decisions are made by the token holders. Further information on DAOs can be found at https://ethereum.org/en/dao/

that smart contracts that enable ponzi schemes, lotteries, and other sort of 'gambling' activities on the blockchain concern the storing and redistribution of funds, too, and, as such, they feature in this category. Lastly, sets of financial smart contracts are usually the infrastructure of automated market makers (AMMs) and pools that is behind decentralised exchanges (DEXs)[55].

- **Operational:** This category comprises smart contracts that, performing general purpose operations, facilitate the functioning of other smart contracts or the interaction between other smart contracts. For instance, operational smart contracts are deployed onto the blockchain to host libraries. The latter can be addressed to by smart contracts pertaining to other domains in order to perform a set of operations. These smart contracts play crucial role in optimising resource allocation and utilisation, as well as in handling errors.
- **Token:** Smart contracts in this category enable the generation of new tokens, their indexing, and their dismissal. More technically, this category is associated with the functionalities involving the approval and management of Ethereum Request for Comments (ERC) standards. Among the most common ERC standards, we should note ERC20 and ERC721. ERC20 defines the standard interface for fungible tokens, which are identical and interchangeable units of value, commonly used for cryptocurrencies, digital assets, and utility tokens. ERC721 specifies the standard for non-fungible tokens (NFTs), which represent unique and indivisible assets like collectibles, digital art, and in-game items.[56]
- **Wallet:** Smart contracts within this category concern the management of fees, sender accounts, balances, public access, requirements, and permission control. They serve primarily to simplify users' interaction with the blockchain, for instance by batching transactions and defining transfer limits.
- **Infrastructure:** This category comprises contracts that deal with the manipulation and processing of string data, Boolean values, signatures, encoding and decoding operations, ABI (Application Binary Interface) functionality, viewing operations, memory usage, sending operations, and payload handling. Such operations are essential building blocks that contribute to the underlying infrastructure of smart contracts and dApps. In this sense, smart contracts belonging to this category can be considered as the underlying infrastructure for other smart contracts. As such, they are key to supporting the interoperability and scalability of blockchain applications.[57]

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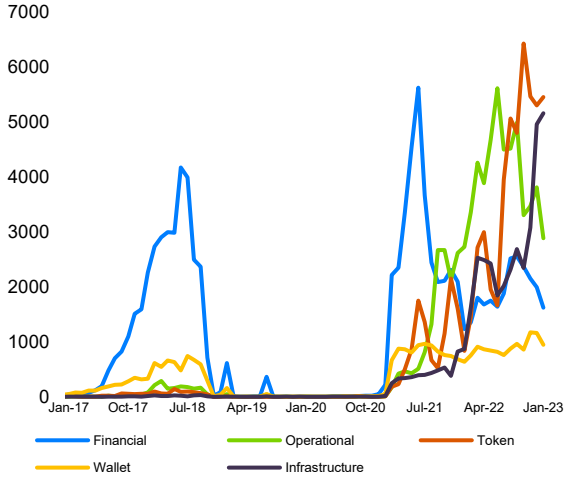
[55] In DEXs, users do not trade against each other, but rather with a of smart contract, which, alone or along a set of other smart contracts, act as an algorithm between the buyer user and the seller user. For an overview of AMMs, see https://chain.link/education-hub/what-is-an-automated-market-maker-amm

[56] For a further overview of ERC standards, we direct the interested reader to https://ethereum.org/en/developers/docs/standards/tokens/

[57] Unlike Ibba et al. (2021), our LDA model did not identify a game category (see also Bartoletti et al., 2017). Yet, the financial category includes keywords such as parameters, external components, pools, balances, public access, and other source code terms that are relevant to the game category. Indeed, in the context of gaming, parameters play a vital role in defining game rules, mechanics, and settings. External components can refer to various game-related entities such as characters, items, or game environments. Balances can represent in-game currencies or resources that players accumulate and utilize. Public access can be associated with multiplayer functionality, enabling players to interact and compete in a shared gaming environment. Besides, games often incorporate financial elements, such as in-game economies, virtual currencies, and transactions. Many modern games utilize blockchain technology and cryptocurrencies, enabling players to trade virtual assets or participate in decentralized gaming platforms. We thus reckon that financial aspects within games cannot be entirely separated from their gameplay and interactive elements. In this view, the convergence of the financial and the game categories allows for a comprehensive understanding of smart contracts' potential in creating innovative gaming experiences with integrated financial mechanics. We should also note that Ibba et al. (2019) defined a notary category. Our model did not yield said category, but a somewhat broader one which we defined as Smart Contract Execution. Besides notary-related contracts, the latter also encompasses a broader range of functionalities, such as interface and data handling.

