Automated Market Maker-based Decentralized Exchanges and their intersection with Artificial Intelligence

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ABSTRACT

The use of Artificial Intelligence (AI) systems in crypto-asset markets is increasing in DeFi protocols, including in Decentralized Exchanges (DEXs). In this paper we analyse the Automated Market Makers (AMMs)-based DEXs and the interconnections that may exist between AI and AMM-based DEXs with a view to understanding how they fit into the current financial regulatory framework, in the event that the crypto-assets traded on AMM-based DEXs qualify as securities under the Portuguese securities law. Although the use of AI in AMM-based DEXs is still at an early stage of development, the potential benefits of this intersection are already evident. Notably, AI can be used to enhance AMM-based DEXs capabilities, to mitigate risks associated with trading with AMM-based DEXs and to improve the functioning of oracles by improving the quality of the data inputs. In terms of the existing regulatory framework, AMM-based DEXs pose high challenges for regulators, considering that EU financial services' legislation is not technologically neutral, and that it was not designed to deal with scenarios where there is no direct intervention by financial intermediaries. We believe that the DLT Pilot Regime, in articulation with the recently approved EU regulation on AI, could be an excellent vehicle for companies in the crypto-asset sector and regulators to test DEXs in a safe and trusted environment in order to better understand the optimal approach to regulate these DeFi protocols and strike a balance between harnessing the benefits of financial innovation and ensuring investor and market protection. ●

1. INTRODUCTION

Artificial Intelligence ("AI") and Distributed Ledger Technology ("DLT") are two of the most transformative technologies in the financial sector.

Technological development in the financial sector related to DLT has been very rapid and has enabled the provision of financial services and products in a new and innovative way as well as the emergence of new financial services and products.

Decentralized Finance ("DeFi") is one of the latest developments in crypto-asset markets and it can be understood as a set of alternative financial markets, products and systems that operate using crypto-assets and smart contracts built upon DLT or similar technology[1]. In the past few years, interest in DeFi rose sharply, with DeFi markets reaching a total value locked ("TVL")[2] of 250 billion USD in November 2021[3].

Furthermore, the use of AI techniques in crypto-asset markets is increasing, being applied in DeFi protocols, including in Decentralized Exchanges ("DEXs"), to provide trading strategy suggestions and to power automated trading systems that make predictions, choose the course of action, and execute trades[4]. It is estimated that there are around 2632 DeFi protocols in existence, and, of these, around 884 are reported to be Decentralized Exchanges (DEXs)[5]. In this paper we will focus on specific type of DEXs, the Automated Market Makers ("AMMs") DEXs. We propose to analyse what interconnections may exist between AI and AMM-based DEXs and how they fit into the current regulatory framework, should the crypto-assets traded on AMM-based DEXs qualify as securities.

To this end, we will start by analysing the DeFi ecosystem, its main technological aspects and governance structure (2). We will proceed by analysing the specific case of AMM-based DEXs (3) and their intersection with AI techniques (4). Next, we will comment on some regulatory implications (5) and finally provide some concluding remarks (6). ●

[1] ESRB, *Crypto-assets and decentralised finance Systemic implications and policy options*, (2023), 68.

[2] TVL is a measure of the amount of capital locked inside DeFi protocols, it measures the value of crypto-assets that have been transferred to the smart contracts underlying a DeFi protocol. Given that DeFi protocols differ in design, TVL is not a standardized measure – see ESRB, *Crypto-assets and decentralised finance Systemic implications and policy options*, (2023),18. Also, it is important to note that reported TVL may vary depending upon the source and is prone to double counting – see FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 22.

[3] See EU BLOCKCHAIN OBSERVATORY AND FORUM, *Decentralised Finance (DeFi)*, (2022), 17.

[4] OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), 24.

[5] According to information as of 24 June 2023 provided by DeFiLlama, available at: https://defillama.com/.

2. DEFI ECOSYSTEM

A DeFi ecosystem offers on-chain financial services, such as borrowing, lending, or trading, without relying on traditional centralized financial intermediaries, with those financial services being implemented on blockchains (or other DLT) as smart contracts[6]. Most DeFi do not provide new financial services but mimic those provided by the traditional financial system ("TradFi")[7].

2.1. Key technological components

From a technological point of view, DeFi is a complex ecosystem composed by multiple "layers", build on each other and creating an open, composable, and interoperable infrastructure, with the following key components: i) permissionless blockchains (or other DLT), ii) smart contracts, iii) DeFi protocols and iv) decentralized applications ("DApps")[8].

In terms of core technology, DLT can be defined as a technology that enables the operation and use of a distributed ledger, which is an information repository that keeps records of transactions that is shared across a set of DLT network nodes, and synchronized between them, using a consensus mechanism[9].

Blockchain technology is a type or ramification of DLT, in which transactions are recorded and organized in blocks that are linked together using cryptography[10]. Nevertheless, blockchain has been the most used DLT so far, namely in the financial sector[11].

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[6] See RAPHAEL AUER ET AL., *The Technology of Decentralized Finance (DeFi)*, (2023), 2.

[7] See ALEXANDRA BORN/ JOSEP M. VENDRELL SIMÓN, *A deep dive into crypto financial risks: stablecoins*, DeFi and climate transition risk, (2022). For an analysis of the limitations of centralized financial markets, particularly the disadvantage faced by non-institutional or small traders due to information asymmetry and better infrastructure access by financial institutions, see RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023).

[8] Regarding the key components of DeFi ecosystem see FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 5.

[9] For a definition of DLT, distributed ledger, DLT network node and consensus mechanism see Article 2, paragraphs 1 to 4 of the Regulation (EU) 2022/858 of the European Parliament and of the Council of 30 May 2022 on a pilot regime for market infrastructures based on distributed ledger technology ("DLT Pilot Regime").

[10] See IGOR MAKAROV/ ANTOINETTE SCHOAR, *Cryptocurrencies and Decentralised Finance (DeFi)*, (2022), 4-5. For more on concepts and principles associated with blockchain technology, see PAOLO TASCA/ CLAUDIO TESSONE, *Taxonomy of Blockchain Technologies. Principles of Identification and Classification*, New York, (2018). It is important to keep in mind the heterogeneity of DLT. Not only are there other types or ramifications of DLT in addition to blockchain technology, but there are also different blockchains with different configurations – see ELIZA MIK, Blockchains *A Technology for Decentralized Marketplaces*, em Larry A. Dimatteo/ Michel Cannarsa/ Cristina Poncibò (eds.), *The Cambridge Handbook of Smart Contracts, Blockchain Technology and Digital Platforms*, Cambridge University Press: Cambridge (2020), 160-182 (162).

[11] In this context, see FRANCISCO MENDES CORREIA, *A tecnologia descentralizada de registo de dados* (blockchain) no setor financeiro, in António Menezes Cordeiro/ Ana Perestrelo de Oliveira/ Diogo Pereira Duarte (org.), FinTech. Desafios da tecnologia financeira, 2nd ed., Almedina: Coimbra (2019), 83-89.

Regarding their architecture, blockchains can be classified based on access rules according to different permission models. It is possible to distinguish between permissioned and permissionless blockchains. In permissioned blockchains, there are restrictions on the blockchain participants who can submit transactions (Write) and execute a consensus protocol and update the state of the ledger with new blocks (Commit). In permissionless blockchains, there are no such restrictions, and anyone can join the network and execute Write and Commit operations[12].[13]

Blockchain offers the possibility to use smart contracts, which are computer programs that, upon the occurrence of pre-defined conditions, run automatically and execute pre-defined actions[14]. These computer programs can be stored, validated, and executed using namely blockchain technology, benefiting from the intrinsic properties of the blockchain technology, e.g., the security of transactions and the immutability of the distributed ledger[15]. In particular, «[s]mart contracts take parameters (as an input) via incoming blockchain transactions, process these parameters according to some deterministic algorithm, and generate (as an output) either a state change in the smart contract memory or a new blockchain transaction»[16].[17]

Furthermore, crypto-assets, which are used to represent and transfer value or rights on the blockchain (other DLT or similar technology)[18], are a fundamental element in DeFi ecosystem, and can be used, for example, as a means of exchange, for investment purposes or to access goods or services[19].

In the light of the above, we can already see that permissionless blockchains, in combination with smart contracts, have enabled the development of DeFi protocols.

The DeFi protocols set out the terms, conditions, and standards by which financial

[12] See STEFANO ANGELIS ET AL., *Blockchain and cybersecurity: a taxonomic approach*, (2019), 3; and EU BLOCKCHAIN OBSERVATORY AND FORUM, *Energy Efficiency of Blockchain Technologies*, (2021), 6-7.

[13] Also, the «consensus mechanism for block creation is a critical component of blockchain technology. It is the process by which the nodes in a decentralized network agree on the validity of a new block and add it to the blockchain. There are several consensus mechanisms, each with their own advantages and disadvantages. The most common ones are as follows: proof of work (PoW), proof of stake (PoS), delegated proof of stake (DPoS), and byzantine fault tolerance (BFT)» - see RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), 9.

[14] See EUROPEAN LAW INSTITUTE, *ELI Principles on Blockchain Technology, Smart Contracts and Consumer Protection*, (2022), 21-22.

[15] PAOLO TASCA/ CLAUDIO TESSONE, *Taxonomy of Blockchain Technologies. Principles of Identification and Classification*, New York, (2018), 6-7. For a study on the immutability and security of blockchains see TOM LYONS/ LUDOVIC COUCERLAS, Blockchain and Cyber Security, (2020), 7-14.

[16] See PRIMAVERA DE FILIPPI/ CHRIS WRAY/ GIOVANNI SILENO, *Smart Contracts*, in Internet Policy Review Journal on Internet Regulation, Vol. 10, Issue 2, (2021), 2-3. For an approach that combines law and technology to develop solutions that encourage the evolution of smart contracts in a direction that preserves and reinforces the digital single market, see THIBAULT SCHREPEL, *Smart Contracts and the Digital Single Market Through the Lens of a 'Law + Technology' Approach*, (2021).

[17] Note that, if the Ethereum blockchain (a blockchain protocol with smart contract functionality that allows developers to build decentralized applications on top of the blockchain) is used, then smart contracts are usually written in the Solidity programming language, and smart contracts run on the EVM (Ethereum Virtual Machine) – see RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), 4.

[18] For a definition of crypto-asset see Article 3, paragraph 1, point 5 of the Regulation (EU) 2023/1114 of the European Parliament and of the Council of 31 May 2023 on markets in crypto-assets ("MiCAR"). According to the mentioned provision, crypto-asset «means a digital representation of a value or of a right that is able to be transferred and stored electronically using distributed ledger technology or similar technology».

