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Applications, limitations, costs, and benefits related to the use of blockchain technology in the food industry

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Report

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Summary/recommendation:

This report was commissioned to outline applications, limitations, costs, and benefits related to the use of blockchain technology in the food industry, and in particular to evaluate the pros and cons of having a blockchain-based food traceability system compared to a traditional electronic traceability system. The key concepts relating to traceability, and the components of a food traceability system are outlined in this report, as well as an indication of how traceability relates to other methodologies and approaches for ensuring food product authenticity. The core principles of blockchain technology are outlined, including different types of blockchain implementations, their characteristics, and some examples of solution providers and existing applications in the food industry. The last part of the report compares the functionality of traditional vs. blockchain-based food traceability systems, evaluates costs and benefits, and provides some practical advice on implementation issues, exemplified in the red meat supply chain and the herbs and spices supply chain.

The overall conclusion is that unless speed of operation or confidentiality are considered to be the most important characteristics of the traceability system, a blockchain-based implementation may be very suitable. The main benefit related to a blockchain-based food traceability system is that, at least for now, the blockchain-based systems are more homogenous than traditional electronic traceability systems, so interoperability between different blockchain-based systems is likely to be easier to implement than interoperability between different traditional electronic traceability systems. Lack of interoperability is one of —, or probably the biggest current obstacle preventing system-wide, farm-to-fork food product traceability, so this advantage associated with blockchain-based implementations is significant.

Summary/recommendation in Norwegian:

Rapporten gir en oversikt over konsepter og systemer relatert til sporbarhet i næringsmiddelindustrien, og gir også en grunnleggende innføring i blockchainteknologi. Tradisjonelle elektroniske sporbarhetssystemer basert på relasjonsdatabaser sammenlignes med blockchainbaserte sporbarhetssystemer, og fordeler og ulemper med de respektive løsningene evalueres.

Hovedkonklusjonen er at dersom hurtighet eller konfidensialitet er de viktigste systemegenskapene så er tradisjonelle sporbarhetssystemer sannsynligvis bedre. Hovednytten av blockchainsystemer er at de er likere i oppbygging og struktur, og at det derfor er lettere å dele og integrere data mellom bedrifter og mellom verdikjeder. Dette er en veldig viktig utfordring i næringsmiddelindustrien, da manglende integrasjon er en av de viktigste utfordringene som hindrer tilgang til data som registreres på ulike steder i kjeden, og nytteverdien av blockchainbaserte sporbarhetssystemer er signifikant dersom de kan bidra til å løse dette problemet.

Preface

This study was undertaken in response to a tender from the Food Fortress research programme which is part of the EIT Food Knowledge and Innovation Community (KIC) of the European Institute of Innovation and Technology (EIT). The tender was facilitated by -, and the report was delivered to Queens University Belfast, UK.

Abbreviations and acronyms used in this report

API	Application Programming Interface
BaaS	Blockchain as a Service
CoC	Chain of Custody
EAN.UCC	European Article Numbering — Uniform Code Council
EC	European Commission
EDI	Electronic Data Interchange
EIT	European Institute of Innovation and Technology
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FBO	Food Business Operator
GC-MS	Gas Chromatography–Mass Spectrometry
HPLC	High-Performance Liquid Chromatography
IPOA-IUU	International Plan Of Action to Prevent, Deter, and Eliminate Illegal, Unreported, and Unregulated fishing
IUU	Illegal, Unreported and Unregulated Fishing
KIC	Knowledge and Innovation Community
NIR	Near-InfraRed (spectroscopy)
NMR	Nuclear Magnetic Resonance
PBFT	Practical Byzantine Fault Tolerance
PoA	Proof of Activity
PoS	Proof of Stake
PoW	Proof of Work
SSCC	Serial Shipping Container Code
TRU	Traceable Resource Unit

Table of Contents

1 Background

Blockchain technology has existed since 2008 and it is expected that this technology will disrupt many traditional business sectors and models, in particular those that are virtual in nature; online banking is one such example. Blockchain technology will definitely have relevant applications also in the food industry, but there is no doubt that the blockchain suppliers are currently overselling their products and they are promising more than they can deliver. This report aims to disentangle hype from truth when it comes to the capability of blockchain technology to achieve traceability in food supply chains. It builds on the request by the EIT Food Knowledge and Innovation Community (KIC) to analyse two broad themes:

1. How does blockchain compare and contrast with alternative technologies and methodologies to achieve a similar outcome and what are the key selection criteria for deciding which technology to adopt?

2. What are the cost benefits and practical considerations of blockchain as applied to the food industry?

Section 2 explains the methodology followed by this study and Section 3 defines the core concepts used here. Section 4 gives an overview of providers of blockchain technology and briefly describes various applications of the blockchain technology in the food sector. Section 5 compares the functionality of traditional vs. blockchain-based traceability systems and examples of costs, benefits, and practical considerations in various supply chains and for authorities are presented in Section 6. Conclusions and recommendations are made in Section 7.

2 Methodology

This study employed a methodology that involved the conceptualization of key terms (Section 3) and a literature review of the application of blockchain technology in the food sector (Section 4). The conceptualisation of terms related to food traceability and electronic traceability systems was based on relevant scientific publications and reports in this area, in particular general publications that focused on defining terms and concepts. The conceptualisation of terms related to blockchain and blockchain technology was partly based on relevant scientific publications and reports in this area, and partly on online articles, white papers, and expert user opinions. This study is limited to application of blockchain technology in the (food) production industry and, as such, it does not analyse other possible applications of blockchain technology, of which there are many. The conceptualisation, and the subsequent literature review, forms the basis for the comparison of the functionality of traditional vs. blockchain-based traceability systems (Section 5) and the analysis of costs, benefits, and practical considerations relating to the use of blockchain technology in two food sectors (red meat sector and herbs and spices) and for authorities (Section 6).

3 Conceptual framework

3.1 Traceability and traceability systems

The following constitutes a short, and by no means exhaustive, primer on traceability terms and concepts. The terms and concepts outlined are the ones needed for comparing a traceability system based on blockchain technology with a traditional electronic traceability system.

3.1.1 Traceability concept, terms, and definitions

There are numerous definitions of traceability, most of them recursive in that they define traceability as “the ability to trace” without defining exactly what “trace” means in this context. An attempt to merge the best parts of various existing definitions while avoiding recursion and ambiguity was made by two of the authors of this report (Olsen & Borit, 2013):

Traceability
The ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications.

This emphasises that any information can be traced, that traceability applies to any sort of object or item in any part of the life cycle, and that recorded identifications need to be involved. “That which is under consideration” is normally a batch (i.e. a unit of food or material used or produced by a food business operator (FBO)) or a trade unit (i.e. a unit of food or material sold by one partner, transported to, and received by another FBO). In scientific literature, the common term for “that which is under consideration” is a Traceable Resource Unit (TRU) (Kim *et al.*, 1999). The TRU is then “the unit that we want to trace” or “the unit that we record information on in our traceability system”.

