A Case for a Currencyless Economy Based on Bartering with Smart Contracts

Carlos Molina–Jimenez¹, Hazem Danny Al Nakib², Linmao Song³, Ioannis Sfyrakis⁴, and Jon Crowcroft¹

¹ Department of Computer Science and Technology, University of Cambridge
carlos.molina@cl.cam.ac.uk https://www.cl.cam.ac.uk/~cm770/
jon.crowcroft@cl.cam.ac.uk

² Department of Computer Science, University College London
hazemdanney.nakib@gmail.com

³ Independent researcher
linmao.song@gmail.com

⁴ School of Computing, Newcastle University, UK
ioannis.sfyrakis@ncl.ac.uk

University of Cambridge, 8 Oct 2020

Abstract. We suggest the re–introduction of bartering to create a crypto-
currencyless, currencyless, and moneyless economy segment. We con-
tend that a barter economy would benefit enterprises, individuals, gov-
ernments, and societies. For instance, the availability of an online peer–
to–peer barter marketplace would convert ordinary individuals into po-
tential traders of both tangible and digital items and services. For ex-
ample, they will be able to barter files and data that they collect. Equally
motivating, they will be able to barter and re–introduce to the econ-
omy items that they no longer need such as, books, garden tools, and
bikes which are normally kept and wasted in garages and sheds. We argue
that most of the pieces of technology needed for building a barter system
are now available, including blockchains, smart contracts, cryptography,
secure multiparty computations and fair exchange protocols. However,
additional research is needed to refine and integrate the pieces together.
We discuss potential research directions.

Keywords: barter, bartering, smart contracts, blockchains, fair exchange,
fiat money, cash, banking, cryptocurrencies

1 Introduction

In this article, we make a case for re–introducing the barter trade model, un-
derpinned by the latest advances in decentralised technologies. We focus mainly
on peer–to–peer (direct) bartering as opposed to indirect bartering where the
barter operations (also called transactions) are mediated by a trade exchange.
Such a system would allow the execution of both face–to–face and remote barter
transactions to trade both tangible and digital items, and services. To this end,
bartering would target a specific economic segment and complement the current trade models. We present our views on the limitations of the current trade systems, the potential of a barter system and the challenges involved.

The most attractive features of bartering is that it is inherently peer–to–peer and bank–independent: it consists in the exchange of item–for–item on a peer–to–peer basis. Fig. 1 illustrates the idea:

Alice meets Bob and she gives her book to him in exchange for a pizza. In this, and subsequent figures, we use Alice and Bob to represent two participants in a barter transaction. In some situations, Alice and Bob are humans operating on their own initiative but in others they represent institutions like companies and governments. Their interaction is either face–to–face or remote, that is, online.

Bartering was widely practiced in all eras until it was replaced by the currency–based trade model that underpins today’s trade through both private currencies and state-backed government led fiat monies [1].

Why do we care about bartering now? We are interested in bartering because it has intrinsic features that in some situations make it more suitable than the current fiat–money–based trade system. We care about it now because, after
decades of research we now have all the pieces of technology to implement it, admittedly, after solving some pending research questions.

The remaining sections of this article are organised as follows: Section 2 includes background material to help understand the advantages and disadvantages of the current fiat–based trade system. This is followed by Section 3 which introduces bartering and discusses its potential contribution to the economy. Section 4 outlines research questions that need to be solved to progress towards a potential implementation of a peer–to–peer barter system that can complement the existing trade system. In Section 5, we suggest references where the topics outlined in this article are discussed in depth. Concluding remarks are presented in Section 6.

2 Pros and cons of fiat–based trade

The origin of currency–based trade has a rich history that can be traced back to as early as circa 9000–6000 BC. There is evidence that cattle were used as a medium of exchange, that is, as money [2]. Different societies used different objects such as beads, shells, furs, seeds and metals. These objects were gradually replaced by coins, minted coins and finally paper money [3]. Private moneys were used until governments introduced fiat money like dollars and euros.

Currently, in the post-Gold Standard era, fiat currencies that are not backed by any assets dominate trade, however, cryptocurrencies like Bitcoin are emerging. Bartering predates the appearance of currency–based trade and operated fairly actively alongside the currency–based model until the appearance of market–integrated economies. In such economies, currency offers noticeable advantages over bartering; for instance, it helps to maintain consistency within marketplaces, it provides efficiency and scalability, and simple access and ease of use.

2.1 Advantages

Currency is a common medium of exchange that helps individuals to exchange items and services indirectly. We are not very interested in the concept of money and the requirements of money per se but rather in how and in what way currency compares with barter models. Relevant to our discussion are the following properties of currency:

– eliminates the difficulties of finding a matching barterer to perform a simultaneous tit for tat barter operation.
– is a common and standard measure of value.
– is a medium of condensing and accumulating wealth.

These properties of currency significantly simplify trade operations.
2.2 Disadvantages

A salient feature of currency–based trade is that it is inherently centralised: the bank plays the role of a trusted third party that is responsible for mediating all the trade operations. From this fact, emerge the strengths discussed above in Section 2.1 and the weaknesses pointed out by some authors \[4,5\] and summarised as follows:

- **mediated trade**: fiat money is inherently a mediation mechanism and as such it prevents peer–to–peer trade as conducted in the example of Fig. [1].
- **transparency**: the mediating role of the banking system compromises transparency. Transaction records are regarded as private data that only the bank can access.
- **privacy**: nothing escapes from the banker’s sight. The bank gathers records of absolutely all transactions. Cash payment offers better privacy protection, however, with the success of online shopping, the use of cash is becoming old fashioned, in particular with the threat of the SARS–CoV–2 virus.
- **delays**: bank transactions are still unacceptably slow; for example wire payment can take up to five days to complete. Non surprisingly, payment and money transfer mechanisms like PayPal, Western Union and TransferWise have emerge to help reduce payment delays to minutes or seconds; they are based on the execution of digital accounting operations that conceal, from the customer’s view, the bank delays.
- **fees**: banks services are not free. The charges discourage the execution of transactions of small value. Moreover, banks lend out most of the capital, in fact banks are indebted to their depositors, a point that many people misunderstand.
- **financial exclusion**: bank services are granted only to those that satisfy the bank’s requirements which are normally related to age, financial status, legal status and so on. It has been estimated that within the current world population of 7.8 billion \((7.8 \times 10^9)\), about 1.7 billion of adults remain unbanked. The reason being that they fail to meet the requirements or that there are no banking services where they live \[6\]. This disappointing figure includes 1.5 million unbanked in Great Britain and 40 million in the European Union notwithstanding the fact that within the European Union it is a requirement for financial institutions to provide free bank accounts to those who need them.