[19] See RAPHAEL AUER ET AL., *The Technology of Decentralized Finance (DeFi)*, (2023), 8.

services are offered in a DeFi ecosystem[20]. Thus, DeFi protocols are applications implemented by a set of smart contracts on blockchain (or other DLT), utilizing crypto-assets, and providing some financial service functionality. Based on the offered functionalities of DeFi protocols, we can roughly distinguish among lending protocols, derivatives protocols, and decentralized exchanges ("DEXs")[21]. In this paper, our attention will be on DEXs, which facilitate the programmatic exchange of crypto-assets[22].

In this context, another feature of DeFi is its non-custodial nature. In order to engage with DeFi protocols, blockchain participants typically maintain control of their crypto-assets and the ability to transact until they lock their crypto-assets into a smart contract[23].

In turn, the DApps facilitate the provision of financial intermediation in DeFi by allowing users to interact with smart contracts via a set of graphical interfaces and other components. Today, these applications are primarily hosted off-chain, meaning that they do not operate on the blockchain but instead rely on traditional internet infrastructure (website or mobile applications)[24]. It should also be noted that there are DApps that are protocol-specific, allowing a user to engage in transactions using one protocol's smart contracts, while other DApps are protocol-agnostic (often referred to as "**Aggregators**"), acting across multiple protocols to identify transactions that meet certain parameters[25]. For example, «DEX Aggregators redirect users programmatically towards the DEX offering the best price for the swap of a crypto[-asset] pair, while Yield Aggregators implement strategies to invest user funds in other DeFi protocols and maximize their returns»[26]. Thus, for a fee, DEX Aggregators facilitate complex strategies that typically involve the shifting of crypto-assets around multiple different platforms[27], providing for the optimal routing of trade orders across multiple DEXs[28].[29]

Finally, it must be noted that DeFi needs to interact with off-chain events (that happen in the physical world), namely when DeFi protocols require to use information that does not existing on the blockchain (for example crypto-asset's market price on a centralized crypto-asset trading platform, or the occurrence of an event, such as which team won a sports match)[30].

[20] See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 8.

[21] See RAPHAEL AUER ET AL., *The Technology of Decentralized Finance (DeFi)*, (2023), 4.

[22] *Ibidem*, 11.

[23] See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 9.

[24] *Ibidem*, 8; see also, IOSCO, *Decentralized Finance Report*, (2022), 3, 7.

[25] See IOSCO, *Decentralized Finance Report*, (2022), 7.

[26] See RAPHAEL AUER ET AL., *The Technology of Decentralized Finance (DeFi)*, (2023), 4.

[27] See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 15.

[28] See KRZYSZTOF GOGOL ET AL., *SoK: Decentralized Finance (DeFi) - Fundamentals, Taxonomy and Risks*, (2023), 10.

[29] Also, another appealing feature of DeFi ecosystem is the concept of composability, which refers to the interaction between different DeFi protocols and applications. In this context, «[a]ny two or more pieces can be integrated, forked, or rehashed to create something entirely new. Anything that has been created before can be used by an individual or by other smart contracts. This flexibility allows for an ever-expanding range of possibilities and unprecedented interest in open financial engineering» - see FABIAN SCHÄR, *Decentralized Finance: On Blockchain- and Smart Contract-Based Financial Markets*, in Federal Reserve Bank of St. Louis Review, Vol. 103, No. 2, (2021), 153-174 (169).

[30] See IOSCO, *Decentralized Finance Report*, (2022), 7.

Since the execution environment of a blockchain is self-contained, i.e., «it can only access information present in a transaction or in the transaction history of the blockchain, and the states of external systems are not directly accessible»[31], the connection between the on-chain and off-chain environments is established through oracles, which connect smart contracts to off-chain data[32]. Oracles are a fundamental component of AMM-based DEXs, particularly for sourcing price feeds[33].

2.2. The (apparent) decentralized governance

In DeFi ecosystem, governance is transferred to a community, often organized around a decentralized autonomous organization ("DAO"), which is a key component of this ecosystem[34]. DAOs are forms of organization based on blockchain technology that are characterized by adopting a decision-making process on the management or administration of the DAO based on the votes of holders of governance tokens (collective administration), instead of the decision-making power being centralized in a management or board of directors (centralized administration)[35]. However, in practice, «the extent of actual voting participation can be low and a DAO's governance actions through voting tokens can have a very concentrated distribution, with less than 1% of token holders controlling 90% of voting power of DAOs»[36].

DeFi protocols claim to have a decentralized governance structure, yet in reality it is often concentrated[37]. The degree of decentralization may vary from one DeFi project to another, and the decentralization should be understood as being on a spectrum[38]. In particular, it is worth noting that centralization remains present in the governance of DeFi ecosystems: either through the concentration of governance tokens in a very small number of holders who are referred to as "whales", or through the holding of administrator keys[39], for example, by the original core developers who built the DeFi protocol[40]. ●

[31] See XIWEI XU ET AL., *A Taxonomy of Blockchain-Based Systems for Architecture Design*, (2017), 4.

[32] See MICHEL CANNARSA, *Contract Interpretation*, em Larry A. Dimatteo/ Michel Cannarsa/ Cristina Poncibò (eds.), *The Cambridge Handbook of Smart Contracts, Blockchain Technology and Digital Platforms*, Cambridge University Press: Cambridge (2020), 102-117 (106), and IOSCO, *Decentralized Finance Report*, (2022), 8.

[33] See SAM WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 11.

[34] See MICHAEL ANDERSON SCHILLIG, *DAOs Under English Law*, in Madalena Perestrelo de Oliveira/ António Garcia Rolo (org.), *Decentralised Autonomous Organisations (DAOs) in Various Jurisdictions: from Old Rules to Innovative Approaches*, AAFDL: Lisboa (2023), 57-74 (60).

[35] See ESRB, *Crypto-assets and decentralised finance Systemic implications and policy options*, (2023), 68.

[36] IOSCO, *Policy Recommendations for Decentralized Finance (DeFi) Consultation Report*, (2023), 70-71.

[37] See ALEXANDRA BORN ET AL., *Decentralised finance – a new unregulated non-bank system?*, (2022). For an interdisciplinary introduction that analyses DeFi and provides policymakers and regulators with a tool to identify the differences between independent, neutral infrastructure and fake decentralization - see KATRIN SCHULER/ ANN SOFIE CLOOTS/ FABIAN SCHÄR, On DeFi and *On-Chain CeFi: How (Not) to Regulate Decentralized Finance*, (18-April-2018).

[38] See OCDE, *Why Decentralised Finance (DeFi) Matters and the Policy Implications*, (2022), 20.

[39] Administrators key (or Admin keys) allow the project core team to, for example, upgrade smart contracts on which protocols are based, perform emergency shutdowns if needed – see MARC TRUCHET, *Decentralized Finance (DeFi): opportunities, challenges and policy implications*, (2022), 69.

[40] See OCDE, *Why Decentralised Finance (DeFi) Matters and the Policy Implications*, (2022), 19-22, 33-36.

3. AMM-BASED DEXS

Decentralized exchanges ("DEXs") are a class of DeFi protocols that facilitate the non-custodial exchange of crypto-assets, where all trades are settled on-chain and thus publicly verifiable[41].

DEXs distinguish from centralized exchanges ("CEXs"), namely by not allowing users to exchange crypto-assets for fiat currencies and also by not requiring users to deposit funds with the trading platform, as occurs in CEXs[42].[43] It must be noted that one of the main advantages of DEXs is the ability to allow users to keep control of their private keys[44], and since trading on DEXs is governed by smart contracts, users also may benefit, in principle, from a reduce counterparty risk[45].

DEXs facilitates peer-to-peer or peer-to-pool trades that are settled atomically based on smart contracts[46]. In this context, two types of DEXs can be distinguished, namely, order book-based DEX[47] and automated market

[41] See SAM M. WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 3.

[42] See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 14. See also FABIAN SCHÄR, *Decentralized Finance: On Blockchain- and Smart Contract-Based Financial Markets*, in Federal Reserve Bank of St. Louis Review, Vol. 103, No. 2, (2021), 153-174 (160).

[43] Examples of CEXs include *Coinbase and Binance*. Recently, the United States Securities and Exchange Commission («SEC») announced that is charging Coinbase for operating as unregistered securities exchange broker and clearing agency. According to SEC, *Coinbase* allegedly «provides a marketplace and brings together the orders for securities of multiple buyers and sellers using established, non-discretionary methods under which such orders interact» – see SEC, *SEC Charges Coinbase for Operating as an Unregistered Securities Exchange, Broker, and Clearing Agency*, (2023).

[44] In this context, please note that blockchain technology uses public key cryptography, which «involves a pair of keys known as a public key and a private key (*a public key pair*), which are associated with an entity that needs to authenticate its identity electronically or to sign or encrypt data. Each public key is published, and the corresponding private key is kept secret. Data that is encrypted with the public key can be decrypted only with the corresponding private key» - see IBM, Public key cryptography, (2021). The private key is used to generate a signature for each blockchain transaction a user sends out, which is used «to confirm that the transaction has come from the user, and also prevents the transaction from being altered by anyone once it has been issued» – see PAOLO TASCA/ CLAUDIO TESSONE, *Taxonomy of Blockchain Technologies. Principles of Identification and Classification*, New York, (2018), 6-7.

[45] In this regard, «smart contracts might have some potential benefits in terms of reducing counterparty risk due to their ability to conduct 'atomic swaps', i.e. the wallet-to-wallet exchange of two digital assets simultaneously and in a single operation» - see FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 18. However, there are interdependencies between DEXs and CEXs. On the risks associated with CEXs being likely to directly affect DEXs see – IOSCO, Decentralized Finance Report, (2022), 15, 19, 42; and FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 11, 22.

[46] See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 14.

[47] Examples of order-book based DEXs are *Serum* and *dYdX*. In order-book based DEXs, usually order books are maintained off-chain, while settlement occurs on-chain, specifically, «[b]uyers and sellers communicate their order to a third party (relayer) or DEX operator, who posts it to the order book and publishes that information so that an interested counterparty (taker) can match it» – see FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 14. However, order-book based DEXs can also maintain an on-chain order book where every order is recorded on the blockchain, which have the disadvantage of being a more expensive model – see VIJAY MOHAN, *Automated market makers and decentralized exchanges: a DeFi primer*, in Financial Innovation 8, Article no. 20, (2022), 2. It must be noted that «[b]oth on-chain and off-chain order books perform regularly in markets with high liquidity, but when the assets being traded are not highly liquid, they are not very useful. To solve this problem, some decentralized exchanges have adopted a new technique called automated market makers, or AMMs» - see RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), 4.

maker ("AMM")-based DEX (also called, liquidity pool-based DEX)[48]. We will focus on the latter for the purpose of this paper.