Internal traceability is the traceability within a link or a company. Internal traceability is the backbone of traceability in general; everything else depends on each company in the chain having good systems and good practices when it comes to recording all the relevant internal information. Chain traceability is the traceability between links and companies, and it depends on the data recorded in the internal traceability system being transmitted, and then read and understood in the next link in the chain. For an illustration of the relationship between internal traceability and chain traceability, see Figure 1.

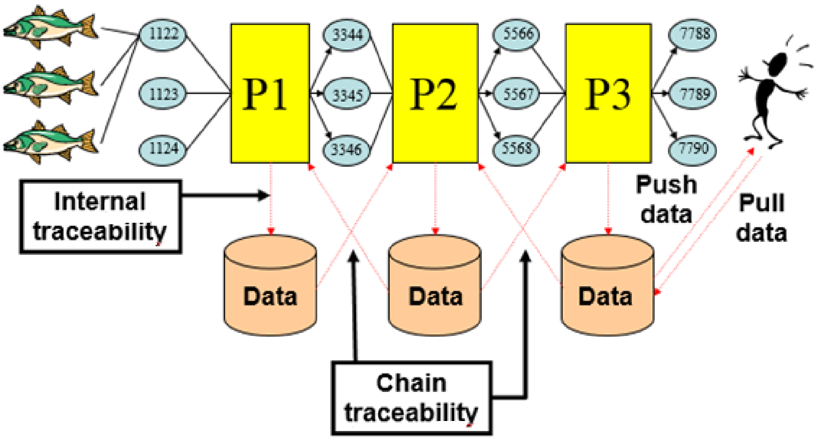


Figure 1 Internal versus chain traceability (TraceFood 2008)

3.1.2 Traceability systems and their components

For traceability, we want to “access any or all information relating to that which is under consideration”, so this means that the information recorded in the first link of the chain must somehow be made available in (or transported to) the next link of the chain. This is what the traceability system does; it makes sure that the recorded information is made available elsewhere and it is not lost. This means that if we want to describe or analyse the properties of a traceability system, we need to distinguish clearly between the following component types:

- The systems and processes that relate to the identification of the TRUs, which includes choosing a code, deciding on uniqueness and granularity of the code, and selecting how to associate the identifier with the TRU.
- The systems and processes that relate to the documentation of the transformations in the chain, which includes recording of the TRU transformations[1], the weights or percentages, and the related metadata.
- The recording of the attributes of the TRU, which can basically be anything that describes the TRU (e.g. attributes of the producing FBO, origin of the TRU, description of the TRU, measurements taken on the TRU, process parameters recorded when the TRU was produced etc).

The components of a traceability system are illustrated in Figure 2.

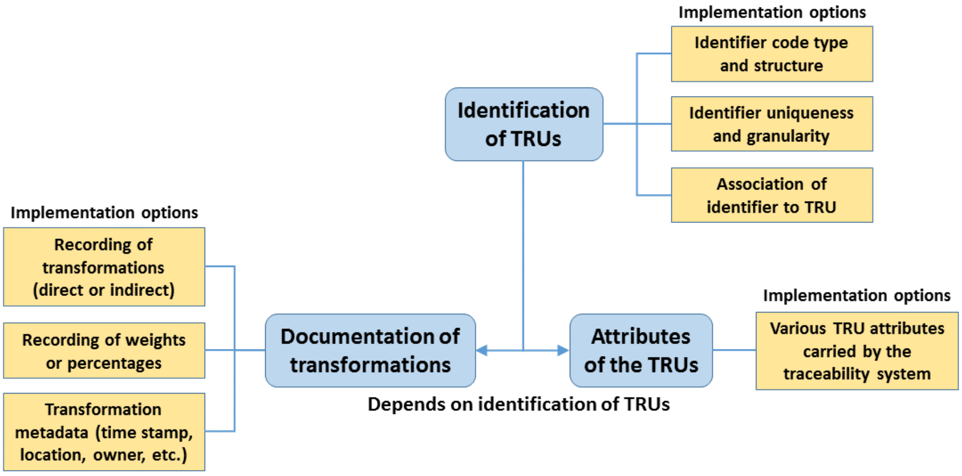

Implementation options
Identifier code type and structure
Identifier uniqueness and granularity
Association of identifier to TRU
Identification of TRUs
Implementation options
Recording of transformations (direct or indirect)
Recording of weights or percentages
Transformation metadata (time stamp, location, owner, etc.)
Documentation of transformations
Attributes of the TRUs
Implementation options
Various TRU attributes carried by the traceability system
Depends on identification of TRUs

Figure 2 The components of a traceability system (Olsen & Borit, 2018)

3.1.3 Drivers of traceability systems

Different purposes/drivers for implementing a traceability system trigger different expectations in producers and consumers that do not always correspond to the traceability system in use. Table 1 summarises different characteristics of traceability systems, including drivers for implementing these.

[1] A transformation is an instant or a duration of time where, at a given location, a process uses a set of inputs (TRUs) to generate outputs (new TRUs).

Table 1 Traceability systems: purpose/driver, objective, attributes, standard and example (Borit & Olsen, 2016).

Purpose/Driver	Objective	Attributes	Standard	Example
Safety	Consumer protection (through recall and withdrawal)	Specified in food & fish safety regulations	Mandatory Voluntary (1)	EU regulation US regulation
Security	Prevention of criminal actions (through verifiable identification and deterrence)	Specified in security regulations Verification of selected attributes on package and/or food	Regulatory (2) Voluntary (no common standard)	US Prevention of Bio-terrorism, regulation Brand & product protection
Regulatory quality	Consumer assurance (through recall and withdrawal)	Specific attributes included in regulations	Regulatory (3)	EC labelling, mandatory consumer information.
Non-regulatory quality & marketing	Creation and maintenance of credence attributes	Specific attributes included in public standards	Voluntary (common standard) (4)	Public Quality seals (e.g. Label Rouge, France) Organic fish, Eco- labelling
Food chain trade & logistics management	Food chain uniformity & improved logistics	Specific attributes required to food and services suppliers by contract	Private standards (4) Public standards for encoding information	Own traceability systems (e.g. Wal- Mart) EAN.UCC 128 (5), (e.g. with TRACEFISH (6) standard) SSCC (7)
Plant Management	Productivity improvement and costs reduction	Internal logistics and link to specific attributes	Voluntary (internal traceability; own or public standards)	From simple to complex IT systems.
Documentation of sustainability	Natural resource sustainability	Specified in environmental protection regulations	Mandatory Voluntary	EU IUU Regulation FAO IPOA-IUU (8)

(1) Recall and withdrawal can become compulsory if a responsible company does not take action.

(2) Includes the possibility of mandatory disposal, recall and withdrawal, legal and police actions but primary purpose is prevention.

(3) Includes the possibility of mandatory disposal, recall and withdrawal and administrative actions, but primary purpose is consumer assurance.

(4) Could include voluntary (contractual) recall and withdrawal and agreed (contractual) sanctions.