As explained in Section 3, the decentralised (peer–to–peer) nature of bartering and its non–reliance on banks makes it immune to the drawbacks listed above. Bartering can be used as an option, in particular where the advantages that currency offers are irrelevant to the traders, for example, where the difficulty to find barter partners is not an issue, say, because the Internet offers mechanisms to surmount the obstacle.

Recently introduced cryptocurrencies which are based on decentralised technologies (for example, blockchains) have generated a lot of excitement in finance and other fields. Though they can be used to exchange tokens, we do not see their
potential to support bartering. Firstly, the ledger that mediates all cryptocurrency transactions introduces unnecessary complexity for the needs of barter operations. Secondly, they are focused on tokenised items. Thirdly, state-of-the-art cryptocurrencies are afflicted by several drawbacks which we will discuss separately in Section 2.3.

2.3 Observations on cryptocurrency

Decentralisation was one of cryptocurrencies’ original goals. Despite the significant amount of interest, investment (in terms of not only money, but also, industrial and research efforts) and speculation, the real-world benefits of cryptocurrencies still remain to be seen, after more than a decade since their birth. One of the possible reasons for the lack of adoption in practical applications might be cryptocurrencies’ built-in weaknesses. To start with, the consensus algorithms (for example, proof-of-work and proof-of-stake) that are used to synchronise the decentralised ledgers introduce efficiency and scalability issues [4,5]. Secondly, the cost of cryptocurrency transactions is high. Bitcoin and Ethereum have already experienced average transaction fees of 54.90 and 4.15 USD, respectively [7]. There is insufficient evidence to suggest that cryptocurrencies are not suitable for conducting large numbers of transactions involving small payments. Thirdly, to the average user, cryptocurrencies are not simple to use, their focus on decentralisation introduces some complexities. For instance, the requirement that users need to manage private keys introduces the risk of accidental loss. Mitigating this issue, e.g., by using exchange wallets, defeats the purpose of decentralisation and without the added benefit of protection that would come from centralised banks. Fourthly, another issue that afflicts cryptocurrencies is security. A notorious example of a security hole is the MtGox case that resulted in the theft of 850,000 bitcoins (about 620 million USD [8]) in Feb 2014. Real world abuses include duplication, counterfeits, multiple-spending and money laundering [9,9]. Cryptocurrencies also facilitates new crimes, such as ransom payments. For example, victims of CryptoLocker (a well known ransomware trojan) were forced to pay 310 472 USD in 2013 [11]. Finally, in addition to these marketing and technical issues, the practicality of decentralised cryptocurrencies that allow individuals to conduct transactions freely outside a regulatory supervising bank system has been challenged by several authors. The lack of Automated Clearing House (ACH) reversal in blockchain systems is only one of the concerns [12,13]. Several mechanisms are currently under active investigation to ameliorate these and other issues that afflicit current state-of-the-art cryptocurrencies.

3 Barter-based trade

A barter system operating along the currency-based trade system would enable individuals and institutions to barter a variety of items and services. The example of Fig. 1 shows a familiar situation: Alice gives away an item that otherwise would have become wasted food; regarding Bob, he reintroduces to the economy
an item that bears no value to him. To appreciate the impact, it is worth taking into account that a study from 2017 reports [14] that the average household lost £470 a year because of avoidable food waste. Similarly, there are reports that the average household in UK has accumulated £1 784 worth of items that are no longer needed including, books, bikes, and garden tools [15].

3.1 Do I have something to barter?

Though the example of Fig. 1 involves two tangible items, bartering can be extended to cover a great variety of items and services. We conceive bartering as an operation executed between the two participants. The complexity of such transaction and the technology needed to execute it depend to a great extent on the properties of the items. To start reasoning, it might help to distinguish between the following categories:

– **tangible items**: within this category fall physical items like the pizza and book of the example of Fig. 1. A salient property of these items is that they are not transferable over electronic communication channels.

– **digital items**: within this category are items that can be manipulated electronically, for instance, they can be stored (normally as a file on disk) and transferred, electronically. Examples of digital items are photos, videos, e-books and pieces of personal data. Two salient properties of digital items are that they possess value in their own right and that they exist only in the digital world. The universe of digital items is large and includes items with different properties and as such it can be further divided into other subcategories. For example, depending on their uniqueness, a digital item can be fungible or non-fungible [16]. Bartering of digital items has great business potential because the number of digital items that each individual owns can only increase and will be, in the near future, larger than the number of his or her tangible items.

– **online services**: an online service (also called e-service) is an network-accessible facility that satisfies some user’s needs. Their electronic nature makes them amenable to barter transactions. As an opening example, we can mention that current access to online services (for example, google, gmail and facebook) is granted on the basis of bartering: online services exchange their services in return for the personal data that they collect about the individuals’ activities. This practice has been in place since the early 90s and so far it seems to satisfy both parties. That said, one can argue that it is an unfair barter operation since the economic power of the service providers allows them to dictate the rules.

Another practical example of bartering of online services is found in the current operation of the GBP (Gateway Border Protocol). A typical arrangement is a peer-to-peer relationship where two ASs (Autonomous Systems) agree to exchange traffic for free, that is, without the exchange of actual money [17].
A large number of similar examples can be found in the cloud computing domain where cloud providers agree to barter idle resources with each other. Another application domain where bartering takes place is community networks where individuals like Alice and Bob contribute resources (for example, a segment of the communication link) to a communal resource pool to earn the right to access the shared communication and computation facilities [18]. Also, a barter system can be used to barter unused spectrum to save money and contribute to the currently pressing issue of spectrum scarcity [19]. For example, individuals can barter their unused home bandwidth [20].

- **services:** services and skills can also be swapped. Therefore, within this category we place conventional services whose delivery requires the physical presence of the service provider. A good example of service is repair work, for example of a plumber [21].

### 3.2 Barter models

We anticipate that both ordinary human beings, business enterprises and governments will participate in barter transactions. Though in this article we focus mainly on direct (also called peer–to–peer) Individual–to–Individual bartering, we expect other models, including Individual–to–Business bartering and Business–to–Business bartering.

![Fig. 2. Bob, Alice and Clare bartering.](image-url)
In the most simple case, like in the example shown in Fig. 1, bartering involves only two tangible items and two parties (one item each) that are willing to exchange their items simultaneously. A similar situation is shown in Fig. 2a where Bob trades with Alice directly: he barters his apple in exchange for Alice's banana. However, by extension of this simple model one can imagine situations of arbitrary complexity involving more than two parties where each of them owns more than one item. For example, in the scenario shown in Fig. 2b, Bob has an apple, Clare an orange, and Alice a banana. Imagine that, as shown in the figure, Bob trusts Clare but not Alice, Clare trusts both Bob and Alice, and Alice trusts Bob and Clare. Imagine that Bob is interested in bartering his apple in exchange for a banana and that Alice is interested in bartering her banana in return for an apple. As shown in the figure, bartering can be conducted only indirectly, for example, with Clare’s assistance (as opposed to peer–to–peer) who operates as a trade exchange (a broker) and for free.