The AMM allows multiple parties to interact directly with smart contracts of the DeFi protocol, without requiring the matching of individual buy and sell orders[49], thus, not relying on a centralized order book.

An AMM-based DEX employs reserves of two or more crypto-assets, called liquidity pools. Liquidity pools provide counterparty crypto-assets to swap against, and the swap price is determined algorithmically by the pricing rules called AMM[50].

In an AMM-based DEX, the liquidity providers contribute with crypto-assets to liquidity pools in return for a share of the fee paid by traders for exchanging crypto-assets (trading fee)[51], noting that «[t]he process of providing liquidity to the DEX, or other class of DeFi protocols, in return for profit, is called yield farming and is similar to market making in traditional finance»[52]. Thus, the investor's return from AMM-based DEXs may arise in two ways: directly from their trading activities or from commission-like income generated as a result of the investor's deposit of crypto-asset into the protocol[53].

Considering the above, an AMM can be defined as a «mathematical function that algorithmically determines the swap price between tokens in the liquidity pool via a scoring rule»[54]. It is important to note that AMMs can also assume various forms, «[p]rediction markets for example commonly employs logarithmic market scoring rule (LMSR), whereas constant function market maker (CFMM) is the primary underpinning for DEXs»[55].[56] In particular, note that the combination of AMMs and prediction

[48] Note that «[t]he primary example of an AMM on Ethereum is Uniswap» - see CAMPBELL R. HARVEY ET AL., *DeFi and the Future of Finance*, Wiley: New Jersey (2021), 95. From a monthly trading volume perspective, at the month of August 2022, «Uniswap [led] the AMM market by a distance, with 39 billion trades, outstripping the next two highest AMMs Curve and Balancer, at 6 and 2 billion respectively. At its peak, there were 86 billion trades traded on Uniswap. Other popular protocols are Sushiswap, Synthetix, DODO and Ox Native» – see TRISTAN LIM, *Predictive Crypto-Asset Automated Market Making Architecture for Decentralized Finance using Deep Reinforcement Learning*, V2 (2023), 3.

[49] See TRISTAN LIM, *Predictive Crypto-Asset Automated Market Making Architecture for Decentralized Finance using Deep Reinforcement Learning*, V2 (2023), 2.

[50] See KRZYSZTOF GOGOL ET AL., *SoK: Decentralized Finance (DeFi) - Fundamentals, Taxonomy and Risks*, (2023), 8.

[51] Note that there are other transaction costs that an agent may incur when utilizing an AMM besides the trading fee, for example, the cost to changing the ledger entries on the blockchain to record changes in the ownership of crypto-assets – see VIJAY MOHAN, *Automated market makers and decentralized exchanges: a DeFi primer*, in Financial Innovation 8, Article no. 20, (2022), 5. For an identification of explicit and implicit costs resulting from the interaction with AMM protocols, see JIAHUA XU ET AL., *SoK: Decentralized Exchanges (DEX) with Automated Market Maker (AMM) Protocols*, V7 (2023), 4-6.

[52] *Ibidem*, 8. In this context, note that «[i]n general, a market maker is an institution that stands ready to buy or sell an asset, generating a profit from the bid-ask spread: the difference between the ask or offer rate (the rate at which the market maker sells an asset) and the bid rate (the rate at which the mare maker buys an asset). An AMM automates this by allowing traders to place orders with the AMM, which then algorithmically provides a price. (…). AMMs provide liquidity algorithmically through simple pricing rules with on-chain liquidity pools in place of order books» - see SAM WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 3.

[53] See IOSCO, *Decentralized Finance Report*, (2022), 14.

[54] *Ibidem*.

[55] See JIAHUA XU ET AL., *SoK: Decentralized Exchanges (DEX) with Automated Market Maker (AMM) Protocols*, V7 (2023), 6.

[56] The constant product market-maker algorithm is also known as the $X \times Y = K$ formula, where X and Y are assets (crypto-assets) in the pool, both valued relative to each other, and K is their product. For an explanation of constant product, constant sum, constant mean, and hybrid constant market markers formulas, which are some of the AMM formulas currently used in various DEXs - see RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), 6-9.

markets (markets that allow individuals to bet on the likelihood of future events, such as election outcomes, sports events, or even the weather) has become increasingly popular in recent years, with several platforms offering decentralized prediction markets powered by AMMs[57].

Furthermore, the arbitrageurs play a significant role in the price synchronization among various AMMs, buying and selling the same crypto-assets in different exchanges in order to profit from the price differences (this process is called arbitrage)[58], contributing for an alignment of prices across external crypto-asset markets. Without prejudice, another way for the alignment of the price in an AMM with that of the external market is by allowing the reference market to function as an oracle[59].[60]

Finally, it should be noted that there are risks associated with trading with an AMM-based DEX to which investors are exposed, namely, i) smart contract risks, ii) governance risks; iii) oracle risks; and iv) environmental risks.

Smart contract risks can take several forms, for example, a logic error in the code[61] or an economic exploit in which an attacker can withdraw funds from the platform beyond the intended functionality[62].[63]

Governance risks can take the form of governance extractable value ("GEV")[64], which occurs when there are not enough incentives for the governance token holders, and it is more profitable to them extracting value in less desirable ways[65].[66]

The oracle risks take the form of attacks

[57] See RADHAKRISHNA DODMANE ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), 9. According to these Authors, «[o]ne of the benefits of using AMMs in prediction markets is that they provide liquidity, which means that users can easily buy and sell shares without worrying about finding a counterparty. Additionally, AMMs are transparent, which allows users to see how prices are determined and make informed decisions about their trades» - *ibidem*, 9.

[58] KRZYSZTOF GOGOL ET AL., *SoK: Decentralized Finance (DeFi) - Fundamentals, Taxonomy and Risks*, (2023), 8.

[59] VIJAY MOHAN, *Automated market makers and decentralized exchanges: a DeFi primer*, in Financial Innovation 8, Article no. 20 (2022), 3.

[60] For a detailed explanation regarding the transactions in the AMM pool, see SAM M. WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 3.

[61] Logical errors are internal errors in the smart contract, missed by its developers, that make them susceptible to exploitation by hackers.

[62] An example is a reentrancy attack, which «occurs between two smart contracts, where an attacking smart contract exploits the code in a vulnerable contract to drain it of its funds. The exploit works by having the attacking smart contract repeatedly call the withdraw function before the vulnerable smart contract has had time to update the balance. This is only possible because of the order in which the vulnerable smart contract handles transactions, with the vulnerable smart contract first checking its balance, then sending funds, and finally updating its balance. The time between sending the funds and updating the balance creates a window in which the attacking smart contract can make another call to withdraw its funds, and so on until all funds are drained» – see OFFICER'S BLOG, *Reentrancy Attacks on Smart Contracts Distilled*, (2022).

[63] On smart contract risks see CAMPBELL R. HARVEY ET AL., *DeFi and the Future of Finance*, Wiley: New Jersey (2021), 131-132.

[64] As seen above, governance of a DeFi is typically tied to holders of governance crypto-assets (or tokens). In order to mitigate related risks, the protocol governance shall «incentivize good stewardship from its governance token holders by compensating governance with cashflows from the system. In this case, governance token value is derived from future discounted cashflows. Another possibility is that governance is directly aligned with underlying users–e.g., because they are the same» - see SAM WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 10.

[65] For example, the governors may effect changes to the protocol in order to provide outside benefits, or there may be an explicit governance attack. An example of the latter is «the governance takeover of the Build Finance DAO, where a malicious actor passed a proposal to take control of the Build token contract and was thereby not only able to drain various AMM pools by minting and swapping Build tokens, but to ultimately remove the DAO from any form of control over the core protocol» - see SAM WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 10.

[66] In this context, it should be noted that «[g]overnance attacks (in which an entity controls 51 % of governance tokens) are a source of vulnerability specific to DeFi. Unlike a Sybil attack, which targets the underlying blockchain consensus, governance attacks involve the accumulation of governance tokens that may enable attackers to manipulate voting on DeFi protocol design parameters» - see ESMA, *Crypto-assets and their risks for financial stability*, (2022), 7.

in which malicious actors manipulate an oracle smart contract, leading to system failure, theft, and damages. In the context of AMM-based DEXs, oracle price manipulation stands out[67]. It should be noted that oracle price manipulation is different from a situation where the price is manipulated yet correctly supplied by an oracle, which is market manipulation[68].[69]

It is also important to consider the environmental risks associated with trading with AMM-based DEXs, especially considering the collective effort to reduce carbon emissions[70]. As such, when using AMM-based DEXs to transact crypto-assets, investors should consider the carbon footprint of the underlying blockchain technology (or other DLT)[71], and also the environmental risks related to the specific crypto-assets transacted.

As we will see below, AMMs-based DEXs can be complemented by artificial intelligence (AI), which has the potential to enhance its capabilities and to mitigate associated risks[72]. ●

[67] For more information regarding oracle manipulation see SAM WERNER ET AL., SoK: Decentralized Finance (DeFi), V6 (2022), 11. Also, regarding oracle's related aspects/dimensions where public attention may be appropriate see TARIK ROUKNY, *Decentralized Finance: information frictions and public policies, Approaching the regulation and supervision of decentralized finance*, (2022), 42-46.

[68] The market price (on-chain or off-chain) of a crypto-asset can be manipulated by an adversary, e.g., by taking positions in a DeFi protocol that uses that market price as an oracle - see SAM WERNER ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), 11.

[69] Note that one form of such market manipulation is known as wash trading, which consist of «investors simultaneously sell and buy the same financial assets to create artificial transactions, distorting price and quantity dynamics and hurting investor confidence and participation in financial markets» - see LIN WILLIAM CONG ET AL., *Crypto Wash Trading*, (2023), 2. For an academic study of wash trading and misreporting on cryptocurrency exchanges see the work cited, in which the Authors conclude, inter alia, that «centralized exchanges, due to their opacity, vertical integration, and lack of regulation, create ample opportunities for market manipulation, particularly by exchanges themselves. In response, consumers might be inclined to seek alternative trading venues, such as DEXs» - *ibidem*, 32.