(5) GS1 System standardizes bar codes (www.GS1.com)

(6) TRACEFISH, "Traceability of Fish Products" (EC funded project) http://www.tracefish.org/

(7) SSCC: Serial Shipping Container Code (UCC)

(8) IPOA-IUU: I International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported, and Unregulated fishing

3.1.4 Traceability and analytical methods

An important realisation is that what is recorded in a traceability system are (largely unsubstantiated) claims about the food product in question, and that these claims might not be true, either because of errors or because of deliberate fraud. There are methods and instruments for testing the veracity of claims related to biochemical food properties and these claims are particularly relevant because of the potential food safety implications if an erroneous claim is made. These methods include DNA-based analyses, stable isotope and trace element analyses, analysis of lipid profiles, high-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), nuclear magnetic resonance (NMR) spectroscopy, near-infrared (NIR) spectroscopy, metabolite profiling, chemical profiling, proteomics, and many more. Collectively these methods are referred to as "analytical methods". What they have in common is that they analyse a food item sample and conclude with respect to the value of one, or a set of biochemical food item properties. Properties that to some degree can be verified by analytical methods include species, geographical origin (broadly), process status (e.g. fresh or frozen), presence of additives, some aspects of organic production, remaining shelf life, and some others, depending on the type of food item. While the list of food item properties that can be verified analytically is extensive and growing as the methods and technologies improve, it is worth noting that this is only a small subset of the properties recorded in a traceability system. Analytical methods cannot tell you who the owner of the TRU is, or the name of the farm or farmer, or the route the TRU took in the supply chain, or whether the production was ethical of fair trade, or similar. While practitioners and publications sometimes refer to these types of methods as "methods for traceability", that is inaccurate, at least in relation to most definitions of traceability (including the one chosen here), because they do not deal with "recorded identifications". What these methods can be used for is to verify some of the claims in the traceability system. It is important to keep in mind that a traceability system is made up of statements that are claimed to be true, but we do not know for sure that they actually are true, so that is something we need to check.

This means that analytical methods are very important when we are dealing with traceability, but these methods do not in themselves provide traceability. What they do provide is a way of verifying most of the claims relating to biochemical attributes of the food item in question. While these claims are only a subset of the total number of claims in a traceability system, they are among the most important ones, because if there is a food safety problem related to a food item, it will be detectable through application of analytical methods, and food safety, as we have seen, is a strong driver for implementing a traceability system.

3.1.5 Traceability and chain of custody

"Chain of custody" (CoC) is a term related to — , and sometimes confused with traceability, and in this report it is useful to clarify the distinction between the terms. CoC encompasses the responsibility for, and control of inputs and outputs as they move through each step in the relevant supply chain, and a chain of custody system is the set of measures designed to implement a CoC, including documentation of the measures taken. There are several different models for implementing CoC systems, including identity preserved, segregation, and mass balance, but to describe each of these is beyond the scope of this study. The main differences between traceability and CoC are summarised in Table 2.

Table 2 Main differences between traceability and chain of custody (CoC) (after (Borit & Olsen, 2016))

	Traceability	Chain of custody (CoC)
Objective	To associate recorded data with TRUs; to document what happens	To prevent mixing that violates the CoC requirements; to document that no such mixing has occurred
Of what?	Anything	With respect to some particular property which the CoC is in relation to, often origin or ecolabel status
The traced unit	A batch or a trade unit (the TRU)	The units with the same CoC identifier
Mix/join units	Yes, but must be documented	Only the units with the same CoC identifier
After mix/join	New unit and new identifier created	Considered same unit and receiving the same CoC identifier

3.1.6 Traceability and transparency

Being directly linked to trust building among stakeholders, transparency is a critical element in risk communication (Hofstede, 2004; Renn, 2008). Transparency of a supply chain is the degree of shared understanding of —, and access to product-related information as requested by a supply chain's stakeholders without loss, noise, delay, or distortion (Hofstede, 2004). Nevertheless, transparency and traceability are not the same thing, because the latter only sets the framework for the former (Egels-Zandén *et al.,* 2014). A good traceability system can provide product-related information to stakeholders with little loss, noise or delay, but when it comes to distortion one has to remember that a traceability system basically contains mostly unverified claims, and if we want transparency, we also need some mechanisms for verifying the data (see Section 3.1.4). A traceability system can provide a coherent overview of all the raw materials, ingredients, transformations, processes, and products in the supply chain and one cannot really have transparency without traceability, but for transparency some other components are needed as well. While the concept of traceability is quite generic and could be summarised as "keep a record of what you are doing in the chain", transparency has a specific application and target audience in mind (e.g. general public vs. decision-makers).

3.2 Blockchain and blockchain technology

3.2.1 Blockchain definition

A blockchain is type of database that contains a digital recording of the history of some transactions. While databases and database systems come in a wide variety of structures and architectures, the blockchain data structure is more narrowly defined and blockchain systems have several features that set them apart from traditional digital ledgers or relational databases. Blockchain systems are normally distributed across a network of computers, thus not centrally managed, and the transactions within a blockchain are shared among all the participants of the blockchain network. The transactions are checked and validated through a consensus mechanism before they become part of the blockchain, and consensus is required so all the blockchain participants agree on the 'truth' of the blockchain, that is, the blockchain that contains all the valid and executed transactions. By linking transactions cryptographically to previous transactions, data immutability is secured; meaning that changing or tampering with the data becomes (practically) impossible. One of the main advantages of a blockchain is that transactions can be traced back all the way to the start of the blockchain, so that it can provide info of an asset on the blockchain and inform how this asset has originated and changed over time. Figure 3 shows a graphical representation of how a blockchain system can work; from creating a transaction, to validating that transaction, to finally appending the transaction to the blockchain.

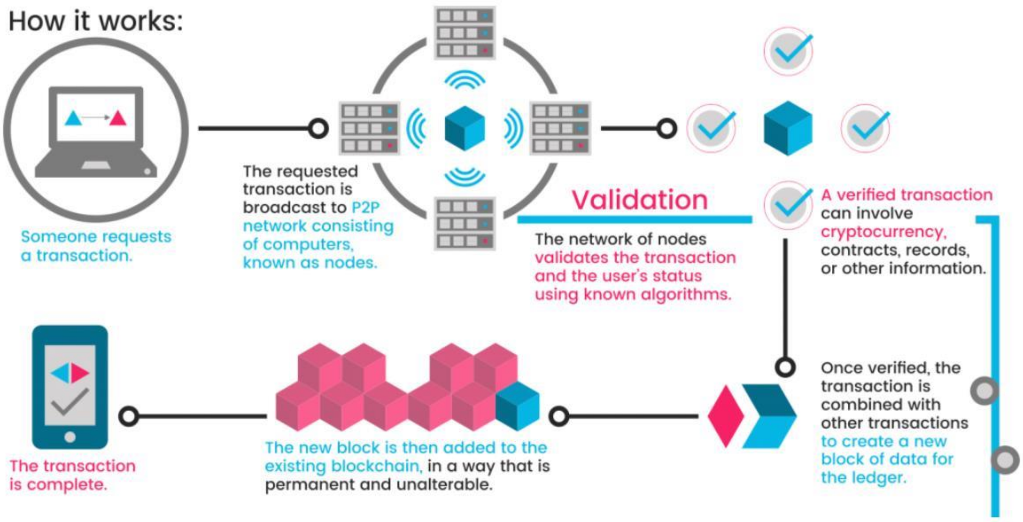

How it works:
Someone requests a transaction.
The requested transaction is broadcast to P2P network consisting of computers, known as nodes.
Validation
The network of nodes validates the transaction and the user's status using known algorithms.
A verified transaction can involve cryptocurrency, contracts, records, or other information.
Once verified, the transaction is combined with other transactions to create a new block of data for the ledger.
The new block is then added to the existing blockchain, in a way that is permanent and unalterable.
The transaction is complete.