One can imagine more elaborated scenarios for example where Alice, Bob and Clare have several items to barter and where the exchange is \( m \geq 1 \) for \( n \geq 1 \) and where Clare charges for her brokering service. Notice that this indirect barter model (see [22]) re–introduces a mediating party, however, in some applications, the flexibility facilitated by Clare can justify her involvement.

The scenario becomes more demanding when more parties are involved and where one would account for time constraints and exceptions such as potential failures of the parties to deliver their items as well as several additional variables and dimensions. The complexity becomes more challenging when the bartered items are complex (for example, electronic or electromechanical devices) that are expected to deliver a functionality and used under the observance of some rules, for example, to guarantee performance. A practical barter system would offer means of modelling tangible objects as digital objects (called tokens) that can be negotiated and bartered online.

### 3.3 Contribution of bartering to the economy

We believe that the facilities that decentralised technologies provide can help bring back the advantages offered by the ancient barter trade system:

- **peer–to–peer trade**: bartering obviates the involvement of fiat cash and consequently of banks in trade.
- **robustness**: bartering is robust, that is, immune to the financial threats that afflict fiat–based trade; this valuable characteristic emerges from its simplicity.
- **ad–hoc trade**: with a barter system in place and facilities to locate items and barterers online, ad–hoc bartering would flourish.
- **re–distribution of items**: re–introducing of pre–owned items to the economy. To some extent, this is already in practice in some countries like the UK through garage sales, flea markets, second hand marketplaces, auctions, antique fairs. A barter system would encourage the development of this segment of the economy as it would facilitate non–monetized exchange at any time.
– **resource sharing**: bartering will facilitate and encourage resource sharing as in the example of spectrum sharing mentioned above. In the tangible world, it would offer the underpinning technology to support services such as car and accommodation sharing.

– **reciprocal lending**: bartering can also facilitate the temporary exchange of items where the owners are interested only on lending their items, as opposed to parting with them permanently.

It is worth noticing that some of these features are central to Collaborative Consumption and Shared Economy—two emerging economic concepts that have the potential to reduce waste and environmental damage [23,24].

### 4 Research challenges

We suggest a peer–to–peer barter system that offers the necessary services to support the exchange of the items listed in Section 3.1 and others that are likely to emerge, in a decentralised manner. Such a systems would involve the exchange of items and related documents on a peer–to–peer basis. Barter operations that involve only digital items will be completed fully online. That is, Alice and Bob will use their devices to exchange the actual digital items, and if they wish to, related documents to record evidence of the transaction. In barter operations that involve tangible items, Alice and Bob will use their devices to exchange related documents. The exchanged documents might be actual contracts that the participants agree to execute manually or automatically after converting them into smart contracts and deploying them on blockchains.

In summary, the responsibility of the barter system is to offer the necessary services to assist barterers in:

– the exchange of the items, possibly electronically over Internet communication channels.
– the exchange of related documents.
– the deployment and execution of contracts that result from barter transactions.
– the prevention of the occurrence of disputes where the nature of the items makes dispute prevention feasible. On the contrary, the barter service needs to provide dispute resolution mechanisms.

The barter system should play a passive role, in the sense that it will get involved only when the barter transaction fails to complete smoothly. This will happen only occasionally as most of the barter transactions will be completed successfully between the participants. The implementation of such services will require solutions to several research questions. We will discuss those that we consider central.
4.1 Trust, agreements and legal contracts

Note that the exchange of items shown in Fig. 1 takes place without any documentation. This is suitable only when the two participants trust each other completely. This is realistic when the parties know each other or when the exchange is face-to-face and simultaneous to enable the parties to verify that the items are what they expect before accepting them. However, in the absence of trust, a barter transaction will involve the exchange of contracts that protect the participants from potential frauds; for example, a party delivering the wrong item, delivering too late or not delivering it at all. We believe that these situations will be also common. In Fig. 1, for example, Alice and Bob are likely to bring and use their mobile phones to sign and exchange an agreement to document their trade.

We anticipate agreements of different types. At one end of the spectrum we envisage an informal agreement where the participants exchange, along with the items, informal documents with some basic information about the barter operation, such as date and names of the participants and descriptions of the items. The salient feature of these agreement documents is that they do not need to be enforced as part of the barter operation; their role is merely prove that the barter operation took place.

At the other end of the spectrum we envisage situations where the barter operations are protected by legal contracts that are signed and exchanged, possibly before the exchange of the items takes place or during the operation. Such contracts will be expressed in a natural language (for example, in English) and stipulate some rights, obligations and prohibitions that the two parties are expected to honour after remotely signing them. The salient feature of the contracts is that they do not need to be enforced either manually or automatically. The manual enforcement option is the simplest and requires that the parties sign the contract, store it safely, for example, on their local disk and retrieve it only if one of the parties raises a dispute. The automatic enforcement option is more practical and more challenging but the technology to implement it has been available for decades [25,26]. We will elaborate on this point below.

**Automatic enforcement of barter contracts** The executable contract encodes the rules that the participants of the barter operation agree to observe. Two examples of rules that might appear in barter contracts are: “Alice and Bob are expected to send their items to each other immediately” and “Alice is expected to send her item to Bob by Friday midnight and Bob is expected to send his within three days after receiving Alice’s”. With automatic contract enforcement, failures to observe the rules will be detected and signaled by the contract, automatically. This requires that the text of the contract which includes rules like those above, is converted into executable code (written in a programming language), that is capable of monitoring and enforcing the contract with little or no human intervention. Automatic contract enforcement is far more demanding due to several associated problems, including the formal verification of the smart contract to confirm its logical consistency and its deployment. The technology
to address these challenges has been around for decades and is now more mature.

**Contract deployment** Good alternatives to deploy executable contracts are decentralised blockchain ledgers. The Bitcoin platform was a significant step in this direction. They demonstrated the use of smart contracts (a fancy name for executable contracts) in the implementation of Bitcoin. More complex (Turin complete) contracts can be deployed on the Ethereum ledger and the Hyperledger. An important hallmark of blockchains is that they offer middleware services for implementing decentralised applications such as decentralised barter smart contracts. The cost of decentralisation is the execution of consensus protocols among the smart contract instances deployed on the blockchain. The consensus protocol inflicts several scalability constraints that are hard to overcome such as transaction throughput, consistency, latency, and transaction fees. There are reports that Bitcoin and Ethereum have already experienced average transaction fees of 54.90 and 4.15 USD, respectively. There are other deployment alternatives that might help to circumvent these issues. For instance, in applications where decentralisation is not a priority, the designer can consider centralised deployment where the executable contract is deployed on a centralised trusted third party that offers a contract execution environment. Also, in applications where centralisation is unacceptable, the designer should consider hybrid deployment where the contract is split into two complimentary pieces: one of them in deployed on–chain and another one off–chain. Several hybrid approaches have been reported.