Annex I provides an overview of the most relevant terms for the definition of each of these categories, and explains how said 'relevance' has been determined.

Chart 8
Smart contract deployment per topic



Note: Monthly smart contracts deployment rate per category of contract (January 2017 - January 2023)
Source: ESMA

The incidence of each of the five categories varies significantly over time (see Chart 8). We note two major 'surges' in smart contracts deployment, one running from 2017 to the end of 2018 and another running from late 2020 to January 2023. These largely coincide with the two major Ethereum price surges (see Chart 4). The prevalence of different categories in these two 'waves' differs significantly, with the latter wave remarkably more heterogenous than the former.

These trends in smart contract categories can be explained by developments in the DeFi deployed on the Ethereum blockchain. Indeed, during the initial Ethereum bull run, coinciding with the first 'wave' of smart contracts deployment, *financial* smart contracts were significantly dominant, outnumbering all other categories. Said prominence can be attributed to the prevalence of Initial Coin Offerings (ICOs).[58] Market intelligence suggests that ICOs account for a substantial number of financial contracts being deployed on the Ethereum blockchain between 2017 and 2018, leading to the predominance of the *financial* smart contracts that characterises this period.

The second 'wave' of smart contracts deployment, running from late 2020 to January 2023, which largely reflects the surge in interest in DeFi applications, is remarkably more heterogeneous in terms of categories of smart contracts being deployed. In particular, worth

[58] An Initial Coin Offering (ICO), also known as a token sale, is an asset distribution methodology that involves selling digital assets to raise funds for a blockchain-based project (Cryptopedia, 2022). They involve the sale of digital tokens or coins to investors in exchange for established cryptocurrencies, such as Ethereum. It is worth mentioning that while ICO contracts also enclose a token creation (which could lead one to label them as token smart contracts), these are better placed as within the financial category as they enclosed a set of financial related functions and codewords.

noting is the surge in the *token,* the *operational*, and the *infrastructure* categories. The rise of the *token* category is linked to the proliferation of token-related projects and the growing importance of token standards like ERC20 and ERC721 in facilitating token creation and management. The increase of the latter two categories, on the other hand, can be attributed to the evolution and diversification of the Ethereum system, characterised by a broad development of various dApps and protocols.

Interestingly, the *wallet* category, which pertains to the management and storage of cryptocurrencies and tokens, exhibits a lower, yet relatively more stable rate of deployment throughout both waves. This suggests a consistent demand for wallet-related functionalities, possibly reflecting the ongoing need for secure storage and convenient access to digital assets within the Ethereum system.

Overall, the shift from predominantly *financial* smart contracts during the early ICO-driven phase to the increased deployment of contracts across various categories indicates the growth, diversification, and evolution of the Ethereum blockchain. This trend is driven by the increasing adoption of more sophisticated protocols, the development of smart contract-based solutions, and the continued importance of wallet-related functionalities.

2.4 Potential model improvements

While we deem the results yielded by the model to be satisfactory, we do not exclude that more sophisticated polishing techniques might further improve the model performance, yielding a higher coherence score. Furthermore, other approaches to identifying smart contract categories could be explored. For instance, future studies could leverage on a dynamic LDA model, that is, an LDA model where the number of topics is not set ex-ante. Besides, we should note that both the classic LDA model and its dynamic version are bag-of-words models, as in they consider the incidence (distribution) of words in documents (smart contracts in this context), while disregarding their sequence. A more complex approach could thus take said sequence into account. This, for instance, could be achieved through a doc2vec embedding of smart contracts, which allows to embed smart contracts into numeric vectors of discretionary length and, provided that said vectors are sufficiently heterogeneous, cluster them in a vector space comprising as many dimensions as the length of vectors.[59] A further method could be the one implemented by Grava (2021), who relies on a two-step approach, consisting in (i) the definition of a large of number of topics (30) via LDA and (ii) the subsequent 'manual' clustering of these topics.[60] Besides testing the validity of model alternatives, future research could also assess the feasibility of feeding these models with bytecodes data as