Figure 3 Graphical representation of a blockchain system (Blasetti, 2017).

Normally, blockchain implementations are based on five basic principles that underly its technology (Lansiti & Lakhani, 2017), see list below. However, while the blockchain technology is typically viewed from the perspective of a public blockchain — and commonly tied to its use in cryptocurrencies — it does not mean that the blockchain technology is exclusively tied to the characteristics found in such systems.

1. **Distributed database**
    a. Each user in the network has access to the full database and all its transactions.
    b. No single user controls the database.
    c. Every user can verify the transactions directly.
2. **Peer-to-peer transmission**
    a. Communications between users in the blockchain happens directly without the use of an intermediary.
    b. Each user stores and broadcasts information to the full network.
3. **Transparency with pseudo-anonymity**
    a. Every transaction on the blockchain is visible to anyone who has access to the blockchain.
    b. Each user has a unique address (typically a public-key) that identifies them.
    c. Users can be anonymous or can choose to reveal their identity.
    d. Transactions occur between user addresses.
4. **Irreversibility of records**
    a. Once a transaction is stored into the blockchain it cannot be altered.
    b. Transactions within blocks are linked to other blocks.
    c. Algorithms are used to make sure transactions are recorded permanently, are chronologically ordered, and are available to all users on the network.
5. **Computational logic**
    a. Blockchain transactions can be tied to computational logic and can thus programmed.
    b. Users can set up algorithms to trigger transactions between nodes.

Care should be taken when looking at the usability and applicability of the blockchain technology. In many cases, the advantages of the blockchain technology are almost always linked to public blockchains, such as found within the bitcoin cryptocurrency blockchain. The blockchain technology, as proposed by Satoshi Nakamoto (Nakamoto, 2008) (the inventor of the bitcoin cryptocurrency), is an open source technology. Anyone can fork the code and alter it according to his or her own use case. For instance, developing a blockchain technology for a restricted set of users would change the technology into a more centralised ledger system. Since the inception of blockchain, one of the core promises of blockchain technology has been decentralisation. However, as the technology matures many have come to acknowledge that there must be trade-offs in practice—even calling decentralization a myth. No business can be fully centralised or decentralised without compromising in another area such as security, privacy, performance or scalability. This is an important consideration when determining the best blockchain approach for any use case. Understanding the differences between public and private blockchains is crucial to understanding the kind of trade-offs necessary to consider when developing a blockchain solution.

3.2.2 Blockchain characteristics

Blockchain implementations normally have the following four main characteristics: decentralisation, persistency, anonymity, and auditability (Zheng *et al.,* 2017; Wang *et al.,* 2018).

Decentralisation
In a traditional centralised transaction system, each transaction needs to be validated by a central trusted agency, such as a bank. Validation is required to make sure transactions are authenticated. This validation process can result in cost and performance bottlenecks at the central servers. With blockchain technology, transactions within the blockchain network can be performed between two users without the need for authentication by a single central authority or agent. In doing so, blockchain can reduce the server costs and mitigate the performance bottlenecks at the central server.

Persistency
Each transaction that is broadcasted throughout the blockchain network needs to be confirmed and recorded in blocks that will then be distributed to the whole network. As a result, any node in the blockchain network will have a copy of the blockchain. This also means that any node will validate the block and check the validity of the transactions it contains, making tampering of the data (nearly) impossible. Falsification of data, in terms of inconsistencies with existing blocks, can easily be detected.

Anonymity
Users interact with the blockchain network by using a generated address. This address is completely removed from a physical address, or an address tied to a specific user account. Blockchain users can, effortless, create a multitude of accounts, avoiding any form of identifying exposure. A high degree of privacy is achieved when creating blockchain transactions, although a perfect privacy preservation has been shown to not be possible. For instance, public keys, transactions, and therefore balances are visible to the whole network resulting in some form of identity detection (see (Meiklejohn *et al.,* 2013; Kosba *et al.,* 2016)).

Auditability
All transactions on the blockchain are validated and recorded with a timestamp. This makes it possible to check the veracity of previous records and verify existing ones as the history of transactions all the way up to the genesis block (first block of transactions) are maintained and accessible. This characteristic of the blockchain improves traceability and transparency of the data stored in the blockchain by ensuring that information once recorded is never overwritten or lost.

3.2.3 Blockchain types

Public vs. private vs. consortium/federated blockchain architecture

General considerations
Currently, the blockchain system can be categorised into three types: (1) public blockchain, (2) private blockchain, and (3) consortium or federated blockchain (sometimes also referred to as hybrid blockchains). This section describes some differences between the three types of blockchains from a more general perspective.

Public blockchains
Public blockchain protocols based on the 'proof of work' consensus algorithms are open source and not permissioned. This means that anyone can download the public blockchain technology and start

running a public node on his or her local device, validate transactions within the network, and participate in the consensus process (the process of creating new blocks that are then added to the blockchain) without permission. Anyone can also send transactions to the blockchain network, and if valid, can see them stored permanently in the blockchain. In addition, anyone can read the transactions listed on the blockchain, for instance with a public block explorer. Typically, these transactions are anonymous or pseudo-anonymous.

Examples of public blockchains are Bitcoin (bitcoin.org), Ethereum (ethereum.org), Monero (monero.org), Dash (dash.org), Litecoin (litecoin.org), and Dogecoin (dogecoin.com). Public blockchain technology has the potential to disrupt current business models through disintermediation. In addition, there is no need to maintain servers or system admins, which radically reduces the costs of creating and running decentralised applications.

Consortium or federated blockchains

Consortium or federated blockchains are typically managed by a group of people, entities, or trusted authorities. In essence, joining the blockchain network is restricted and it is only granted to a selected set of nodes. This is one of the main differences when comparing it to a public blockchain, where any person with access to the Internet can participate in the process of verifying transactions and creating new blocks. Consortium blockchains are faster (higher scalability) and provide more transaction privacy. Such blockchain types are typically used in the banking sector. The consensus process is controlled by a pre-selected set of nodes; for example, one might imagine a consortium of 15 financial institutions, each of which operates a node and of which 10 must sign every block in order for the block to be valid. The right to read the blockchain may be public or restricted to the participants.