**Multi–party barter contracts** In general, a barter transaction can involve more than two parties, one or more items each (see Fig. 2). Since collective trust is more difficult to achieve than bilateral, these operations are likely to involve the exchange of contracts, or more precisely, of multi–party contracts. Multi–party exchange is more challenging than bilateral exchange; its complexity depends on the topology of the interaction (for example, start, ring, graph, etc.). Some protocols that facilitate multi–party exchange of items have been reported. However, they do not seem to be mature enough to be used in practical applications, for instance, they seem to work for some classes of items but not for others. Regarding contracts, one–to–one oblivious transfer was suggested in a pioneering article for signing contracts between two parties. Multi–party signatures are more challenging but they have been explored.

**4.2 Privacy-preserving bartering**

In some situations, barterers might wish (for the sake of privacy and business strategies) to conceal some details of their barter activities from counter parties and third parties. In contrast, in other situations (for example, to enhance the reputation of the barterer or the item) they might wish to make these details public. Examples of details are the identities of the barterers, offers, counter–offers,
agreed upon values of the items and historical records of barter transactions including unsuccessfully negotiated transactions. Mechanisms that help to conceal information might be needed at different stages of the barter process, including negotiation and enforcement of agreed upon contracts. We believe that Secure Multiparty Computation (SMC) in combination with zero-knowledge authentication techniques is a promising approach to address the problem.

The idea of SMC is that $N$ parties run a cryptography protocol that allows them to compute a function without relying on a TTP (Trusted Third Party) and without revealing to each other the input provided by each party. Recent works in barter protocols demonstrate that SMC can be utilized to create privacy-preserving barter protocols. In [46], the authors demonstrate how to create a privacy-preserving two-party barter system without relying on a TTP. The authors in [47,48] create a privacy-preserving protocol between two parties, where the barter quotes are kept private using homomorphic encryption. The protocol is secure against semi-honest adversaries. Wüller et al. [49] propose a two-party privacy-preserving barter protocol that is secure against active attackers and is based on threshold homomorphic cryptosystem.

Apart from two-party privacy-preserving protocols, there are research works that focus on multi-party protocols. Wüller et al. [50] suggested the first privacy-preserving multi-party barter protocol where each party creates a quote that includes the offered commodity and the requested commodity alongside the required ranges of the commodity. The quote is kept private from all the other parties. At the end of the barter protocol each party has learned nothing about the other parties’ trades. The authors use a threshold homomorphic cryptosystem to realize the multi-party barter protocol. Another recent proposal for multi-party privacy-preserving barter protocol uses differential privacy to achieve the privacy guarantees required in a barter-based economy [51]. This work requires the presence of a TTP to realize the barter protocol.

Regarding zero-knowledge authentication, the idea is that a party can prove its identity without leaking information to the challenger. The problem of these solutions is the high cost of running the zero-knowledge protocol and potential incompatibility problems when blockchains are involved [40]. These ideas are currently active research topics. Pioneering work is reported in [52] and [53], respectively.

### 4.3 Exchange of tangible items under privacy

The exchange of tangible items requires the physical presence of the participants. Consequently, the observance of privacy is challenging as it conflicts with the need to identify individuals. There are situations when the participants need to be identified to hold them accountable for their actions; for example, when the exchange of the items is not simultaneous and as result, one of the participants is expected to deliver his or her item later, for example, on the following weekend. A potential solution to address the issue is the Proof of Personhood (PoP) protocol suggested by Ford [54]. The PoP protocol provides individuals with
pseudonym certificates that protect their privacy but makes them accountable for their actions.

4.4 Fair Exchange

Central to bartering is the operation to exchange the items and possibly signed contracts (see Section 4.1). Depending on the properties of the items, the operation can be executed remotely and entirely automatically over electronic communication channels.

The challenge here is to develop protocols that guarantee fair exchange of both, the items and the signed contracts. Imagine that Alice owns item $I_A$ and Bob owns item $I_B$, that the two items can be transferred electronically and that they have agreed to barter them; to explain the definition of fair exchange let us assume that the exchange involves only the items. A fair exchange protocol run between Alice and Bob to exchange their items will guarantees only two alternative outcomes: either success or abort. If the exchange completes successfully, Alice is left in possession of $I_B$ and Bob is left in possession of $I_A$ and both assured that the received items satisfy certain properties and therefore can be accepted as valid. Conversely, if the protocol is aborted, Alice remains in possession of $I_A$ and Bob remains in possession of $I_B$ and neither Alice or Bob is revealed sensitive information that gives them some advantage. Fair exchange of contracts is similar: either Alice gets a contract signed by Bob and Bob gets a contract signed by Alice or the exchange is aborted. Fair exchange has been a topic of research interest since the 1990s [55] with the success of e-commerce. Though several protocols have been suggested [56,57], they are mainly based on the use of stateful trusted third parties that facilitate the exchange and help to solve disputes when they occur. The main advantage of using TTP-based protocols is that they are simple. However, though the inclusion of a stateful TTP is beneficial in some applications, its involvement brings several economic, privacy and security concerns [31]. To start with, the TTP charges for its service and might charge extra when it is required to solve disputes. Secondly, the TTP introduces delays. More worryingly, the TTP gathers significant amount of sensitive information about the transactions, consequently it introduces several risks: the TTP will delay the progress of the protocol if it becomes unreachable; also there is a risk that the TTP might abscond with the items, loose them or collude with one of the participants. Additional research is needed to devise fair exchange protocols that are able to exchange items on a peer-to-peer basis; that is, without the intervention of stateful trusted third parties and without the occurrence of disputes. Such protocols would facilitate the exchange of items of any value.

4.5 Taxation of barter transactions

One can argue that a barter transaction involves the transfer of income, but also of assets in exchange for assets; accordingly, the participants are subject to
tax on the realised gain. The observance of this regulation requires that barter transactions are reported to the government tax department for tax purposes.

Taxation of peer–to–peer barter transactions is extremely challenging because the government currently has no mechanisms to detect the occurrence of barter transactions immediately as in the case for currency–based transactions. In a strict peer–to–peer model, immediate report of barter transactions is at the discretion of the participants. However, barter transactions might become detectable by the government tax department later, for example, if a participant sells his or her item or barter it through indirect bartering or if a conflict between the participants arises. The deployment of mechanisms to report barter transactions immediately would compromise to a greater or lesser extent the peer–to–peer model. If this is acceptable, one can for example, delegate the responsibility of reporting the transaction to the trusted mediator that the fair exchange protocol used to exchange the items will inevitably involve [58] (see fair exchange bullet of Section 5). In this manner, the production and notifications of records for taxation purposes is integrated with execution of the transaction. For example, the trusted mediator can be programmed to delay the peer–to–peer exchange until it receives a proof that a transaction in progress has been reported to the government.