[70] In this context, it is important to note that «[w]hile governments are primarily responsible for policy, financial institutions and prudential standard-setters also have a role to play. Public authorities will have to evaluate whether the outsized carbon footprint of certain crypto-assets undermines their green transition commitments. Investors will have to assess whether investing in certain crypto--assets is in line with their ESG objectives. Financial institutions will have to incorporate the climate-related financial risks of crypto-assets into their climate strategy» - See ALEXANDRA BORN/ JOSEP M. VENDRELL SIMÓN, *A deep dive into crypto financial risks: stablecoins, DeFi and climate transition risk*, (2022).

[71] In this context, it should be noted that most of DeFi activity resides on the Ethereum blockchain – see CAMPBELL R. HARVEY ET AL., *DeFi and the Future of Finance*, Wiley: New Jersey (2021), 146. In 2022, Ethereum shift from proof-of-work (PoW) to the proof-of-stake (PoS) consensus mechanism, reducing its energy footprint and becoming more environmentally friendly. The same cannot be said of Bitcoin blockchain, which continues to use PoW consensus mechanism for the validation of transaction in the network. Note that it is essential to distinguish between electricity consumption and environmental footprint. The first concerns the total amount of electricity used by the DLT to run its consensus mechanism. The latter concerns the environmental implications of consensus mecha-nism. What ultimately matters for the environment is not the level of electricity consumption per se, but the **carbon intensity of the energy sources** used to generate that electricity – see CAMBRIDGE CENTRE FOR ALTERNATIVE FINANCE, *What is the link between electricity consumption and carbon emissions?*, in FAQ Power Consumption, (2023). For a study of the aspects related to the energy efficiency of blockchain technologies see EU BLOCKCHAIN OBSERVATORY AND FORUM, *Energy Efficiency of Blockchain Technologies*, (2021).

[72] Please note that while an AMM incorporates algorithmic calculations and smart contracts, it is not considered AI, and does not heave AI features. In particular, the notion of 'AI system' «should be based on key characteristics of AI systems that distinguish it from simpler traditional software systems or programming approaches and should not cover systems that are based on the rules defi-ned solely by natural persons to automatically execute operations. A key characteristic of AI systems is their capability to infer. This capability to infer refers to the process of obtaining the outputs, such as predictions, content, recommendations, or decisions, which can influence physical and virtual environments, and to a capability of AI systems to derive models or algorithms from inputs or data. The techniques that enable inference while building an AI system include machine learning approaches that learn from data how to achieve certain objectives, and logic - and knowledge - based approaches that infer from encoded knowledge or symbolic representation of the task to be solved. The capacity of an AI system to infer transcends basic data processing, enables learning, reasoning, or modelling. The term 'machine-based' refers to the fact that AI systems run on machines» - see Recital 12 of the the Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 ("Artificial Intelligence Act" or "AI Act"), available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1689.

4. INTERSECTION OF AI WITH AMM-BASED DEXS: POTENTIAL BENEFITS

DeFi is inspired by FinTech and the practical applicability of blockchain technology[73].

In FinTech[74], AI empowers more personalized, advanced, and newer mainstream and alternative economic-financial mechanisms, products, models, services, systems, and applications[75]. In addition, AI «helps FinTech companies to analyse consumer behaviour in their financial transactions and provide valuable insights for decision-making», thus, AI «will be also beneficial in making smart investments»[76].

During the XXI century, AI has proliferated in various dimensions of life in developed societies[77], and notwithstanding the fact that is has been in development for decades, recently, AI has gathered massive attention with the release of ChatGPT[78].

Although there is not yet a universal and consensual definition of AI, which is still evolving, AI can be generally understood as the «capacity of computers or other machines to exhibit or simulate intelligent behaviour»[79].

The use of AI in AMM-based DEXs is still at an early stage of development, however,

[73] See NAFIZ SADMAN ET. AL, *Promise of AI in DeFi, a Systematic Review*, in Digital Journal, Volume 2, Issue 1, (2022), 88-103 (89).

[74] FinTech can be defined as «Technology-enabled innovation in financial services that could result in new business models, applications, processes or products with an associated material effect on the provision of financial services» - see ESRB, *Crypto-assets and decentralised finance Systemic implications and policy options*, (2023), 68.

[75] See LONGBING CAO, *AI in Finance: A Review*, (2021), 1.

[76] HAMED TAHERDOOST, *Fintech: Emerging Trends and the Future of Finance*, in Abeba N. Turi (Ed.), *Financial Technologies and DeFi A Revisit to the Digital Finance Revolution*, Springer Nature: Switzerland (2023), 29-39 (35).

[77] See JOÃO MARQUES MARTINS, *Inteligência Artificial e Direito: Uma Brevíssima Introdução*, in Revista da Faculdade de Direito da Universidade de Lisboa, Year LXIII 2022 No. 1 and 2, 487-506 (489).

[78] According to the ChatGPT itself, «Chat GPT is a language model developed by OpenAI. It is based on the GPT-3.5 architecture, which stands for 'Generative Pre-trained Transformer 3.5'. GPT-3.5 is a highly advanced and large-scale language model trained on a vast amount of text data from the internet. Chat GPT is designed to generate human-like text responses to prompts or questions. It can understand and generate coherent and contextually relevant responses across a wide range of topics. It leverages the power of deep learning and natural language processing techniques to generate text that simulates human conversation. The model is trained in an unsupervised manner, meaning it learns from the patterns and structures of the training data without explicit guidance. It has been trained on a diverse range of internet sources, including books, Articles, websites, and other text documents, to gain a broad understanding of human language. Chat GPT can be used for various applications, including answering questions, providing explanations, generating text, assisting in writing, brainstorming ideas, offering suggestions, and engaging in interactive conversations. It has the ability to comprehend and respond to both simple and complex queries and can adapt its responses based on the context provided. It is important to note that while Chat GPT can generate impressive responses, it may occasionally produce incorrect or nonsensical answers. It is always advisable to verify the information provided by the model and not rely solely on its responses for critical tasks or decisions. OpenAI continually works to improve the capabilities of language models like Chat GPT, and ongoing research and development efforts aim to enhance their accuracy, reliability, and safety» - this was the answer provided on 18 June 2023 to the question *«What is Chat GPT?»*. For an analysis of generative AI and emerging challenges, risks, and harms, see NORWEGIAN CONSUMER COUNCIL, *Ghost in the machine – Addressing the consumer harms of generative AI*, (2023).

[79] See OXFORD ENGLISH DICTIONARY, *artificial intelligence*, (2023).

the potential benefits of this intersection are already evident.

AI can be used to enhance AMM-based DEXs capabilities. Rresearch has looked into the application of machine learning[80] to the analysis and forecasting of crypto-asset markets, namely, with the prices of crypto-assets being predicted using a variety of models and methods, «including linear regression, gradient-boosting decision trees, ARIMA, FBProphet, XGBoost, KNN, and others», and «[t]he findings point to the promise of machine learning as a tool for forecasting [crypto-assets] values and enhancing trading approaches»[81]. Another type of machine learning, reinforcement learning, has been the subject of research to increase trading techniques, control inventory risk, and provide liquidity. The findings «point to opportunities for improving market-making and other trading scenarios, although forecasting financial markets presents difficulties due to factors like inventory complexity, counterparty risk, and information asymmetry. Reinforcement learning techniques are presented as new ways to enhance trading performance»[82]. Also, research has looked into the application of deep reinforcing learning to improve liquidity in AMM-based DEXs[83]. In sum, research has found that machine learning techniques have the potential to be a valuable tool in the crypto-asset markets, allowing traders to make more informed decisions and achieve better results[84].

On the other hand, AI can be used to mitigate risks associated with trading with an AMM-based DEX. In particular, AI can help augmenting the capabilities of smart contracts, namely when it comes to risk management and the identification of flaws in the code of the smart contract. For example, natural language processing (NPL) can be used to «analyse the patterns of the smart contract execution and detect fraudulent activity and enhance the security of the system»[85].[86]

Also, AI can be used to potentially improve the functioning of oracles, by improving «the quality of the data inputs into the chain, as the responsibility of data curation shifts from third party nodes to independent, automated AI-powered systems, enhancing the robustness of information recording and sharing as such systems are more difficult to manipulate».[87]

It is important to note that the

[80] «Machine learning approaches include for instance supervised, unsupervised and reinforcement learning, using a variety of methods including deep learning with neural networks, statistical techniques for learning and inference (including for instance logistic regression, Bayesian estimation) and search and optimisation methods» - see recital 6a of the proposal for an AI Act, the version of the text resulting from the Council common position adopted on 6 December 2022, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=consil%3AST_15698_2022_INIT).

[81] See ZOHREH KARIMI, *An overview of Artificial Intelligence approaches in the cryptocurrency market makers*, (2023), 1.

[82] *Ibidem*, 2-3.

[83] *Ibidem*, 4-6.

[84] *Ibidem*, 6. See also DEEPLINK, *Machine Learning Applications in DEX Aggregation and Smart Order Routing*, (2022).

[85] See OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), 33. For a study of AI language models, which are part of a subset of AI known as natural language processing (NLP), see OCDE, *AI Language Models Technological, Socio-Economic and Policy Considerations*, (2023).

[86] In this context, see the research on BLOCKGPT, an innovative transaction anomaly ranking tool for Ethereum-based blockchains. «The proposed system can trigger smart contract pause mechanisms in response to malicious blockchain transactions, thus preventing attacks» - YU GAI ET AL., *Blockchain Large Language Models*, V2 (2023), 13.

[87] OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), 33.

introduction of AI does not solve the problem of poor quality or inadequate data inputs, which is a problem that is also observed in AI-based mechanisms and applications[88]. In particular, further considerations regarding the information available in crypto-asset markets are worthwhile, given the importance of quality of the data used in AI[89].

In general, data on crypto-asset markets, and specifically in DeFi, lack transparency, consistency, and reliability, which also applies to data on the interconnections of DeFi with the traditional financial system[90]. Among other reasons[91], the low quality of the information available on DeFi ecosystem is due to the fact that certain parties in the DeFi ecosystem do not comply with existing regulatory requirements, for example, common disclosure, recordkeeping and reporting requirements covering entities in traditional finance. Thus, much of the available data is self-reported by industry participants, which undermines the quality and comparability of data, and can lead to significant discrepancies across commercial data providers[92].

Regarding environmental risks, it must be noted that AI and big data could be used for Environmental Social and Governance ("ESG") investing to «(i) assess company data (issuer data); (ii) assess non-company data; and (iii) assess the consistency and comparability of ratings to understand the drivers of scores»[93]. In this context, «[i]n particular, NPL can be used to analyse massive amounts of unstructured datasets (geolocalisation, social media) in order to perform sentiment analysis, identify patters and relationships in these data. The results of such analysis can be used to assign quantitative values to qualitative data for sustainability parameters, based on AI techniques»[94].