Examples of consortium blockchain are R3 (Banks), EWF (Energy), B3i (Insurance), and Corda. Successful implementations of consortium blockchains can reduce transaction costs, reduce data redundancies, replace legacy systems, simplify document handling, and create full compliance mechanisms. There is still debate whether consortium blockchains systems can actually be defined as a blockchain.

Private blockchains

A private blockchain is regarded as a centralised network since it is fully controlled by one organization. With private blockchains, write permission to the blockchain is commonly kept centralised to one organisation. Reading the blockchain may be (partly) public or restricted to a selected few; for example, by being invited to join the network or having granted access. A private blockchain is almost always a permissioned blockchain. Private blockchains are thus highly restricted. The access control mechanism can vary, for instance, existing participants can invite new members, a regulatory authority can issue a license to participate, or a group of members can make such decisions. Private blockchains are a way of taking advantage of blockchain technology by setting up groups and participants who can verify transactions internally. In contrast to public blockchains, members who control the blockchain are at risk for security breaches, similar to a centralised system. Private blockchains have their uses in scalability, state compliance of data privacy rules, and other regulatory issues. Examples of private blockchains are MONAX and Multichain. Private blockchains, similar to consortium blockchains, are argued not to be proper blockchains.

Comparison of the blockchain types

A comparison between the different types of blockchains is a challenging one, especially since the technology has not yet matured and important classification criteria are not yet established. The three types of blockchains are compared here based on six criteria: consensus determination, read permission, immutability, efficiency, centralisation, and consensus process.

Consensus determination

Consensus determination relates to the validation of a new block—including all its transactions—and demonstrates to the blockchain network that some form of block validation has been established. A consensus is required to allow the full network to accept the new block and its transactions into the blockchain, and it creates a starting point from where subsequent new blocks can build upon. In a public blockchain, each node could take part in the consensus process, there is no entry requirement to mine blocks. Within a consortium blockchain, only a selected set of nodes are responsible for validating new blocks, typically nodes that have been granted some form of authority or trust. Within private blockchains, one organisation or trusted authority is fully responsible for validating the blocks and the underlying consensus mechanism.

Read permission

Read permission relates to the visibility of the transactions within the blockchain. Within a public blockchain, anyone can view the transactions; from the first all the way up to the latest. There is no restriction in terms of reading the transactions. However, with private or consortium blockchains, the read permission is regulated and can be constructed in a variety of ways. For instance, only some transactions are visible to everyone or some transactions are visible to some users. Read permissions are up to the trusted authorities who maintain the blockchain.

Immutability

Immutability relates to the ability of transactions or values within the blockchain being altered or tampered with. For example, a value x of transaction y in block z will be changed to a different value. The public blockchain technology is often characterised for its high degree of immutability since transactions are stored in different nodes in the distributed network, which makes it nearly impossible to tamper with a public blockchain. One of the current trends in mining blocks within a public blockchain, for example with the bitcoin cryptocurrency blockchain, is that miners join their computational power in mining pools, which, when they have more than 51% of the computational power of the network, could potentially endanger the immutability of the whole blockchain network. For private and consortium blockchains, immutability is low since the majority of block validators can easily reverse or tamper with the blockchain if they choose to do so.

Efficiency

Efficiency relates to the handling of transactions and blocks within the blockchain network, or simply put, how the flow of data propagates throughout the network. Within a public blockchain, the propagation or broadcasting of transactions and blocks takes more time, typically because there are more nodes in the network. When taking network safety into consideration, restrictions on public blockchain would be much more strict. As a result, transaction throughput is limited and the latency is high. Within consortium and private blockchains, the small number of validators could make data propagation more efficient.

Degree of centralisation

A centralised network relates to control that is carried out by a single entity, for instance, a trusted party. The main difference between the three types of blockchain types is that a public blockchain is fully decentralised; meaning that no single authority handles or controls the blockchain network. The consortium blockchain is partially centralised and private blockchain is fully centralised as it is controlled by a single group.

Consensus process

The consensus process relates to the process whereby new blocks and its transactions are validated and are appended to the existing blockchain. This 'new' validated block becomes the starting point from where subsequent new validated blocks will be linked to. The validation process is the consensus process, and the mechanisms behind the process itself can take on many variations, which will be described later on. Within a public blockchain, anyone can join the consensus process and start validating blocks. There is no entry requirement other than hardware to be able to execute the validation mechanism (such as solving computational puzzles). In contrast, with a consortium and private blockchain, participating in the consensus process is restricted; a permission is required to join the process. Since the consensus process determines what new transactions are being entered into the blockchain, within a private and consortium blockchain, typically a validation node needs to be certified to take part in this process.

A summary of the three blockchain types with their six characteristics is given Table 3.

Table 3 Overview of blockchain types

	Public	Consortium/Federated	Private
Consensus determination	everyone	selected (few)	single authority
Read permission	public	public, partly public, restricted	public, partly public, restricted
Immutability	nearly impossible	possible with majority of validators	possible
Efficiency	low	high	high
Centralised	no	partially	yes
Consensus process	permissionless	permissioned	permissioned

It is important to note that when choosing a specific type of blockchain it does not necessarily mean that one is better than the other. In other words, what might work for one might not necessarily work for another. The implementation of the blockchain type is highly case dependent. Presently, there are no real standards to measure the quality of the blockchain against, which would also mean that relying on the blockchain vendor's pros and cons might not necessarily paint the right picture. Other criteria not mentioned above might include governance, trust, and resources aspects of the blockchain. In essence, the choice for a type of blockchain would for a large part depend on (1) who is allowed to participate in the blockchain network and execute the consensus protocol, and (2) who is able to view of the content of the blockchain, such as the transactions.

Consensus mechanism

In blockchain, a consensus mechanism is required to enable the nodes in the blockchain network to decide on which new transactions to add to the blockchain. This means to decide what the new and updated version of the blockchain will be, or more specifically, what new blocks will be added to the chain. In a (public) blockchain, typically all nodes are seen as untrustworthy nodes, and to reach consensus within the blockchain the problem can be framed as a version of the so called Byzantine Generals problem. In short, the Byzantine army consists of different groups of generals with their soldiers surrounding a city. The generals, even though they are all surrounding the same city, are not in the same place. To successfully attack the city, all generals must attack the city. Thus, an attack would fail if only a part of the generals attack the city. Generals can communicate through messengers and they need to reach an agreement whether to attack or not. The problem is that some of the generals might be traitors and they can send different messages to different generals. This scenario can be seen as a trustless environment and the challenge is to reach consensus among the generals. The Byzantine Generals problem is analogous to a (public) blockchain network, where nodes in the network need to agree on the state of the ledger; agreeing on one version of the ledger. Various protocols to reach consensus are developed, which are described below (Zheng *et al.,* 2017).