[59] For an overview of the doc2vec embedding, see Mikolov et al. (2013) and Quoc and Mikolov (2014).
[60] We implemented this approach, yet replacing the manual clustering of topics, which would have proved too burdensome and somewhat discretionary, with (i) the transposition of topics onto the first two principal components of the multidimensional space defined by the dictionary, and thus (ii) a k-means clustering of the topics. However, this approach did not yield satisfactory results, possibly because the limited vocabulary that characterises smart contract source code does not allow for the definition of a high number of topics.

opposed to source code. Potentially, this would allow for the analysis of a much larger dataset of smart contracts, comprising 'unverified' smart contracts, too.

Moreover, future research could complement these results with network analysis. For this purpose, all incoming and outgoing transactions for each of the smart contracts being assigned to a category via topic modelling could be retrieved. Given that both the sender and the addressee are available for every transaction, this would allow for the definition of a directed network (where smart contracts are the nodes and the flow of tokens among are the [directed and possibly weighted] edges). Leveraging this network and its properties (density, node centrality, transitivity, shortest paths, categories-based homophily, etc.), one can infer insightful information both on the smart contract system as a whole or on a specific category of smart contracts. The relevance of such an analysis would be twofold. First, it would allow one to assess by what extent DeFi is actually decentralised. Indeed, while it is clear that its 'infrastructure' is obviously decentralised, the financial dynamics that characterise it are not necessarily. A network analysis focusing on nodes centrality could uncover to what extent trading, lending and investment of cryptoassets are concentrated in or influenced by a limited number of smart contracts. This, in turn, would shed light as to what extent the DeFi system is subject to concentration risk, which has important implications for financial stability.

3 Conclusion

In this article, we use on-chain smart contract source code data to discern among different categories of smart contracts and shed light on the underlying infrastructure of DeFi.

With reference to smart contracts deployed from January 2017 to January 2023, we identify five main categories of smart contracts: *financial*, *operational*, *token*, *wallet*, and *infrastructure*. Moreover, examining their deployment rate over time, we note two main surges, one running from 2017 to the end of 2018 and another running from late 2020 to January 2023. These two 'waves' of smart contract deployment differ in terms of heterogeneity, with the latter being remarkably more heterogenous in terms of categories comprised therein.

This can be explained by the fact that the first 'wave' consists virtually exclusively of smart contracts that, be they lending protocols or lotteries or similar, performed relatively simple transactions. Starting in 2020, however, this category gave way to more complex smart contracts whose purpose was not the mere redistribution of tokens (the main purpose of *financial* smart contracts), but rather that of supporting more complex applications such as derivatives management, prediction markets, insurance, yield farming, stablecoins, decentralised asset management, and other.

These sophisticated applications, while also involving *financial* smart contracts, entail a more intricate smart contract logic and an increased level of interaction among smart contracts, which explains the surge in the other four categories (*operational*, *token*, *wallet*, and *infrastructure*). This reflects the increased versatility of DeFi, but also its growing complexity. It also entails a series of risks, ranging from the growing difficulty that users inevitably face

when dealing with an increasingly complex system whose dynamics are hard to comprehend, to the increased 'dependency risk' that is inherent to said system. Indeed, the fact that smart contracts build on top of each other and are increasingly intertwined not only enhances their functionality, but also exacerbates their reliance on each other. In this regard, imagining stacked contracts as Lego building blocks, we can appreciate that the vulnerability of a 'primitive' one has the potential to affect many others and thus, at least partly, the entire system.[61]