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88 *Ibidem*.

89 Note that «[d]ata quality generally refers to whether the received data are fit for their intended use and analysis. The basis for assessing the quality of the provided data is to have an updated metadata section, where there is a proper description of each feature in the analysis. It must be stressed that a large part of the data scientist's job resides in checking whether the data records actually correspond to the metadata descriptions. Human errors and inconsistent or biased data could create discrepancies with respect to what the data receiver was originally expecting (...). Financial institutions are properly instructed on how to provide data; however, various error types may occur. For example, rates could be reported as fractions instead of percentages, and loans may be indicated as defaulted according to a definition that varies over time and/or country-specific legislation» - see LUCA BARBAGLIA, ET AL., *Data Science Technologies in Economics and Finance: A GentleWalk-In Data Science Technologies in Economics and Finance: A GentleWalk-In*, in Sergio Consoli/ Diego Reforgiato Recupero/ Michaela Saisana (Eds.), *Data Science for Economics and Finance Methodologies and Applications*, Springer Nature: Switzerland (2021), 1-17 (8).

90 See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 2.

91 In particular, it should be noted that «[d]ata issues are largely due to the nature of crypto-assets and the associated blockchains as well as the incentives of market participants, in particular: (i) the **difficulty in aggregating and analysing the vast amount of data** available on distributed ledgers. Data available from public blockchains may be transparent and immutable in some respects, but they are generally difficult to collect and analyse. (ii) the **pseudonymous nature of information** on public ledgers inhibits the ability to ascertain the types of investors in the crypto-asset ecosystem. (...). (iii) the large number of **off-chain transactions**, i.e., those that occurs outside of public distributed ledgers, and other off chain data. As such, on-chain data may give an incomplete picture of the overall activity in the market. (...). (iv) the l**ack of reporting** producing consistent and reliable data because parts of the crypto-assets ecosystem fall outside of, or are in non-compliance with, the regulatory perimeter at present. (...) (v) Some data providers, notably crypto-asset trading, and lending platforms, may be **incentivised to manipulate their data** (e.g. through practices such as wash trading) to make their respective platforms appear more significant and attract additional volume or investment (...)» - *ibidem*, 31-32.

92 See FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), 32.

93 See OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), 35.

94 *Ibidem*.

It is therefore evident that there are multiple possibilities for applying AI techniques to AMM-based DEXs, bringing numerous benefits, but it is also clear that AI adds a layer of complexity to the system, and it may even amplify risks experienced in DeFi markets[95]. ●

[95] *Ibidem*, 10.

5. REGULATORY CONSIDERATIONS ON AI POWERED AMM-BASED DEXS

DeFi protocols, including DEXs, have raised serious concerns for regulators[96], particularly in the area of anti-money laundering and combating the financing of terrorism (AML/CFT) and consumer safeguards[97].

In order to analyse any regulatory implications, it is important firstly to note that the applicable rules and regulations may depend on the features of the particular AI-powered AMM-based DEX and that the regulatory landscape may vary depending on the jurisdiction(s) involved in the crypto-assets transactions.

For the purpose of this paper, we will assume that the crypto-assets traded in the AI powered AMM-based DEX (hereinafter, the "Platform") are subject to the Portuguese law and that they qualify as securities under the Portuguese securities law[98]. In this context, the following understanding adopted by the Portuguese Securities Market Commission ("CMVM") should be noted: the crypto-assets that «qualify as securities or financial instruments that have been issued or are being marketed in Portugal, are subject to a set of rules, which include, in particular and without prejudice to others: (i) the rules regarding the issue, representation and transmission of securities; (ii) the rules relating to the trading of financial instruments; (iii) requirements on the quality of information; (iv) and the market abuse regime», and, «if the platform/

[96] See AUTORITÉ DES MARCHÉS FINANCIERS, *AMF Discussion Paper on Decentralised Finance (DeFi)*, (2023); ESMA, Crypto-assets and their risks for financial stability, (2022); and EUROPEAN SUPERVISORY AUTHORITIES, *EU financial regulators warn consumers on the risks of crypto-assets*, (2022).

[97] For a study regarding the importance of anti-money laundering (AML) regulations among prosumers in DeFi in establishing cybersecurity, see DESTAN KIRIMHAN, *Importance of anti-money laundering regulations among prosumers for a cybersecure decentralized finance*, in Journal of Business Research, Volume 157, (2023).

[98] Under the Portuguese securities law, crypto-assets may be considered securities if they are documents representing homogeneous legal situations, provided that they can be transferred on the market. For a study on the types of securities, including on the criteria for classification of atypical securities under the Portuguese law, see PAULO CÂMARA, *Manual de Direito dos Valores Mobiliários*, 4th ed., Almedina: Coimbra, (2018), 140-144. For a study regarding the qualification of investment crypto-assets (or tokens) as securities see A. BARRETO MENEZES CORDEIRO, *Manual de Direito dos Valores Mobiliários*, Almedina: Coimbra (2018), 186-188; ANTÓNIO GARCIA ROLO, *As criptomoedas como meio de financiamento e a qualificação dos tokens de investimento emitidos em ofertas públicas de moeda (ICO) como valores mobiliários*, in António Menezes Cordeiro/Ana Perestrelo de Oliveira/Diogo Pereira Duarte (org.), *FinTech II: Novos estudos sobre tecnologia financeira*, Almedina: Coimbra, (2019), 249-298 (279-290); ANTÓNIO GARCIA ROLO, *Criptoativo - Conceito, Modalidades, Regime e Distinção de Figuras Afins*, CIDP research paper no. 18, (2022), 16-19; JOÃO VIEIRA DOS SANTOS, *Regulação de Formas de Financiamento Empresarial FinTech: Em especial o Crowdfunding e as Initial Coin Offerings*, Almedina: Coimbra, (2022), 504-521; JOSÉ ENGRÁCIA ANTUNES, *Os Instrumentos financeiros*, Almedina: Coimbra, (2020), 182-184; LUÍS GUILHERME CATARINO, *Inovação financeira e icos: mercados privados alternativos?*, in CEDIPRE online, no. 36, (2019), 65-70; e LUÍS ROQUETTE GERALDES/ MARIANA SOLÁ DE ALBUQUERQUE/ JOÃO LIMA DA SILVA, *ICOs: security tokens vs. utility tokens*, in António Menezes Cordeiro/Ana Perestrelo de Oliveira/Diogo Pereira Duarte (org.), *FinTech II: Novos estudos sobre tecnologia financeira*, Almedina: Coimbra, (2019), 327-361 (341-344).

exchange in question purports to transact a [crypto-asset] that qualifies as a security or financial instrument, this platform will need to register in advance with the CMVM in order to establish itself as a regulated market management entity, multilateral trading system or organised trading system and is subject to the respective regime provided for in the [Portuguese Securities Code]»[99].

According to the European Financial Securities Market Authority ("ESMA"), DEXs can be defined as «Marketplaces where transactions occur directly between crypto-asset traders»[100].

In particular, regarding the nature of DeFi, and specifically DEXs, we are of the opinion that they do not eliminate financial intermediation but enable new ways to provide the financial service functionalities[101].

That said, note that depending on the instruments traded and the mode of execution of orders, under the MiFID II[102], a platform may fall under the category of regulated market ("RM"), multilateral trading facility ("MTF") or organized trading facility ("OTF")[103]. RMs are operated or managed by a market operator, and MTFs and OTFs are operated by a market operator or an investment firm. The MiFID II framework subjects both the platforms and their operators to strict requirements[104]. DEXs, in specific, are more likely to be organized as MTFs deploying multilateral

99 See CMVM, *Questions and Answers for Entities on Cryptoassets*, (2018).

100 ESMA, *Crypto-assets and their risks for financial stability*, (2022), 16.

101 The following understanding is stressed: «humans prompt their servers to function as nodes, and humans write or upload the protocol, respectively, on their computers, which then later provide the (decentralized) operations. (…). At the heart of fully decentralized platforms thus lies **human cooperation**, exercised through the steering of computers and servers. (…). Given that the smart contracts that underlie the functioning of DeFi protocols are coded, put into operation and modified by humans, and humans decide to let them operate on their information technology, the argument that the mere use of smart contracts results in a product that is something different from the result of human cooperation, is inconclusive. If all parts of something involve human cooperation, then the sum of the parts cannot be something else» - see D.A. ZETZSCHE/ R.P. BUCKLEY/ D.W. ARNER/ M.C. VAN EK, *Remaining regulatory challenges in digital finance and cryptoassets after MiCA*, (2023), 115. See also LAURA GRASSI ET AL., *Do we still need financial intermediation? The case of decentralized finance – DeFi*, in Qualitative Research in Accounting & Management Journal, Volume 19, Issue 3, (2022), 323-347 (340); and see also SIRIO ARAMONTE/ WENQIAN HUANG/ ANDREAS SCHRIMPF, *DeFi risks and the decentralisation illusion*, (2021) – the Authors argue that full decentralisation in DeFi is an illusion, since DeFi platforms have groups of stakeholders that take and implement decisions, exercising managerial or ownership benefits, particularly considering that «[t]hese groups, and the governance protocols on which their interactions are based, are the natural entry points for policymakers» - ibidem, 33.

102 Directive 2014/65/EU of the European Parliament and of the Council of 15 May 2014 on markets in financial instruments, as amended ("MiFID II").

103 Note that «Regulated markets and MTFs are multilateral systems, which bring together or facilitate the bringing together of multiple third-party buying and selling interests in financial instruments in accordance with their non-discretionary rules [see Articles 4, paragraph 1, points 21 and 22 and 19, paragraph 1 of MiFID II]. An OTF is a multilateral system which is not a regulated market or an MTF and in which multiple third-party buying and selling interests in non-equity instruments, such as bonds, structured finance products, emission allowances or derivatives are able to interact in the system [see Article 4, paragraph 1, point 23 of MiFID II]. Furthermore, OTFs carry out execution on a discretionary basis» - see EMILIOS AVGOULEAS/ ALEXANDROS SERETAKIS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!*, in Avgouleas/ Marjosola (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), 1-35 (24).