In the indirect barter model (see Section 3.2) the problem is simpler because it assumes the involvement of a trade exchange which acts as a trusted mediator. A simple solution is to delegate the responsibility of reporting barter transactions to the trade exchange. Once the transaction is in the government’s records, the government can apply the corresponding taxation rules required.

Tax collection from barter transactions is far more complicated than tax collection from currency–based transactions. The difficulty is that in a barter transaction, liquidity to pay the tax is absent and the valuation of the items traded may be unclear. Several approaches have been suggested that overcome the difficulties. For instance, the taxation can be deferred until the barterers sell the items. Another possibility is that, the government waives the taxation of transactions where the barterers are not making profit or seeking to make profit but contributing to the society to ongoing exchange; transactions that involve the exchange of gardening tools rescued from sheds fall within this category. These and other ideas are elaborated in [59]. This is, however, a difficult bar to integrate into a barter system due to some grey area of discerning whether and to what extent some or certain barter transactions can be considered to be the public interest or contributing to society. Nonetheless much still needs to be done to understand how to best integrate tax reporting requirements into barter transactions, but also to explore normative solutions to deal with tax issues, were bartering to become a widespread and adopted avenue for conducting business.

5 Further reading

– bartering: to the best of our knowledge, currencyless economy based on barter trade is a new concept. However, the concepts and its practice can be
traced back to the early days of human civilization. Some historic facts are mentioned in [60,61]. In [61] the authors analyse some disputes about the origins of bartering and point out that simultaneous exchange of items was unpractical and therefore less practiced than asynchronous delivery of the items. Cash as legal tender is discussed in Section 2. See also [62].

- **centralisation / re–decentralisation:** a motivating discussion of the reason and implications of the centralisation of the Internet and the advantages of reversing it, is presented in [63]. The same topic, but with a legal and technical view is discussed in [64] and [65], respectively.

- **contracts:** smart contracts and decentralised ledgers to deploy them are now widely documented. Satoshi’s Bitcoin paper [66] gets all the credits for triggering the now widely spread interest on descentralised technologies; complementary, the Ethereum yellow paper [67] brought the notion of smart contracts to the attention of the general public. Comprehensive and accessible discussions of these topics can be found in [68] and [69], respectively. The benefits of deploying smart contracts in a decentralised manner are several and valuable. That said, let us not forget that decentralisation inevitably brings complexity. In situations where centralisation is tolerable, the designer might favour simplicity and opt for centralised deployment of contracts on trusted third parties. This idea is suggested in [34] where the authors argue that full decentralisation is extremely difficult to achieve; non–surprisingly, all centralised platforms include some elements of centralisation.

For instance, to be certain about the authenticity of a server with whom a blockchain wish to interact, the blockchain would rely on a X.509 certificate issued by centralised authorities. Likewise, the use of oracles in some blockchains like Ethereum introduces some degree of centralisation. An executable contract is a piece of code written in a programming language; as such, it is likely to include bugs unless counter measures are taken [70,71,72]. To reduce the risk of deploying unsound smart contracts, designers need tools for conducting formal validation at design time by means of model checking complemented by systematic testing of the actual executable code. Model checking is aimed at uncovering typical errors that impact contractual clauses, such as contradictions, omissions, replications [73].

- **decentralised ledgers:** a decentralised ledger can be implemented on the basis of a blockchain data structure, but other data structures can be used to avoid or ameliorate scalability and other problems mentioned in Section 4.1. Trees and Direct Acycled Graphs (DAG) are examples of data structures that are currently under exploration. A notable example if the work being conducted by TODA [74]: they have build a distributed ledger on the basis of Merkle tries that does not suffer from scalability problems. Another distinguishing feature that makes TODA particularly attractive for implementing barter systems is its inherent notion of exchange of ownership that is implemented in their underlying protocol, as opposed to application level.

- **decentralised finance:** the recent rise of Decentralised Finance (DeFi) in the cryptocurrency space is related to our work. To some extent DeFi has some elements of bartering since it enables parties to exchange crypto tokens
in a peer–to–peer basis and in a decentralised manner. An early example of a DeFi system is Kybernet which facilitates the instant exchange and conversion of digital assets like cryptotokens and cryptocurrencies like Bitcoins and ETHs. More recent examples have proven to be more successful and, unfortunately, more complex. The DAI token has successfully maintained its ration to USD to about 1:1. Recent research focuses mainly on the vulnerabilities that DeFi has inherited from its underlying blockchain construct. A discussion of flash loan attacks is presented in the argument is that the security hole is caused by Ethereum’s “all or none” transaction execution model.

– **privacy:** in , the authors explore the SMC techniques to provide privacy in cryptocurrency transactions conducted on Hyperledger—a blockchain with support for permissioned access. Practical progress has been achieved in this direction. There are libraries for the implementation of APIs to basic SMC, for example, to create, send and evaluate garbled circuits .

– **fair exchange:** a good starting point to understand the relevance of fair exchange in bartering and e–commerce is Asokan’s PhD Dissertation which can be complemented by the concise summary of fair exchange protocols presented in . Fair exchange impacts payment for items using cryptocurrencies such as bitcoins. The lack of a central authority that can offer escrow services makes the exchange of the bitcoin for the item, extremely challenging. It has been proved that it is impossible to solve strong fair exchange without the inclusion of a trusted mediators. Traditionally, such trusted mediators have been implemented as conventional trusted third parties; recently, the availability of trusted hardware embedded in commodity devices has opened other possibilities.

6 Conclusions

We have made a case for a currencyless and cryptocurrencyless economy based on bartering. Bartering could offer an alternative to existing currency–centric traditional payment mechanisms, namely, cash, conventional banking and cryptocurrency. Bartering could complement and substitute them in a wide variety of instances.

We envisage both fully–fledged business entities and individuals bartering with each other online to exchange digital items, tangible items, services and on–line services. In most of these exchanges, transaction contracts (or least some informal documentation) will be used to regulate, outline and govern the transactions. Such contracts will be negotiated, signed, exchanged under privacy in a peer–to–peer manner and enforced online after deploying them by following centralised, decentralised or hybrid architectures depending on the requirements of the particular exchanges and their parameters.