The OECD (2022) notes these risks, stating that "[the] level of automation and dependence on the functioning of smart contracts and their underlying code intensifies the corresponding risks to users."[62] It points out that, consequently, "there is a need for policy makers to closely monitor this market to better understand its mechanics, potential benefits and underlying risks" (ibid.). While the Markets in Crypto Assets Regulation (MiCA) entered into force in June 2023[63] and does not directly regulate DeFi, the OECD's call for a closer, consistent monitoring of the DeFi system is echoed by a number of legislators, foremost the European Commission. The latter, acknowledging the limited enforcement power that can be exerted on DeFi, points to a few potential policy initiatives, including "a public observatory of DeFi activity operated by a public authority", and goes on to explain that such an institution "would deploy public investigations and issue opinions and warnings publicly about specific DeFi protocols" (European Commission, 2022).[64] The ESRB (2023), by a similar token, points to the need of promoting EU-level knowledge exchange and monitoring of market developments relating to DeFi. Against this background, the model presented, being robust to changes in the dataset, able to identify new smart contracts categories as they emerge, and able to assign a new smart contract to a category as of the moment it is deployed on the network (that is, before other nodes on the blockchain network start interacting with it), is a useful tool that can contribute to an enhanced and nuanced understanding of DeFi, as well as to identifying related significant risks.

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61 To further explore the interlinkage between smart contracts, which in itself can be seen as a proxy of 'dependency risk', we believe that future research could rely on network analysis. In this respect, a network could be built by defining smart contracts as nodes and the flow of cryptocurrencies among them as (directed) edges. Said network could thus be examined, for instance in terms of network metrics such as node centrality, so to gain insight on the DeFi system. This analysis would not only shed light on the risks to financial stability, but would also allow one to assess by what extent DeFi is actually decentralised. Indeed, while it is clear that its 'infrastructure' is obviously decentralised, the financial dynamics that characterise it are not necessarily. As pointed out by the Aramonte et al. (2021), there seems to be a "'decentralisation illusion' in DeFi since the need for governance makes some level of centralisation inevitable and structural aspects of the system lead to a concentration of power."

62 We should note that the ESRB (2023), too, points to the 'composability' feature of DeFi and the risks that it entails.

63 Its application is scheduled within a 12 or 18-month deadline depending on the provision. The text of the Regulation is available at: eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023R1114

64 We should note that these policy initiatives draw, at least partly, from those proposed by Auer (2022).

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Annex I – defining the relevance of terms for a topic

To define the relevance of words for a given topic, we draw from Sievert and Shirley (2014), who define it in the following way:

Let p(*w*|*k*) denote the probability of term $w \in \{1, ..., V\}$ for topic $k \in \{1, ..., K\}$, where V denotes the number of terms in the vocabulary, and let p(*w*) denote the marginal probability of term w in the corpus. We define the relevance of term *w* to topic *k* given a weight parameter *λ* (where $0 \leq \lambda \leq 1$) as:

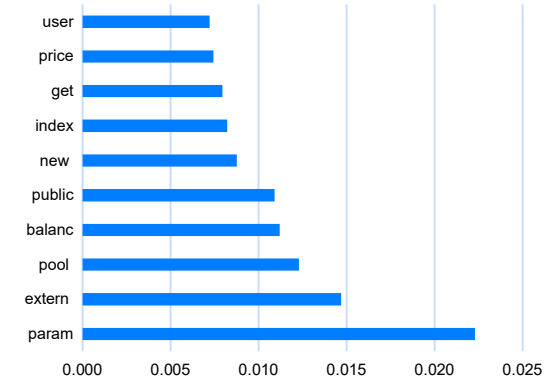
$$r(w, k \mid \lambda) = \lambda \log(\mathrm{p}(w|k)) + (1 - \lambda)\left(\log \frac{\mathrm{p}(w|k)}{\mathrm{p}(w)}\right)$$

Note that $r(w, k \mid \lambda)$ is directly proportional to $\log(\mathrm{p}(w|k))$ and inversely proportional to $\log(\mathrm{p}(w))$. The parameter *λ* serves to weight the marginal probability p(w). For *λ*=1, the second term in the equation will be equal to 0 and the relevance will be determined solely by $\log(\mathrm{p}(w|k))$. To avoid identifying terms whose relevance is mostly determined by their low influence throughout the corpus, we decided to set λ=1.