104 For example, investment firms need to comply with minimum capital requirements as set out in Article 15 of MiFID II and Directive 2013/36/EU and Regulation (EU) no. 575/2013 and will have to comply with organizational requirements (see Article 16, of MiFID II) and, depending on the type of platform, additional requirements shall apply. In particular, investment firms and market operators operating an MTF or an OTF shall establish transparent rules regarding the criteria for determining the financial instruments that can be traded under its systems and also establish, publish and maintain and implement transparent and non-discriminatory rules, based on objective criteria, governing access to their facility (see Article 18, paragraphs 2 and 3 of MiFID II). Furthermore, «investment firms and market operators operating an MTF, in addition to meeting the requirements laid down in Articles 16 and 18, shall establish and implement nondiscretionary rules for the execution of orders in the system» (see Article 19, paragraph 1 of MiFID II).

systems and carrying execution based on non-discretionary rules[105].

Since integrated platforms neither operate on a bilateral basis nor deal on their own account, they cannot take the form of systematic internaliser ("SI")[106]. However, it is possible that in the event that DEXs offer trading services in MiFID II financial instruments, then the AMMs may be regarded as SI[107].

With this in mind, and if the EU financial services legislation were technologically neutral, notwithstanding the use of DLT, then, in principle, it would apply to centralized FinTech platforms, which would be subject to the MiFID II different licenses and rules depending on the type of trading platform they were operating[108].

However, the EU financial services legislation is not technologically neutral, which was recognized by the European institutions and resulted in the publication of the Digital Finance Package on 24 September 2020. This package of legislative proposals resulted in the adoption of the following regulations that will shape the future of the financial markets in the coming years: the DLT Pilot Regime[109], the MiCAR[110] and the DORA[111].

In the case of decentralized FinTech platforms, like AMM-based DEXs, the challenges for regulators are much higher, considering that EU financial services legislation is not technologically neutral, and that it was not designed to deal with scenarios where there is no direct intervention by financial intermediaries.

The DLT Pilot Regime creates a pilot regime for market infrastructures based on DLT, allowing for certain DLT market infrastructures to be temporarily exempted from some of the specific requirements of EU financial services legislation that could otherwise prevent operators from developing solutions for the trading and settlement of

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[105] It must be noted that it is very unlikely DEXs to function as OTFs offering discretionary services. It is also very unlikely that DEXs would ever seek authorization as a RM considering that «[t]he principal advantage of RMs apart from the prestige and seal of approval that their listings convey is the depth of their order book. However, as DEXes do not operate on the basis of a trading book they do not have any incentive to ever seek authorization as RMs» - see EMILIOS AVGOULEAS/ ALEXANDROS SERETAKIS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!*, in Avgouleas/ Marjosola (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), 1-35 (26).

[106] According to Article 4, paragraph 1, point 20, of MiFID II, systematic internaliser «means an investment firm which, on an organised, frequent systematic and substantial basis, deals on own account when executing client orders outside a regulated market, an MTF or an OTF without operating a multilateral system».

[107] See EMILIOS AVGOULEAS/ ALEXANDROS SERETAKIS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!*, in Avgouleas/ Marjosola (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), 1-35 (25). Also, according to these Authors, «this would place serious limitations to the function of AMMs on DeFi platforms. Therefore, the hope is that the present SI regime will not apply to automated market makers if they are dealing with low cap stocks and it can be shown that the AMM is offering prices through objective market learning algorithms to facilitate liquidity for a fee and not to leverage a proprietary book for profit, if the pre-committed pool of assets that AMMs operate can be paralleled to a proprietary trading book» - *ibidem*, 25.

[108] See EMILIOS AVGOULEAS/ ALEXANDROS SERETAKIS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!*, in Avgouleas/ Marjosola (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), 1-35 (28).

[109] Regulation (EU) 2022/858 of the European Parliament and of the Council of 30 May 2022 on a pilot regime for market infrastructures based on distributed ledger technology ("DLT Pilot Regime").

[110] Regulation (EU) 2023/1114 of the European Parliament and of the Council of 31 May 2023 on markets in crypto-assets ("MiCAR").

[111] Regulation (EU) 2022/2554 of the European Parliament and of the Council of 14 December 2022 on digital operational resilience for the financial sector ("DORA").

transactions in crypto-assets that qualify as financial instruments[112].

Thus, considering that the current EU financial service rules «are unable to deal with the new conduct, operational and financial stability issues posed by integrated decentralized platforms, such as aggravated conflicts of interests caused by the integration of functions and operational and cyber-security risks»[113], they need to be rethought, and an innovative solution found, including substantial automation of compliance[114].

As such, we believe that the DLT Pilot Regime could be an excellent vehicle for companies in the crypto-asset sector and regulators to test DEXs in a safe and trusted environment[115] in order to better understand the optimal approach to regulate these DeFi protocols and strike a balance between harnessing the benefits of financial innovation and ensuring investor and market protection.

To this end, we stress the importance of recognising the human intervention in the governance of DEXs for the purpose of applying financial rules, noting the recommendation to treat DAOs as entities for licensing purposes under EU financial services regulation[116].

Finally, it should be noted that the EU legislation on AI will also have to be considered, as the use of AI in AMM-based DEXs adds a layer of complexity to the system, raising liability and data protection issues.

In this context, the regulation of the European Parliament and of the Council on laying down harmonised rules on Artificial Intelligence ("AI Act")[117] establishes new harmonized rules for the placing on the market, the putting into service, and the use of AI systems in the European Union, the prohibition of certain AI practices, as well as specific requirements for high-risk AI systems (such as scoring or certain insurance

[112] See, however, that there are limitations on the financial instruments admitted to trading or recorded on DLT market infrastructure, according to Article 3 of the DLT Pilot Regime. Furthermore, note that this act is limited in time and the specific permissions and exemptions granted by a competent authority to an operator of DLT market infrastructure will be granted on a temporary basis (for a period up to six years from the date on which it the specific permission was granted) and it will be valid throughout the Union, but only for the duration of the pilot regime (see recitals 47, 48 and Articles 8, 9 and 10, paragraphs 11 and Article 14 of the DLT Pilot Regime). For more on the DLT Pilot Regime see JOÃO VIEIRA DOS SANTOS, *DLT Pilot Regime - Regulamento (UE) 2022/858*, in Revista de Direito das Sociedades, Year XIV, No. 2, (2022), 317-330.

[113] See EMILIOS AVGOULEAS/ ALEXANDROS SERETAKIS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!*, in Avgouleas/ Marjosola (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), 1-35 (28).

[114] *Ibidem*, 33.

[115] In relation to the information on the functioning, services and activities of the DLT market infrastructure, as referred to in Article 7(3) of the DLT Pilot Regime, to be included in an application for authorisation to operate a DLT market infrastructure, e.g., a DLT MTF (i.e., a multilateral trading facility that only admits to trading DLT financial instruments), in accordance with ESMA guidelines, information should be required on the type of DLT used, by specifying its main characteristics, including whether it is permissioned or **permissionless** - see ESMA, *Guidelines On standard forms, formats and templates to apply for permission to operate a DLT market infrastructure*, (2023), 15.

[116] In this respect and for a full explanation of their proposal see D.A. ZETZSCHE/ R.P. BUCKLEY/ D.W. ARNER/ M.C. VAN EK, *Remaining regulatory challenges in digital finance and cryptoassets after MiCA*, (2023), 116-118. As regards the implications of granting legal personality to DAOs under Portuguese Law see ANA NUNES TEIXEIRA, *DAOs Under Portuguese Law*, in Madalena Perestrelo de Oliveira/ António Garcia Rolo (org.), *Decentralised Autonomous Organisations (DAOs) in Various Jurisdictions: from Old Rules to Innovative Approaches*, AAFDL: Lisboa (2023), 12-23 (21-22). Finally, for an introductory analysis under private international law on the law applicable to smart contracts and DAOs see LUÍS DE LIMA PINHEIRO, *Laws Applicable to International Smart Contracts and Decentralized Autonomous Organizations (DAOS)*, (2023).

[117] The Regulation (EU) 2024/1689 of the European Parliament and of the Council of 13 June 2024 laying down harmonised rules on artificial intelligence and amending Regulations (EC) No 300/2008, (EU) No 167/2013, (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1139 and (EU) 2019/2144 and Directives 2014/90/EU, (EU) 2016/797 and (EU) 2020/1828 ("AI Act"), available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32024R1689.

practices) and obligations for operators of such systems[118].

As regards the AI Act, «the European legislator opted for the 'horizontal approach' by creating one technology-focused regulation that covers AI's many impacts and use-cases. The AI Act is therefore not tailored for specific AI models or economic sectors such as financial sector»[119].

In the context of AI powered AMM-based DEXs, it is noted that the AI Act also applies to providers of AI systems that are established in a third country, to the extent the output produced by those systems is used in the European Union[120].

Also, the definition of a 'provider' is very broad, covering «natural or legal person, public authority, agency or other body that develops an AI system or a general-purpose AI model or that has an AI system or a general-purpose AI model developed and places it on the market or puts the AI system into service under its own name or trademark, whether for payment or free of charge»[121].

This is particularly relevant given the 'decentralized' (a better word would be distributed) nature of the governance in DEXs, allowing, in principle, to subject to EU AI rules, for example, DAOs, which would also be treated as entities for licensing purposes under EU financial services regulation[122]. ●

[118] See Article 1, Article 6, and Annex III of the AI Act. Note that the list of high-risk AI systems in Annex III is dynamic and, when certain conditions are met, the EU Commission can change it (see Article 7 of the AI Act).

[119] See DELOITTE, *EU AI Act adopted by the Parliament: What's the impact for financial institutions?*, (2023). According to Recital 158 of the AI Act, «Union financial services law includes internal governance and risk-management rules and requirements which are applicable to regulated financial institutions in the course of provision of those services, including when they make use of AI systems». However, concerns arise when there is uncertainty over the implementation of European financial services legislation.

[120] See Recitals 21 and 22 and Article 2, paragraph 1(a) and (c) of the AI Act.

[121] See Article 3, paragraph 3 of the AI Act.

[122] See Points 2.2 and 5 above.

6. FINAL REMARKS

In the field of positive regulatory progress, it is worth noting that in September 2023, the International Organization of Securities Commissions ("IOSCO") published a Consultation Report on Policy Recommendations for DeFi (CR/04/2023) and later, in December 2023, IOSCO published the Final Report with Policy Recommendation for DeFi (FR/14/2023). These recommendations are addressed to relevant authorities and look to support jurisdictions seeking to establish compliant markets in the most effective way possible[123]. While the Recommendations for DeFi «are not directly addressed to market participants, all participants in crypto-asset markets are strongly encouraged to carefully consider the expectations and outcomes articulated through the proposed recommendations and the respective supporting guidance in the conduct of regulated and cross-border activities»[124].