Table presents a summary of the main features that distinguish existing trade models and bartering as suggested in our work. We believe that the four models can co–exist independently serving their segments of the economy, speculatively, as follows:
| Peer-to-peer | Cash | Conventional banking (deposits) | Cryptocurrencies | Bartering |
|-------------|------|--------------------------------|------------------|-----------|
| Privacy     | Yes  | No                             | Yes if protection protocols are used | Yes if protection protocols are used |
| Free from transaction fees | Yes  | No                             | No               | Yes       |
| Robust to financial uncertainties | No   | No                             | No               | Yes       |
| Online transactions | No   | Yes                            | Yes              | Yes       |
| Financial services (e.g., credit and escrow) | No   | Yes                            | No               | No        |

Table 1. Comparison of trade models.

- **Cash/currency**: is and will remain as the trade model for unbanked individuals who normally conduct small payments in cash that can be carried around. Also, it is a practical solution when the banking system is temporarily unavailable and where it is not deployed at all, for example, in remote rural communities. People reluctant to leave traces of their financial activities will also consider payments in cash.

- **Conventional banking**: will be used in situations where the traders wish to avail of the services that banks, as trusted intermediaries, offer. Examples of such services include credit, escrow services and signed evidence of the occurrence of the transaction.

- **Cryptocurrency**: will be a convenient alternative where the trade partners are reluctant to expose all the details of their transaction or of themselves to the bank and yet, they need to generate an indelible, publicly verifiable and ubiquitous record of the transaction. In practice, such records are needed to prove, without revealing unnecessary details, that a payment has been conducted and consequently the payer is able to claim the right to access a service.

- **Bartering**: will be a convenient trade alternative to save on fees and delays caused by mediating parties such as banks and blockchain ledgers. Also, bartering will be a convenient alternative to trade under strict privacy, in this regard, it is more convenient even than cash-based trade.

The trade models can combine their strengths and support each other. For instance, cryptocurrency deposits subject to conditional refunds (for example, Bitcoin’s conditional release of payment) can be used as monetary incentives at different stages of the barter process to discourage misbehaviour. For example, if a dishonest party deliberately delays or interrupts a negotiation process, the cryptocurrency deposit is refunded to the honest counterpart.
Most pieces of the technology (blockchain, decentralised smart contracts, centralised smart contracts, secure multiparty computation and zero-knowledge proofs, fair exchange protocols and so on) that are needed to implement a barter system are available but needs further development and integration. The main goal of this article is to enable and contribute to the discussion and motivate research in the direction of barter models and platforms in the everyday lives of individuals, businesses and other entities to drive efficiencies around cost, speed and privacy.

Acknowledgment

Thanks to Rafael Z. Frantz (Applied Computing Research Group, Universidade Regional do Noroeste do Estado do Rio Grande do Sul, UNIJUI) for proof-reading and commenting on a draft of this article. Ioannis Sfyrakis was supported by the European Research Council (ERC) Starting Grant CASCAd (GA n° 716980). Thanks to Melissa Metzger for the drawing of Fig. 1.

References

1. Intuit, Inc.: Barter system history: The past and present. [https://www.mint.com/barter-system-history-the-past-and-present](https://www.mint.com/barter-system-history-the-past-and-present) (2018)
2. Davies, R., Davies, G.: A comparative chronology of money monetary history from ancient times to the present day. [http://projects.exeter.ac.uk/RDavies/arian/amser/chronol.html](http://projects.exeter.ac.uk/RDavies/arian/amser/chronol.html) (2020)
3. Einzig, P.: Primitive Money. Eyre and Spottiswoode (1947)
4. McConaghy, T., Marques, R., Müller, A., Jonghe, D.D., McConaghy, T.T., McMullen, G., Henderson, R., Bellemare, S., Granzotto, A.: Bigchaindb: A scalable blockchain database. [www.bigchaindb.com/whitepaper/bigchaindb-whitepaper.pdf](http://www.bigchaindb.com/whitepaper/bigchaindb-whitepaper.pdf) (Visited 1 Nov 2017 2017)
5. Poon, J., Dryja, T.: The bitcoin lightning network: Scalable off-chain instant payments. [https://lightning.network/lightning-network-paper.pdf](https://lightning.network/lightning-network-paper.pdf) (January 2016)
6. WorldBank2017: The unbanked. [https://globalfindex.worldbank.org/sites/globalfindex/files/chapters/2017%20Findex%20full%20report_chapter2.pdf](https://globalfindex.worldbank.org/sites/globalfindex/files/chapters/2017%20Findex%20full%20report_chapter2.pdf) (2017) visited on 30 Jul 2020.
7. bitinfocharts: Cryptocurrency statistics. [https://bitinfocharts.com](https://bitinfocharts.com) (2018)
8. Decker, C., Decker, C.: Bitcoin transaction malleability and MtGox. [https://arxiv.org/pdf/1403.6676.pdf](https://arxiv.org/pdf/1403.6676.pdf) (August 2014) arXiv:1403.6676 [cs.CR].
9. Law, L., Sabett, S., Solinas, J.: How to make a mint: The cryptography of anonymous electronic cash. American University Law Review 46(4) (1996)
10. Clarke, S.T.A.D., McCorry, P.: Bitcoin: Perils of an unregulated global P2P currency. In: Proc. Security Protocols XXIII, LNCS 9379. (2015)
11. Liao, K., Zhao, Z., Doupé, A., Ahn, G.J.: Behind closed doors: Measurement and analysis of cryptolocker ransoms in bitcoin. In: Proc. APWG Symposium on Electronic Crime Research (eCrime). (2016)
12. Stinchcombe, K.: Blockchain is not only crappy technology but a bad vision for the future. [https://medium.com/](https://medium.com/) (Apr 2017) Visited on 8 May 2018.
13. Stinchcombe, K.: Ten years in, nobody has come up with a use for blockchain. [https://hackernoon.com/] (Dec 2017) Visited on 8 May 2018.
14. House of Commons: Food waste in england. Technical Report Eighth Report of Session 2016–17, House of Commons Environment, Food and Rural Affairs Committee (April 2017)
15. Build: Brits are hoarding £48 billion worth of unused household items. [https://www.build-review.com/2018-brits-are-hoarding-48-billion-worth-of-unused-household-items/] (2019) Visited on 25 Jul 2020.
16. Hyperledger: Using fabtoken. [https://hyperledger-fabric.readthedocs.io/en/master/token/FabToken.html] (2018) Visited on 20 Apr 2019.
17. Quoitin, B., Pelsser, C., Bonaventure, O., Uhlig, S.: A performance evaluation of bgp-based traffic engineering. International Journal of Network Management 15(3) (May/Jun 2005) 177–191
18. Braem, B., Blondia, C., Barz, C., Rogge, H., Freitag, F., Navarro, L., Bonicioli, J., Papathambisou, S., Eschirch, P., Viiñas, R.B., Kaplan, A.L., Neumann, A., i Bala-guer, I.V., Tatum, B., Matson, M.: A case for research with and on community networks. ACM SIGCOMM Computer Communication Review 43(3) (July 2013)
19. Lehr, W., Crowcroft, J.: Managing shared access to a spectrum commons. In: Proc. First IEEE Int’l Symposium on New Frontiers in Dynamic Spectrum Access Networks, (DySPAN’05). (2005)
20. Neagle, C.: Open and regionalised spectrum repositories for emerging countries: BeWiFi makes unused bandwidth in one household available to the neighbors who need it. [https://www.networkworld.com/article/2226220/it-s-getting-easier-to-steal-your-neighbors-unused-wi-fi-bandwidth.html] (April 2014) visited on 26 Jul 2020.
21. Scupola, A., Henten, A., Nicolajsen, H.W.: E-services: Characteristics, scope and conceptual strengths. International Journal of E-Services and Mobile Applications 1(3) (Jul/Sep 2009)
22. Keller, R.I.: The taxation of barter transactions. Minnesota Law Review 67(2229) (1983)
23. Botsman, R.: The rise of collaborative consumption. Aspire (Oct/Nov 2015)
24. Ertz, M., Durif, F., Arcand, M.: Collaborative consumption or the rise of the two-sided consumer. The International Journal Of Business and Management 5(6) (June 2016)
25. Szabo, N.: Smart contracts: Formalizing and securing relationships on public networks. First Monday 2(9) (September 1997)
26. Solaiman, E., Molina-Jimenez, C., Shrivastava, S.: Model checking correctness properties of electronic contracts. In: Proc. Int’l Conf. on Service Oriented Computing (ICSOC’03), Springer, LNCS vol. 2910 (2003) 303–318
27. Molina-Jimenez, C., Shrivastava, S., Strano, M.: A model for checking contractual compliance of business interactions. IEEE Trans. on Service Computing PP(99) (2011)
28. Bitcoin Project: Bitcoin: Bitcoin is an innovative payment network and a new kind of money. [https://bitcoin.org] (2019)
29. Ethereum Foundation: Ethereum: Blockchain app platform. [https://www.ethereum.org] (Visited 23 Oct 2017 2018)
30. Hyperledger: Hyperledger fabric. [https://hyperledger-fabric.readthedocs.io/en/release-1.1/] (2018)
31. Vukolić, M.: The quest for scalable blockchain fabric: Proof-of-work vs. BFT replication. In: Proc. Int’l Workshop on Open Problems in Network Security (iNet-Sec’15), LNCS Vol. 9591. (2015) 112–125