Proof of work (PoW)

Proof of work (PoW) is the consensus mechanism used within the public bitcoin blockchain. PoW provides a way to ensure that some computational work has been performed to validate transactions and to allow the new block to be appended to the blockchain. In essence, the computational work involves solving a cryptographic puzzle that takes time and computing power to solve. Once the puzzle is solved, other nodes within the network can easily verify the answer. Technically, the cryptographic puzzle is calculating a hash value of the transactions that make up the new block. Why solving a puzzle? It provides a mechanism to make sure transactions are valid, and that bitcoin 'money' is not spent twice, this is the double-spending problem. By making sure some form of computational work has been put into a new block, thus making sure that there is only one version of the ledger, blocks that contain invalid or false transactions cannot quickly be added since it required much computational power to validate the block with the answer of the cryptographic puzzle. The nodes that calculate such puzzles are called miners, and they are the ones responsible for bundling transactions into blocks, and adding those blocks to the chain of previous blocks (hence the blockchain).

One of the major downsides of the PoW consensus mechanism is the enormous amount of energy used by the computers in the network to solve the cryptographic puzzle. In addition, since the cryptographic puzzle is difficult to solve, it takes time to validate/create and append new blocks to the blockchain. Though this ensures that no invalid blocks are quickly added to the blockchain, in a consortium or private blockchain there is no need for such delay of block creation. The number of nodes in non-public blockchains is typically an order of magnitudes lower, and there is usually direct network visibility. Slowing down the creation of new blocks through PoW is not required or not to that level to achieve stability.

In private and consortium blockchains, the identities of members are known. There is a restriction on participation, execution of the consensus mechanism, and maintaining the shared ledger. There is no incentive to motivate nodes to join the network and to perform mining (miners in public blockchains such as bitcoin are rewarded by some value of the cryptocurrency, which is absent in blockchains not build around cryptocurrencies). Because members are not anonymous and networks are usually not exposed to hostile public internet environment, the requirements on the cost of immutability are weaker. The blockchain does not have to be guarded by the enormous cost of energy. For immutability integrity through the hash chain and shared distributed ledger is usually sufficient. Differences in the environment and known identity of network participants along with their defined roles remove the need for the high-cost protection through the PoW mining. Typically, more emphasis is put on transaction throughput, fault tolerance, overall efficiency and restriction of access to the blockchain data. These differences make PoW unsuitable for a consortium or private blockchain, especially when high throughput of transactions is wanted. In addition, the enormous waste of energy resources associated with PoW resulted in the development of other consensus mechanisms, such as proof of stake (PoS), delegated proof of stake (DPoS), and Practical Byzantine Fault Tolerance Algorithm (PBFT). We describe the workings of PoS, DPoS, and PBFT below, including a variation of PoW and PoS called proof of activity (PoA).

Proof of Stake (PoS)

One of the most common alternatives to PoW is called proof of stake (PoS). PoS eliminates the need to buy expensive and powerful computer hardware to solve cryptographic puzzles in a short amount of time. The PoS miners, who are called validators, are investing in coins of the system. The coins within the system exist from the creation of the blockchain and are not rewarded by mining blocks. Instead, blocks are simply validated. Validators can be seen as stakeholders, hence the word “stake” in the name. The incentive to validate blocks comes only from the transactions fees linked to the transactions, and no ‘coin’ is created when building the new blocks. Such systems can be seen as performing virtual mining.

The blockchain network selects, based on the amount of stake a member is willing to put into the system, an individual to confirm the validity of the transactions and the creation of the new block. Validators who place (proportionally) more stake are more likely to be chosen to create and append the new block to the blockchain. This is one of the main differences compared to the PoW mechanism. There is no need to solve computational puzzles as quickly as possible, but instead, the system decides who can solve the computational puzzle (without the need to outrace other miners). Once a validator has been selected and the block validated, typically the other validators in the network will perform some check to ensure the block can be appended to the blockchain. Different proof-of-stake systems vary in how they handle this. There are some implementations where every node in the system has to sign off on a block until a majority vote is reached, while in other systems, a random group of signers is chosen. Validators who want to forge the system risk losing their stake, which is typically much higher than the reward obtained from all the transactions fees. Rather than calling the validation process mining, it is called minting within PoW.

It may appear that PoS is a reasonable replacement for PoW as it eliminates the need for massive amounts of computational power. With PoW, although initially started as fully decentralised (many individual nodes), it slowly moved into the direction where many nodes act as groups, known as pools, making the consensus mechanism less decentralised. PoS mitigates this effect and can largely be operated decentralised. However, there are similar problems found in PoS that need to be solved first before the consensus mechanism can largely be adopted by a blockchain system. When evaluating the way PoS works with regards to security, the common questions that could arise would be the following: What is to discourage a validator from creating two blocks and claiming two sets of transaction fees? And what is to discourage a signer from signing both of those blocks? This has been called the ‘nothing-at-stake’ problem. A participant with nothing to lose has no reason not to behave badly. Additionally, since the chance of validating a block increases with the amount of stake invested, those who can afford to invest more stake can potentially end up receiving rewards more often. This causes the system to become more centralised, a drawback as similar to the centralisation by mining pools with the PoW mechanism.

A variation of PoS is called delegated proof of stake (DPoS). The major difference between PoS and DPoS is that there is an overarching entity to represent the participant's stake. In other words, participants can now collectively increase their portion of the stake, thereby creating a mechanism to help balance out the power of large stakeholders.

Practical Byzantine Fault Tolerance (PBFT) algorithm

The Practical Byzantine Fault Tolerance (PBFT) algorithm is a mechanism to solve the problem traditionally known as the Byzantine Generals problem (described earlier), and inherently found in distributed systems with trustless participants. In short, each 'general' maintains an internal state (ongoing specific information or status). When a 'general' receives a message, they use the message in conjunction with their internal state to run a computation or operation. This computation, in turn, tells that individual 'general' what to think about the message in question. Then, after reaching his individual decision about the new message, that 'general' shares that decision with all the other 'generals' in the system. A consensus decision is determined based on the total decisions submitted by all generals. Three examples of blockchains that rely on the PBFT for consensus are Hyperledger, Stellar, and Ripple. One of the advantages of a PBFT consensus mechanism is that it requires less effort in term of computational work.

Proof of Activity (PoA)

Proof of activity (PoA) is a hybrid consensus mechanism that combines proof of work with proof of stake. Mining the blocks is performed in the traditional PoW way, with the exception that the block does not contain any transactions (although this depends on the type of implementation). The race to solve to cryptographic puzzle still exists with accompanying need for computational resources. When the puzzle is solved, the system switches to proof of stake. Random validators are chosen to sign the new block, with those who own more stake have a higher chance of being selected to sign it. After the block has been signed it becomes part of the blockchain and fees are split between the miners and validators who signed off on the block. The downsides of PoW (high energy costs due to enormous computational power) and PoS (double signing of blocks) still exists.

3.2.4 Permissioned vs. permissionless

Permissionless

A permissionless blockchain is a blockchain where no permission is required to read the blockchain, to make transactions to the blockchain, and to validate or mine blocks. A permissionless blockchain can also be viewed as a public blockchain, with the Bitcoin blockchain network being the most popular example. A major advantage of a permissionless (or public/open) blockchain network is that guarding against bad actors is not required and no access control is needed. This means that applications can be added to the network without the approval or trust of others, using the blockchain as a transport layer.