The EU Commission is expected to assess DeFi related developments in markets in crypto-assets and to evaluate the need for the regulatory treatment of DeFi crypto-asset ecosystems following the entry into force of the MiCAR[125] and the AI Act.

At last, we would like to note that alongside the predicted growth and development of AMM-based DEXs in the financial sector, there is the risk that the existing European regulatory framework for markets in financial instruments and also for markets in crypto-assets will not keep pace and will not be able to respond to the challenges it poses.

In this context, it may be beneficial for regulators to use technology to their advantage, noting that «[t]he integration of AI-based solutions in DLT-based systems at the protocol level could help authorities achieve their regulatory objectives in an efficient manner»[126]. Also, the «[p]articipation of regulators as nodes in decentralised networks has been discussed by the market as one of the ways to resolve the challenges

[123] See IOSCO, *Final Report with Policy Recommendations for Decentralized Finance (DeFi)*, (2023). These Recommendations are complementary to the Policy Recommendations for Crypto and Digital Assets Markets issued by IOSCO in 16 November 2023 (FR11/2023).

[124] IOSCO, *Final Report with Policy Recommendations for Decentralized Finance (DeFi)*, (2023), 2.

[125] Note that, by 30 December 2024, ESMA is expected to issue guidelines on the conditions and criteria for the qualification of crypto-assets as financial instruments (see Article 2, paragraph 5 of the MiCAR).

[126] See OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), 32.

of supervision of such platforms that lack a single central authority»[127].

In the end, DEXs and AI are starting to unite, and their combined characteristics are known and show significative potential benefits, for both investors, users, and regulators. Still, they must continue to be monitored by regulators with the aim of ensuring financial stability and investor protection in the crypto-asset markets. To achieve this goal, it is imperative that regulators work closely with the crypto-asset industry to build a solid regulatory framework for DeFi protocols. ●

[127] *Ibidem*, 33. For a study of the concept of embedded supervision, which «is a regulatory framework that provides for compliance with regulatory standards in DLT-based markets to be automatically monitored by reading the market's ledger. It would reduce the administrative burden for firms, while increasing the quality of data available to the supervisor» - see RAPHAEL AUER, *Embedded Supervision: How to Build Regulation into Decentralised Finance*, (2022). Also, note that «[e]mbedded supervision is distinct from other forms of 'suptech' or 'regtech', which aim to use machine learning or artificial intelligence to more efficiently monitor the financial industry» - ibidem, 19.

7. BIBLIOGRAPHY

ANGELIS, STEFANO ET AL., *Blockchain and cybersecurity: a taxonomic approach*, (2019), available at: https://www.eublockchainforum.eu/sites/default/files/research-paper/wrks-main_1.pdf (last accessed 25 June 2023).

ARAMONTE, SIRIO/ HUANG, WENQIAN/ SCHRIMPF, ANDREAS, *DeFi risks and the decentralisation illusion*, (2021), available at: https://www.bis.org/publ/qtrpdf/r_qt2112b.htm (last accessed 25 June 2023).

AUER, RAPHAEL ET AL., *The Technology of Decentralized Finance (DeFi)*, (2023), available at: https://www.bis.org/publ/work1066.htm (last accessed 25 June 2023).

AUER, RAPHAEL, *Embedded Supervision: How to Build Regulation into Decentralised Finance*, (2022), available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4127658 (last accessed 25 June 2023).

AUTORITÉ DES MARCHÉS FINANCIERS, *AMF Discussion Paper on Decentralised Finance (DeFi)*, (2023), available at: https://www.amf-france.org/en/news-publications/public-consultations/amf-discussion-paper-decentralised-finance-defi (last accessed 25 June 2023).

AVGOULEAS, EMILIOS/ SERETAKIS, ALEXANDROS, *Governing the Digital Finance Value-Chain in the EU: MIFID II, the Digital Package, and the Large Gaps between!, in Avgouleas/ Marjosola* (Eds.), *Digital Finance in Europe: Law, Regulation, and Governance*, De Gruyter: Berlin, Boston (2022), available at: https://www.degruyter.com/document/doi/10.1515/9783110749472/html (last accessed 25 June 2023).

BARBAGLIA, LUCA, ET AL., *Data Science Technologies in Economics and Finance: A GentleWalk-In Data Science Technologies in Economics and Finance: A GentleWalk-In*, in Sergio Consoli/ Diego Reforgiato Recupero/ Michaela Saisana (Eds.), *Data Science for Economics and Finance Methodologies and Applications*, Springer Nature: Switzerland (2021), available at: https://link.springer.com/book/10.1007/978-3-030-66891-4 (last accessed 25 June 2023).

BORN, ALEXANDRA/ M. VENDRELL SIMÓN, JOSEP, *A deep dive into crypto financial risks: stablecoins, DeFi and climate transition risk*, (2022), available at: https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/html/ecb.mpbu202207_1~750842714e.en.html (last accessed 25 June 2023).

BORN, ALEXANDRA ET AL., *Decentralised finance – a new unregulated non-bank system?*, (2022), available at: https://www.ecb.europa.eu/pub/financial-stability/macroprudential-bulletin/focus/2022/html/ecb.mpbu202207_focus1.en.html (last accessed 25 June 2023).

7. BIBLIOGRAPHY

CAMBRIDGE CENTRE FOR ALTERNATIVE FINANCE, *What is the link between electricity consumption and carbon emissions?*, in FAQ Power Consumption, (2023), available at: https://ccaf.io/cbeci/faq (last accessed 25 June 2023).

CANNARSA, MICHEL, *Contract Interpretation*, em Larry A. Dimatteo/ Michel Cannarsa/ Cristina Poncibò (eds.), *The Cambridge Handbook of Smart Contracts, Blockchain Technology and Digital Platforms*, Cambridge University Press: Cambridge (2020).

CAO, LONGBING, *AI in Finance: A Review*, (2021), available at: https://ssrn.com/abstract=3647625 (last accessed 25 June 2023).

CMVM, *Questions and Answers for Entities on Cryptoassets*, (2018), available at: https://investidor.cmvm.pt/PInvestidor/Content?Input=260BC96DF13F0BEA4C2E4A9EB601300D1283E1F0B992EB582124A0B73D6FC1BD (last accessed 23 December 2023).

CONG, LIN WILLIAM ET AL., *Crypto Wash Trading*, (2023), available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3530220 (last accessed 25 June 2023).

CORREIA, FRANCISCO MENDES, *A tecnologia descentralizada de registo de dados* (blockchain) *no setor financeiro*, in António Menezes Cordeiro/ Ana Perestrelo de Oliveira/ Diogo Pereira Duarte (org.), FinTech. Desafios da tecnologia financeira, 2nd ed., Almedina: Coimbra (2019).

DEEPLINK, *Machine Learning Applications in DEX Aggregation and Smart Order Routing*, (2022), available at: https://medium.com/@deeplinknetwork/machine-learning-applications-in-dex-aggregation-and-smart-order-routing-fb50880fb390 (last accessed 25 June 2023).

DELOITTE, *EU AI Act adopted by the Parliament: What's the impact for financial institutions?*, (2023), available at: https://www2.deloitte.com/lu/en/pages/investment-management/articles/european-artificial-intelligence-act-adopted-parliament.html (last accessed 25 June 2023).

DODMANE, RADHAKRISHNA ET AL., *Blockchain-Based Automated Market Makers for a Decentralized Stock Exchange*, in Information Journal, Vol. 14, Issue 5, (2023), available at: https://www.mdpi.com/2078-2489/14/5/280 (last accessed 25 June 2023).

7. BIBLIOGRAPHY

Eliza Mik, Blockchains *A Technology for Decentralized Marketplaces*, em Larry A. Dimatteo/ Michel Cannarsa/ Cristina Poncibò (eds.), *The Cambridge Handbook of Smart Contracts, Blockchain Technology and Digital Platforms*, Cambridge University Press: Cambridge (2020).

ESMA, Guidelines On standard forms, formats and templates to apply for permission to operate a DLT market infrastructure, (2023), available at: https://www.esma.europa.eu/document/guidelines-standard-forms-formats-and-templates-apply--permission-operate-dlt-market (last accessed 25 June 2023).

ESMA, *Crypto-assets and their risks for financial stability*, (2022), available at: https://www.esma.europa.eu/document/trv--article-crypto-assets-and-their-risks-financial-stability (last accessed 25 June 2023).

ESRB, *Crypto-assets and decentralised finance Systemic implications and policy options*, (2023), available at: https://www.esrb.europa.eu/news/pr/date/2023/html/esrb.pr230525~c74fa66621.en.html (last accessed 25 June 2023).

EU BLOCKCHAIN OBSERVATORY AND FORUM, *Decentralised Finance (DeFi)*, (2022), available at: https://www.eublockchain-forum.eu/reports/decentralised-finance (last accessed 25 June 2023).

EU BLOCKCHAIN OBSERVATORY AND FORUM, *Energy Efficiency of Blockchain Technologies*, (2021), available at: https://www.eublockchainforum.eu/news/new-thematic-report-energy-efficiency-blockchain-technologies (last accessed 25 June 2023).

EUROPEAN LAW INSTITUTE, *ELI Principles on Blockchain Technology, Smart Contracts and Consumer Protection*, (2022), available at: https://europeanlawinstitute.eu/news-events/news-contd/news/european-law-institute-publishes-eli--principles-on-blockchain-technology-smart-contracts-and-consum/?tx_news_pi1%5Bcontroller%5D=News&tx_news_pi1%5Baction%5D=detail&cHash=a1aac5c1e60ac69166169c0ae66963ad (last accessed 25 June 2023).

EUROPEAN PARLIAMENT, *AI Act: a step closer to the first rules on Artificial Intelligence*, (2023), available at: https://www.europarl.europa.eu/news/en/press-room/20230505IPR84904/ai-act-a-step-closer-to-the-first-rules-on-artificial-intelligence (last accessed 25 June 2023).

EUROPEAN SUPERVISORY AUTHORITIES, *EU financial regulators warn consumers on the risks of crypto-assets*, (2022), available at: https://www.cmvm.pt/en/Comunicados/Comunicados/Pages/20220317b.aspx?v= (last accessed 25 June 2023).

7. BIBLIOGRAPHY

FILIPPI, PRIMAVERA DE/ WRAY, CHRIS/ SILENO, GIOVANNI, *Smart Contracts*, in Internet Policy Review Journal on Internet Regulation, Vol. 10, Issue 2, (2021), available at: https://policyreview.info/glossary/smart-contracts (last accessed 25 June 2023).