32. Decker, C., Seidel, J., Wattenhofer, R.: Bitcoin meets strong consistency. In: Proc. 17th Int’l Conf. on Distributed Computing and Networking (ICDCN’16). (2016)

33. Bailleis, P., Ghodsi, A.: Eventual consistency today: Limitations, extensions, and beyond. ACM Queue 11(3) (March 2013)

34. Molina-Jiménez, C., Sfyrikis, I., Song, L., Nakib, H.D.A., Crowcroft, J.: The benefits of deploying smart contracts on trusted third parties. https://www.researchgate.net/publication/332165550_The_Benefits_of_Deploying_Smart_Contracts_on_Trusted_Third_Parties (April 2019) Visited on 11 Aug 2019.

35. Molina-Jiménez, C., Sfyrikis, I., Song, L., Wong, M.W., Chun, A., Crowcroft, J.: Implementation of smart contracts using hybrid architectures with on and off–blockchain components. https://www.researchgate.net/publication/329561864_Implementation_of_Smart_Contracts_Using_Hybrid_Architectures_with_On_and_Off-Blockchain_Components (January 2019) Visited on 12 Apr 2020.

36. Molina-Jimenez, C., Solaiman, E., Sfyrikis, I., Ng, I., Crowcroft, J.: On alternatives to smart contract implementations. Technical Report CS–TR–1519, School of Computing Science, University of Newcastle (April 2018)

37. Eberhardt, J., Tai, S.: On or off the blockchain? insights on off-chaining computation and data. In: Proc. 6th European Conference on Service-Oriented and Cloud Computing (ESOCC’17). (2017)

38. Dorri, A., Kanhere, S.S., Jurdak, R.: Towards an optimized blockchain for IoT. In: Proc. IEEE/ACM Second Int’l Conf. on Internet-of-Things Design and Implementation (IoTDI). (2017)

39. Idelberger, F., Governatori, G., Riveret, R., Sartor, G.: Evaluation of logic–based smart contracts for blockchain systems. In: Proc. 10th Int’l Symposium RuleML’16: Rule Technologies: Research, Tools, and Applications, LNCS, Vol 9718. (2018) 167–183.

40. Zyskind, G., Nathan, O., Pentland, A.S.: Enigma: Decentralized computation platform with guaranteed privacy. https://arxiv.org/abs/1506.03471 (visited in Mar 2018) (Jan 2015) arXiv:1506.03471v1 [cs.CR].

41. Asokan, N., Schunter, M., Waidner, M.: Optimistic protocols for multi–party fair exchange. Technical Report RZ 2892 29/11/96, IBM (November 1996)

42. Franklin, M., Tsudik, G.: Secure group barter: Multi–party fair exchange with semi-trusted neutral parties. In: Proc. Financial Cryptography (FC’98), LNCS vol. 1465. (1998)

43. Even, S., Goldreich, O., Lempel, A.: A randomized protocol for signing contracts. Communications of the ACM 28(6) (June 1985)

44. Mauw, S., Radomirović, S.: Generalizing multi-party contract signing. In: Proc. Int’l Conf. on Principles of Security and Trust (POST’15), LNCS vol 9036. (2015)

45. Mohassel, P., Franklin, M.: Efficiency tradeoffs for malicious two-party computation. In: Proc. Int’l Workshop on Public Key Cryptography (PKC’06). (2006)

46. Friikken, K., Opyrchal, L.: PBS: Private bartering systems. In: Financial Cryptography and Data Security. (2008)

47. Förg, F., Mayer, D., Wetzel, S., Wüller, S., Meyer, U.: A secure two-party bartering protocol using privacy-preserving interval operations. In: Proc. Twelfth Annual International Conference on Privacy, Security and Trust. (2014)
48. Förk, F., Wetzel, S., Meyer, U.: Efficient commodity matching for privacy-preserving two-party bartering. In: Proc. Seventh ACM on Conference on Data and Application Security and Privacy, (CODASPY’17). (2017)

49. Wüller, S., Pessin, W., Meyer, U., Wetzel, S.: Privacy-preserving two-party bartering secure against active adversaries. In: Proc. 14th Annual Conf. on Privacy, Security and Trust (PST). (2016)