Permissioned

Permissioned blockchains are blockchains where a permission is required to join the blockchain, to have a copy of the blockchain, and in some cases, to be able to validate blocks. Examples of permissioned blockchains are for instance Hyperledger and R3 Corda. Permissioned blockchains use an access control layer to govern who has access to the network. In contrast to public blockchain networks, validators on private blockchain networks are trusted parties chosen by the network owner. There are no anonymous nodes that validate transactions nor nodes that receive mining rewards.

Permissioned blockchains do rely on a consensus mechanism to make sure new blocks on the blockchain are validated and that there exists only one version of the truth. The consensus protocol comprises of three basic steps: (1) determine whether to accept or reject a transaction, (2) sort all transactions within a time period into a sequence, and (3) verify and save into the blockchain. Permissioned blockchains are also called consortium, federated or hybrid blockchains.

Comparison between permissioned and permissionless blockchain types

The comparison between permissioned and permissionless blockchain types in relation to trust and the anonymity of validators is depicted in Figure 4.

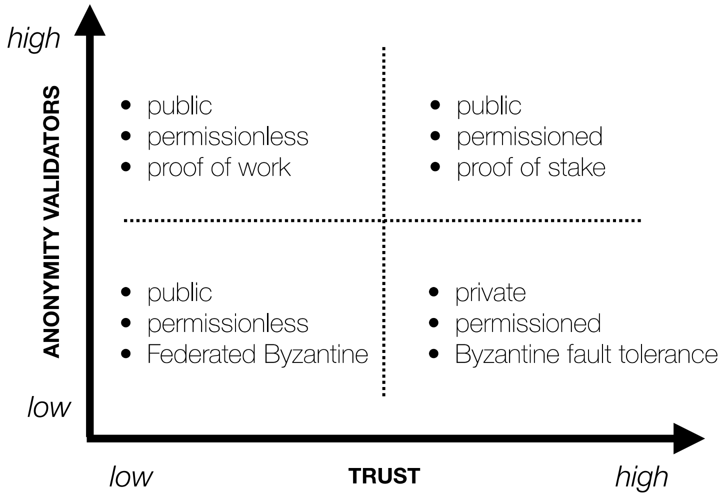


Figure 4 Overview of trust levels vs. anonymity of validators within permissioned and permissionless blockchains

A permissionless blockchain combined with a public blockchain has a high degree of anonymity of the validators with a low degree of trust in the validators. The consensus mechanism can be a proof of work based implementation. Such blockchain types are suitable for full anonymous systems that have no control mechanism of one single entity or person. Examples are Bitcoin and Monero, with full anonymity and decentralisation of mining.

A permissioned combined with a public blockchain has a high degree of anonymity of the validators while simultaneously having a high degree of trust in those validators. The consensus mechanism can be a proof of stake-based implementation. Such types are typically more scalable but have a moderate degree of immutability. They are suitable for community governance, execution of contracts, and private money systems. Examples include Bitshares and Ethereum (with proof of stake implementation) and can evolve in slightly decentralised (a low number of validators have all the stake) but the network becomes fast.

A permissioned combined with a private blockchain will have a low degree of anonymity of the validators, but they will have a high degree of trust. Consensus mechanism is PBFT based, overcoming the need for computation power and energy resources. Such blockchains are applicable to banking, fast payment infrastructure, corporate usage and are generally used for traceability, flexibility, and efficient governance of digital assets. Table 4 shows a comparison between public and private blockchains and permissionless and permissioned.

Table 4 Overview of characteristics between permissionless/permissioned and public/private blockchains. Adapted from (Carson et al., 2018).

	Permissionless	Permissioned
Public	• Anyone can join, read, write and commit • Hosted on public servers • Anonymous, highly resilient • Low scalability	• Anyone can join and read • Only authorised and known participants can write and commit • Medium scalability
Private	• Only authorised participants can join, read, and write • Hosted on private servers • High scalability	• Only authorised participants can join and read • Only the network operator can write and commit • Very high scalability

3.2.5 Blockchain infrastructure

Besides the investments made into setting up or developing the blockchain system, there are very few additional hardware investments to make that would enable information to be stored onto the blockchain. Where one would store the information in a digital database, ledger, or supply chain system, one can now store their information directly (e.g. application programming interfaces) or indirectly (e.g. web interface) on the blockchain. Besides manual entering data into the system, scanners or other electronic reading devices can be used.

Data connector application programming interfaces (APIs) allow companies to efficiently upload supply chain data from existing data stores (such as SAP) to their blockchain system for seamless integration of data from enterprise systems to blockchain solutions. Organisations that do not work with enterprise software can enter data through web interfaces.

3.2.6 Blockchain and transparency

By using blockchain technology, the digital ledger can become more transparent (Nugent *et al.,* 2016; Abeyratne & Monfared, 2016; Underwood, 2016; Wust & Gervais, 2018). Since the blockchain, especially in public blockchain types, are distributed, all network participants have a copy of the same blockchain (i.e. digital ledger). Any new update to the blockchain is governed by a consensus mechanism, which enables a high degree of immutability, and results in everyone having the same copy of the blockchain—resulting in a high degree of shared understanding. In other words, the participants within the blockchain network agree on a single truth of the blockchain and no single participant can make changes or tamper with transactions in the blockchain. This decentralised characteristic of the blockchain creates a high degree of transparency.

However, blockchain technology is not limited to being just decentralised as the centralised or private blockchains also have some advantages for corporations over the public ones. Private blockchains are useful for corporations who want to use the power of decentralised ledgers to improve the ongoing function. From a technical perspective, centralised and decentralised blockchain types are very similar. In both cases, the network consists of nodes responsible for storing and securing the digital ledger, and they require a consensus mechanism to establish a single ledger.

The biggest difference between centralised and decentralised, or public and private, is the number of nodes that participate in the network and make changes to the network (i.e. create new blocks). In the Bitcoin public blockchain case, there are no barriers to entry when it comes to accessing the ledger and taking part in the consensus mechanism to create new blocks. In contrast, in consortium or private blockchains (e.g. IBM's Hyperledger Fabric), typically the organization deploying the blockchain controls many aspects of the blockchain, including participation and access. Thus, the advantage of centralised blockchains is that it offers more customisability and control over the network, resulting in less resources necessary to secure the network, making them essentially more environmentally friendly. At the same time, since the organization deploying the blockchain can choose what hardware the network runs on, they can typically achieve higher overall throughput.

A disadvantage of centralised blockchain systems is that they are less secure, since there is not as much computing power securing the network as compared to (public) decentralised blockchains. It only requires a few of the nodes hosting the network to collude by amassing enough resources to hack the network. This can cause the blockchain to be less transparent, since the degree of shared understanding can more easily be tampered with. This is even worse when the blockchain network is fully centralised, thus managed by a single organisation or entity.