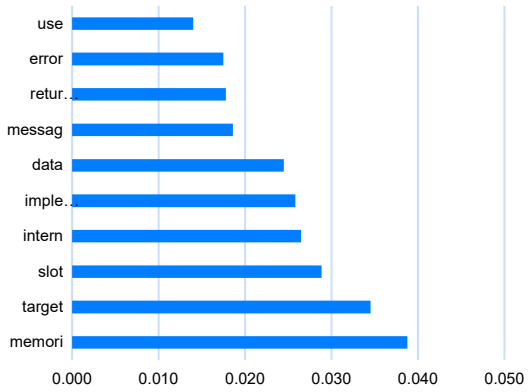
Besides, we direct the interested reader to Chuang (2012), who, in order to determine the importance of a word in the definition of topics, leverages the Kullback-Leibler divergence between the marginal probability of a topic and the probability of a topic conditioned on the given word.

Computing the relevance for each the term in the dictionary and for each of the defined categories, we are able to identify the most relevant words for the latter, as shown in the following graphs (where the horizontal bars represent the relevance for a given word for a given category).

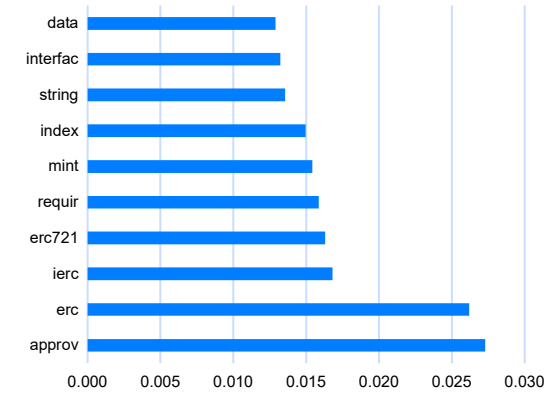
Financial smart contracts



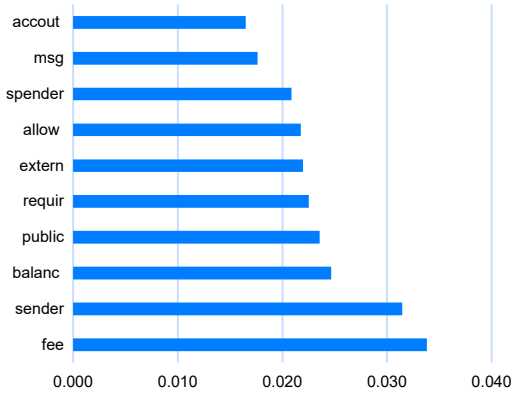
Operational smart contracts



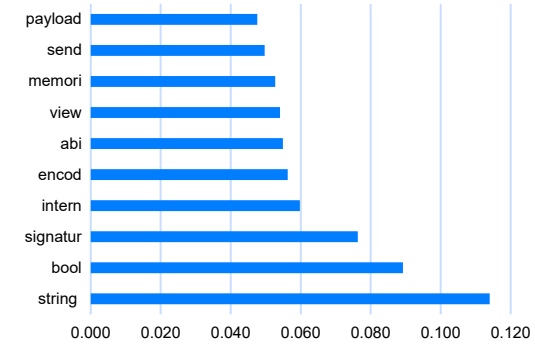
Token smart contracts



Wallet smart contracts



Infrastructure smart contracts



Annex II – Glossary

We hereby provide a glossary for some terms related to DeFi that feature throughout the article. Unless specified otherwise, all definition provided below draw from Coinmarketcap and are available at coinmarketcap.com/alexandria/glossary.

(Smart contract) address: A crypto address is a unique string of characters that represents a blockchain node that can send and receive cryptocurrency. It is akin to a real-life address, email or website. Every address is unique and denotes the location of a node on the blockchain network.

Bytecode: Solidity is a high-level object-oriented programming language that is principally used for the Ethereum blockchain. Solidity is a great tool to write smart contracts, which are self-executing code that enable complex automated functions. The programming language interacts with the Ethereum Virtual Machine (EVM), which is the abstraction layer between the executing code and execution machine. It is influenced by the C++, Python and JavaScript languages.