50. Wüller, S., Meyer, U., Wetzel, S.: Towards privacy-preserving multi-party bartering. In: Proc. Financial Cryptography and Data Security. (2017)

51. Kannan, S., Morgenstern, J., Rogers, R., Roth, A.: Private pareto optimal exchange. ACM Trans. Econ. Comput. 6(3–4) (October 2018)

52. Yao, A.C.: Protocols for secure computations (extended abstract). In: Proc. 23rd Annual Symposium on Foundations of Computer Science, (SFCS’82). (1982)

53. Goldwasser, S., Micali, S., Rackoff, C.: The knowledge complexity of interactive proof-systems. SIAM Journal on Computing 18(1) (1989)

54. Borge, M., Kokoris-Kogias, E., Jovanovic, P., Gasser, L., Gailli, N., Ford, B.: Proof-of-personhood: Redemocratizing permissionless cryptocurrencies. In: Proc. IEEE European Symposium on Security and Privacy Workshops (EuroS&PW). (2017)

55. N.Asokan, P.Janson, M.Steiner, M.Waidner: State of the art in electronic payment systems. Advances in Computers 53 (1997) 425–449

56. Pagnia, H., Vogt, H., Gärtner, F.C.: Fair exchange. The Computer Journal 46(1) (January 2003)

57. Ray, I.: Fair exchange in e-commerce. ACM SIGecom Exchange 3(2) (May 2002)

58. Pagnia, H., Gartner, F.C.: On the impossibility of fair exchange without a trusted third party. Technical Report TUD–BS–1999–02, Darmstadt University of Technology (March 1999) visited on 10 Jul 2019.

59. Elkins, D.: Taxation of barter transactions: Theory, combination transactions, interest-free loans. https://ssrn.com/abstract=2162754 (2012)

60. Intuit: Guide to the barter economy and the barter system history. https://www.mint.com/barter-system-history-the-past-and-present (2020) visited on 26 Jul 2020.

61. Strauss, I.E.: The myth of the barter economy. https://www.theatlantic.com/business/archive/2016/02/barter-society-myth/471051/ (February 2016) visited on 26 Jul 2020.

62. Goldberg, D.: The tax–foundation theory of fiat money. Economic Theory 50(2) (June 2012) visited on 4 Aug 2020.

63. Crowcroft, J., Tyson, G., Mortier, R.: Redhouse gases – a manifesto for re-decentralization. https://www.cl.cam.ac.uk/~jac22/out/redhouse-gases.pdf (April 2020) visited on 1 Aug 2020.

64. Rossi, E., Sorensen, C.: Towards a theory of digital network de/centralization. http://eprints.lse.ac.uk/102963/1/Rossi_towards_theory_of_digital_network_decentralization_published.pdf (June 2020) visited on 31 Jul 2020.

65. Wagner, E.: Design challenges in decentralization. https://simplysecure.org/blog/decentral-patterns (April 2018) visited on 8 Aug 2019.

66. Nakamoto, S.: Bitcoin: A peer-to-peer electronic cash system. http://nakamotoinstitute.org/bitcoin/ (Visited 13 Nov 2017) 2008

67. Wood, D.: Ethereum: A secure decentralised generalised transaction ledger byzantium version 69351d5–2018-12-10. https://ethereum.github.io/yellowpaper/paper.pdf (2018) Yellow Paper. Visited on 28 Feb 2018.

68. Antonopoulos, A.: Mastering Bitcoin. Second edn. O’Reilly (2017)
69. Antonopoulos, A.M., Wood, D.G.: Mastering Ethereum. O’Reilly (2019)
70. Luu, L., Chu, D.H., Olickel, H., Saxena, P., Hobor, A.: Making smart contracts smarter. In: Proc. ACM SIGSAC Conf. on Computer and Communications Security (CCS’16). (2016)
71. Bhargavan, K., Delignat-Lavaud, A., Fournet, C., Gollamudi, A., Gonthier, G., Kobeissi, N., Kulatova, N., Rastogi, A., Sibut-Pinote, T., Swamy, N.: Formal verification of smart contracts (short paper). In: PLAS’16. (2018)
72. Ahrendt, W., Pace, G.J., Schneider, G.: Smart contracts: A killer application for deductive source code verification. In: Principled Software Development. (2018)
73. Molina-Jimenez, C., Shrivastava, S.: Model checking correctness properties of a middleware service for contract compliance. In: Proc. 4th Int’l Workshop on Middleware for Service Oriented Computing (MW4SOC’09). (2009) 13–18
74. Gravitis, A., Goh, N., Toliver, D.: TODA primer. http://todaqfinance.net/TODA_Tech_Primer_v1.0.pdf (2019) Copyright TODAQ Holdings Inc. while paper.
75. Luu, L., Velner, Y.: Kybernetwork: A trustless decentralized exchange and payment service. https://whitepaper.io/coin/kyber-network (2017)
76. Makerdao: A better money. https://makerdao.com (2020)
77. Gudegon, L., Perez, D., Harz, D., Livshits, B., Gervais, A.: The decentralized financial crisis (2020)
78. Qin, K., Zhou, L., Livshits, B., Gervais, A.: Attacking the DeFi ecosystem with flash loans for fun and profit (2020)
79. Benhamouda, F., Halevi, S., Halevi, T.: Supporting private data on hyperledger fabric with secure multiparty computation. In: 1st IEEE Workshop on Blockchain Technologies and Applications (BTA’18). (2018)
80. Zhu, R., Huang, Y., Cassel, D.: Fool: Scalable on-demand secure computation service against malicious adversaries. In: CCS ’17, October 30-November 3, 2017, Dallas, TX, USA. (2017)
81. Huang, Y., Evans, D., Katz, J., Malka, L.: Faster secure two-party computation using garbled circuits. In: Proc. 20th USENIX Security Symposium. (2011)
82. Pinkas, B., Schneider, T., Smart, N.P., Williams, S.C.: Secure two-party computation is practical. In: Proc. 15th Int’l Conf. on the Theory and Application of Cryptology and Information Security: Advances in Cryptology (ASIACRYPT’09). (2009)
83. Goldfeder, S., Bonneau, J., Gennaro, R., Narayanan, A.: Escrow protocols for cryptocurrencies: How to buy physical goods using bitcoin. In: Financial Cryptography and Data Security - 21st International Conference, FC 2017, Revised Selected Papers, LNCS 10322. (2017)
84. Kumaresan, R., Bentov, I.: How to use bitcoin to incentivize correct computations. In: Proc. ACM SIGSAC Conf. on Computer and Communications Security (CCS’14). (2014)
85. Andrychowicz, M., Dziembowski, S., Malinowski, D., Mazurek, L.: Secure multiparty computations on Bitcoin. Communications of the ACM 59(4) (April 2016) 76–84