FSB, *The Financial Stability Risks of Decentralised Finance*, (2023), available at: https://www.fsb.org/2023/02/the-financial--stability-risks-of-decentralised-finance/ (last accessed 25 June 2023).

GAI, YU ET AL., *Blockchain Large Language Models*, V2 (2023), available at: https://arxiv.org/abs/2304.12749 (last accessed 25 June 2023).

GOGOL, KRZYSZTOF ET AL., *SoK: Decentralized Finance (DeFi) - Fundamentals, Taxonomy and Risks*, (2023), available at: https://www.authorea.com/doi/full/10.22541/au.168568220.09436681/v1 (last accessed 25 June 2023).

GRASSI, LAURA ET AL., *Do we still need financial intermediation? The case of decentralized finance – DeFi*, in Qualitative Research in Accounting & Management Journal, Volume 19, Issue 3, (2022), available at: https://www.emerald.com/insight/content/doi/10.1108/QRAM-03-2021-0051/full/html (last accessed 25 June 2023).

HARVEY, CAMPBELL R. ET AL., *DeFi and the Future of Finance*, Wiley: New Jersey (2021), 95, 131-132, 146.

IBM, *Public key cryptography*, (2021), available at: https://www.ibm.com/docs/en/ztpf/2020?topic=concepts-public-key--cryptography (last accessed 25 June 2023).

IOSCO, *Decentralized Finance Report*, (2022), available at: https://www.iosco.org/library/pubdocs/pdf/IOSCOPD699.pdf (last accessed 25 June 2023).

IOSCO, *IOSCO Crypto-Asset Roadmap for 2022-2023*, (2022), available at: https://www.iosco.org/library/pubdocs/pdf/IOSCOPD705.pdf (last accessed 25 June 2023).

IOSCO, Policy Recommendations for Decentralized Finance (DeFi) Consultation Report, (2023), available at: https://www.iosco.org/library/pubdocs/pdf/IOSCOPD744.pdf (last accessed 23 December 2023).

IOSCO, *Final Report with Policy Recommendations for Decentralized Finance (DeFi)*, (2023), available at: https://www.iosco.org/library/pubdocs/pdf/IOSCOPD754.pdf (last accessed 11 September 2024).

7. BIBLIOGRAPHY

KARIMI, ZOHREH, *An overview of Artificial Intelligence approaches in the cryptocurrency market makers*, (2023), available at: https://www.researchgate.net/publication/369588246_An_overview_of_Artificial_Intelligence_approaches_in_the_cryptocurrency_market_makers (last accessed 25 June 2023).

KIRIMHAN, DESTAN, *Importance of anti-money laundering regulations among prosumers for a cybersecure decentralized finance*, in Journal of Business Research, Volume 157, (2023), available at: https://www.sciencedirect.com/journal/journal-of-business-research/vol/157/suppl/C (last accessed 25 June 2023).

LIM, TRISTAN, *Predictive Crypto-Asset Automated Market Making Architecture for Decentralized Finance using Deep Reinforcement Learning*, V2 (2023), available at: https://arxiv.org/abs/2211.01346 (last accessed 25 June 2023).

LYONS, TOM/ COUCERLAS, LUDOVIC, *Blockchain and Cyber Security*, (2020), available at: https://www.eublockchainforum.eu/reports/blockchain-and-cyber-security (last accessed 25 June 2023).

MAKAROV, IGOR/ SCHOAR, ANTOINETTE, *Cryptocurrencies and Decentralised Finance (DeFi)*, (2022), available at: https://www.bis.org/publ/work1061.htm (last accessed 25 June 2023).

MARTINS, JOÃO MARQUES, *Inteligência Artificial e Direito: Uma Brevíssima Introdução*, in Revista da Faculdade de Direito da Universidade de Lisboa, Year LXIII 2022 No. 1 and 2.

MOHAN, VIJAY, *Automated market makers and decentralized exchanges: a DeFi primer*, in Financial Innovation 8, Article no. 20, (2022), available at: https://jfin-swufe.springeropen.com/articles/10.1186/s40854-021-00314-5 (last accessed 25 June 2023).

NORWEGIAN CONSUMER COUNCIL, *Ghost in the machine – Addressing the consumer harms of generative AI*, (2023), available at: https://www.forbrukerradet.no/ai (last accessed 25 June 2023).

OCDE, *AI Language Models Technological, Socio-Economic and Policy Considerations*, (2023), available at: https://www.oecd-ilibrary.org/science-and-technology/ai-language-models_13d38f92-en (last accessed 25 June 2023).

OCDE, *Why Decentralised Finance (DeFi) Matters and the Policy Implications*, (2022), 20, 19-22, 33-36, available at: https://www.oecd.org/finance/why-decentralised-finance-defi-matters-and-the-policy-implications.htm (last accessed 25 June 2023).

7. BIBLIOGRAPHY

OCDE, *Artificial Intelligence, Machine Learning and Big Data in Finance*, (2021), available at: https://www.oecd.org/finance/artificial-intelligence-machine-learning-big-data-in-finance.htm (last accessed 25 June 2023).
OFFICER'S BLOG, *Reentrancy Attacks on Smart Contracts Distilled*, (2022), available at: https://officercia.mirror.xyz/RoWpSjah4hvKvCyrCgqtdyWX657e3-qUeShBZ2VtkUs (last accessed 25 June 2023).

OXFORD ENGLISH DICTIONARY, *artificial intelligence*, (2023), available at: https://www.oed.com/viewdictionaryentry/Entry/271625 (last accessed 25 June 2023).

PINHEIRO, LUÍS DE LIMA, *Laws Applicable to International Smart Contracts and Decentralized Autonomous Organizations (DAOS)*, (2023), available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4467408 (last accessed 25 June 2023).
ROUKNY, TARIK, Decentralized Finance: information frictions and public policies, Approaching the regulation and supervision of decentralized finance, (2022), available at: https://finance.ec.europa.eu/system/files/2022-10/finance-events--221021-report_en.pdf (last accessed 25 June 2023).

SADMAN, NAFIZ ET. *AL*, *Promise of AI in DeFi, a Systematic Review*, in Digital Journal, Volume 2, Issue 1, (2022), available at: https://doi.org/10.3390/digital2010006 (last accessed 25 June 2023).

SANTOS, JOÃO VIEIRA DOS, *DLT Pilot Regime – Regulamento (UE) 2022/858*, in Revista de Direito das Sociedades, Year XIV, No. 2, (2022), available at: https://www.revistadedireitodassociedades.pt/revistas/ano-xiv-2 (last accessed 25 June 2023).

SCHÄR, FABIAN, *Decentralized Finance: On Blockchain- and Smart Contract-Based Financial Markets*, in Federal Reserve Bank of St. Louis Review, Vol. 103, No. 2, (2021), available at: https://research.stlouisfed.org/publications/review/2021/02/05/decentralized-finance-on-blockchain-and-smart-contract-based-financial-markets (last accessed 25 June 2023).

SCHILLIG, MICHAEL ANDERSON, *DAOs Under English Law*, in Madalena Perestrelo de Oliveira/ António Garcia Rolo (org.), Decentralised Autonomous Organisations (DAOs) in Various Jurisdictions: from Old Rules to Innovative Approaches, AAFDL: Lisboa (2023), available at: https://lisbondaoobservatory.cidp.pt/publication/decentralised-autonomous-organisations--daos-in-various-jurisdictions-from-old-rules-to-innovative-approaches/8 (last accessed 25 June 2023).

SCHREPEL, THIBAULT, *Smart Contracts and the Digital Single Market Through the Lens of a 'Law + Technology' Approach*, (2021), available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3947174 (last accessed 25 June 2023).

7. BIBLIOGRAPHY

SCHULER, KATRIN / CLOOTS, ANN SOFIE / SCHÄR, FABIAN, *On DeFi and On-Chain CeFi: How (Not) to Regulate Decentralized Finance*, (18-April-2018), available at: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4422473 (last accessed 24 March 2024).

SEC, *SEC Charges Coinbase for Operating as an Unregistered Securities Exchange, Broker, and Clearing Agency*, (2023), available at: https://www.sec.gov/news/press-release/2023-102 (last accessed 25 June 2023).

TAHERDOOST, HAMED, *Fintech: Emerging Trends and the Future of Finance*, in Abeba N. Turi (Ed.), Financial Technologies and DeFi A Revisit to the Digital Finance Revolution, Springer Nature: Switzerland (2023).

TASCA, PAOLO/ TESSONE, CLAUDIO, *Taxonomy of Blockchain Technologies. Principles of Identification and Classification*, New York, (2018), available at: https://doi.org/10.2139/ssrn.2977811 (last accessed 25 June 2023).

TEIXEIRA, ANA NUNES, *DAOs Under Portuguese Law*, in Madalena Perestrelo de Oliveira/ António Garcia Rolo (org.), *Decentralised Autonomous Organisations (DAOs) in Various Jurisdictions: from Old Rules to Innovative Approaches*, AAFDL: Lisboa (2023), available at: https://lisbondaoobservatory.cidp.pt/publication/decentralised-autonomous-organisations--daos-in-various-jurisdictions-from-old-rules-to-innovative-approaches/8 (last accessed 25 June 2023).

TRUCHET, MARC, *Decentralized Finance (DeFi): opportunities, challenges and policy implications*, (2022), available at: https://www.eurofi.net/wp-content/uploads/2022/05/eurofi_decentralized-finance-defi_opportunities-challenges-and--policy-implications_paris_february-2022.pdf (last accessed 25 June 2023).

WERNER, SAM ET AL., *SoK: Decentralized Finance (DeFi)*, V6 (2022), available at: https://arxiv.org/abs/2101.08778 (last accessed 25 June 2023).

XU, JIAHUA ET AL., *SoK: Decentralized Exchanges (DEX) with Automated Market Maker (AMM) Protocols*, V7 (2023), available at: https://arxiv.org/abs/2103.12732 (last accessed 25 June 2023).

XU, XIWEI ET AL., *A Taxonomy of Blockchain-Based Systems for Architecture Design*, (2017), available at: https://design.inf.usi.ch/publications/2017/icsa/blockchain (last accessed 25 June 2023).

ZETZSCHE, D.A./ BUCKLEY, R.P./ ARNER, D.W./ EK, M.C. VAN, *Remaining regulatory challenges in digital finance and cryptoassets after MiCA*, (2023), available at: https://www.europarl.europa.eu/thinktank/en/document/IPOL_STU(2023)740083 (last accessed 25 June 2023).