Central ledger: A central ledger consists of a physical book or digital file used by individuals or organizations to record and total economic transactions in a centralized manner.

Composability: Composability refers to the ability of combining distinct components to create new systems or outputs. In software development, composability means developers can reuse existing software components to build new applications. A good way to understand composability is to think of composable elements as Lego blocks. Each Lego can be combined with another, allowing you to build complex structures by combining different Legos. In Ethereum, every smart contract is a Lego of sorts—you can use smart contracts from other projects as building blocks for your project. This means you don't have to spend time reinventing the wheel or building from scratch.[65]

Decentralised Exchange (DEX): A peer-to-peer exchange allowing users to trade cryptocurrency without the need for an intermediary.

Decentralized applications (dApps): Apps are any computer applications whose operation is maintained by a distributed network of computer-nodes, as opposed to a single server. The concept of a decentralized application was enabled by blockchain platforms that support smart contracts, the first of which was Ethereum (ETH).

Distributed ledger: A distributed ledger is a system for recording the transaction of assets in a decentralized manner. Unlike centralized solutions, such as databases, distributed ledgers do not have a central repository for storing recorded data. Nodes process and verify transactions.

Ether (ETH): Ether is the native cryptocurrency of the Ethereum network.

[65] Definition retrieved from https://ethereum.org/en/developers/docs/smart-contracts/composability/

Ethereum Virtual Machine (EVM): EVM can be described as a distributed computer whose state at any given moment is perfectly defined via a consensus algorithm. EVM is Turing-complete, which means that it can execute every operation a regular computer is expected to be able to perform. It has its own programming language, Solidity, which allows developers to code and run any application they want on the EVM in a decentralized manner.

Non-fungible tokens (NFTs): Traditionally, cryptocurrencies like Bitcoin are fungible, meaning that every one unit of BTC is exactly the same as another unit of BTC and they can be exchanged for one another with no further considerations. Fungibility is one of the fundamental properties of traditional currencies too, like the USD. But in some use cases, tokens might be non-fungible, most commonly when they are used as digital proof-of-ownership of underlying assets. For example, NFTs can be used to represent digital art: at one point, an extremely popular Ethereum-based blockchain game CryptoKitties associated its tokens with unique images of cartoon cats and allowed users to trade those cats by exchanging the corresponding tokens.

Opcode(s): All Ethereum bytecode can be broken down into a series of operands and opcodes. Opcodes are predefined instructions that the EVM interprets and is subsequently able to execute. For example, the ADD opcode is represented as 0x01 in EVM bytecode. It removes two elements from the stack and pushes the result.[66]

Open source: Open source refers to the open nature of a software or code, which are deemed by the copyright holders or the creators to be open for inspection, duplication and modification. Being open source allows users to use, analyze, modify, change and distribute the software or the code, as per their requirements and needs, for anything without restrictions. This ensures that end-users are able to use the software freely without having to face any lawsuit or other liabilities from the original developers. However, open source doesn't necessarily mean free, and developers can still charge for services, namely consultancy and troubleshooting, among others.

Private key: A private key generally refers to an alphanumeric string that is generated at the creation of a crypto wallet address and serves as its password or the access code. Whoever has access to a private key has absolute control over its corresponding wallet, access to the funds contained within, and can transfer or trade assets and use the account for other purposes.

Token: In the blockchain system, any asset that is digitally transferable between two people is called a token. These tokens are issued on a blockchain, most often on Ethereum.[67]

Wallet: A wallet is an application that let one interact with an Ethereum account.

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66 See Yamagata (2022).

67 Definition available at https://www.coinhouse.com/learn/blockchain-technology/what-is-a-token/#:~:text=In%20the%20Blockchain%20ecosystem%2C%20any,blockchain%2C%20most%20often%20on%20Ethereum.

ESMA Working Paper, No. 3, 2024
Authors: Zeno Benetti, Federico Piazza
Authorisation: This Working Paper has been approved for publication by the Selection Committee and reviewed by the Scientific Committee of ESMA.

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