Within a public blockchain, all the information stored within blocks is publicly visible to anyone. This can be made clear by illustrating it with the Bitcoin public blockchain. Public blockchains typically have an explorer; an online chain browser that displays the content of individual blocks, accounts, balances of addressees, and transactions. Bitcoin has many explorers, for instance, BlockExplorer (blockexplorer.com) or Block Explorer (blockchain.com/explorer), which can be utilised to find information of particular blocks and its content. For example, each block contains a summary of when it was created, the reference (i.e. hash) to the previous block, the solution to the cryptographic puzzle (based on PoW), who mined the block and other information. In addition, the transactions are listed that show from which account to which other account Bitcoins were transferred and the amount. Every transaction and every created block since the first genesis block are publicly available and fully transparent. However, account holders are listed by their public key addresses (which is also utilised to digitally sign a transaction), which do not reveal the identity of the individual. This, in the case of Bitcoin, makes the blockchain have a high degree of traceability on the one hand side, but are still private on the other hand. In contrast, the transactions (or any other type of data) within consortium and private blockchains are commonly not completely visible to the public. Depending on the implementation, the information stored on the blockchain can be fully, partly, or not viewable by the public. Verifying the authenticity of the transaction for an outside party becomes harder. Also since private ledgers commonly are not available for public use, they are of little use to anyone besides the corporations that deploy them. Transparency of the transactions is thus lower in such types of blockchains compared to fully public blockchains.

An inherent trade-off exists between privacy and transparency within blockchain technology. When the blockchain is fully transparent—in terms of the transactions on the blockchain—anyone can view information stored on the blockchain and by whom that information was added; meaning that no privacy is provided. Likewise, a fully private system provides no transparency. However, a system can still provide significant privacy-guarantees while making the process of state transitions transparent, e.g. a distributed ledger can provide public verifiability of its overall state without leaking information about the state of each individual participant (Wust & Gervais, 2018). To achieve privacy in a public system, techniques of cryptography can be utilised. However, using cryptography comes at a cost of lower efficiency. The cryptocurrency Zerocash (zerocash-project.org) for example makes use of computationally expensive cryptography to provide full anonymity while still providing sufficient transparency to publicly verify the ledger state.

4 Application of blockchain technology in the food sector

4.1 Overview of providers of blockchain technology

The blockchain technology is open source and free to use, adjust, and extend in any way. The downside of adopting the original source code is that a successful implementation of the blockchain depends on a full understanding of the underlying code base. However, such implementations provide the most degrees of freedom, as every aspect of the blockchain can be tailored towards the specific use case. During recent years, there is a wide array of approaches to implementing a blockchain technology. Many players have emerged, each with their own merits, and a couple of implementation types are listed below.

Blockchain as a Service (BaaS)

The Blockchain as a Service (BaaS) concept can be mapped to the definition of 'Software as a Service' (SaaS), which is a software distribution model in which a third-party hosts an application and offers the application's functionality (i.e. service) through the Internet. Typical examples of SaaS solutions are Google Apps, Dropbox, Salesforce, and Cisco WebEx. This type of service is sometimes called 'on-demand software'. A subscription or registration is typically needed to make use of the functionality or service. Other variants are, for example, platform as a service (PaaS) and Infrastructure as a Service (IaaS). Blockchain as a service follows the same ideology, and it prevents users from developing blockchain systems from scratch.

Some of the big cloud providers such as Amazon (with AWS), Microsoft (with Azure), and IBM (with BlueMix) are starting to offer blockchain as a service on their cloud platforms. Users adopting BaaS solutions will benefit from not having to deal with the problems concerning configuration, setting up a working blockchain, and not needing hardware investments.

Amazon AWS blockchain solutions:

Amazon offers end-to-end BaaS solutions with a wide range of blockchain frameworks for developing blockchain applications. Examples of frameworks are Hyperledger Fabric, Hyperledger Sawtooth, Ethereum, and Corda. Amazon offers developers a one-click deploy of the underlying blockchain and connectivity to supplemental applications.

Microsoft Azure blockchain workbench:

Microsoft offers modular, pre-configured networks and infrastructure. Development of blockchains can be done by the blockchain workbench. The workbench is a collection of Azure services and capabilities designed to create and deploy blockchain applications to share business processes and data with other organisations. Microsoft provides the infrastructure scaffolding for building blockchain applications, allowing developers to focus on creating business logic and smart contracts. Other Azure services can easily be integrated. Examples of blockchain solutions offered are Corda, Ethereum, and Hyperledger Fabric. A solution architecture for supply chain track and trace is also offered.

IBM BlueMix Blockchain:

IBM offers BaaS on their BlueMix cloud platform. IBM blockchain solution and services are built on Hyperledger technologies which provide the framework and tool set. IBM claim to have successfully implemented over 400 blockchain solutions, and their best practices can be found in their enterprise ready blockchain services.

Blockchain first
A blockchain first implementation works directly with the blockchain tools and stack. A complete assembly is required, which makes this type of implementation difficult. The upside is that working directly with the blockchain creates the most degrees of freedom, and allows for a high degree of innovation. Typically, new blockchain technology provider companies start building their solutions by working directly with the blockchain tools. Examples here include working with the original Bitcoin (github.com/bitcoin/bitcoin) and Ethereum (github.com/ethereum) source code available on Github.

Development platforms
Several development platforms exists that allow for fast development of a blockchain implementation. Such platform focus not on a specific blockchain technology, but allow for rapid development with a strong focus on the blockchain programmability. Examples include, BlockApps (blockapps.net), Blockstream (blockstream.com), Monax (monax.io), Parity (parity.io), Hyperledger (hyperledger.org), and Tendermint (tendermint.com).

Vertical solutions
Vertical blockchain solutions are industry specific, and are based on private blockchain or ledger infrastructure. Some vertical blockchain solutions are arguably not a proper blockchain solution, but more a distributed ledger solution (which can be viewed as a subset of the blockchain technology). Examples include Axoni (axoni.com), Chain (chain.com), Clearmatics (clearmatics.com), Digital Asset Holdings (digitalasset.com), itBit (itbit.com), and R3 (r3.com).

APIs & Overlays
This approach uses the blockchain as an asset, ownership or identity-binding infrastructure, and it is typically used for a specific purpose, for example, chains of proof, ownership rights, title registries or other specific services with a built-in trust-based component. Examples include Blockstack (blockstack.org), Factom (factom.com), Open Assets (openassets.org), and Tierion (tierion.com).

4.2 Overview of existing applications of blockchain technology in the food sector

There are relatively many applications (test / trials) of blockchain in food chains, addressing specific issues (e.g. traceability) or sectors. However, there is a lack of common technology that can connect different blockchains (Ciaian, 2018). Most existing blockchain systems for traceability management have been developed since 2015 (Galvez *et al.,* 2018). Table 5 summarises some of the blockchain technology initiatives/projects in the agricultural and farming food-supply chain, together with the objective(s) of the implementation of this technology. For a summary of topics that have been addressed in current research on blockchain for agriculture, see (Bermeo-Almeida *et al.,* 2018).

Table 5 Selected applications of blockchain technology in the agricultural and farming food-supply chain

Goods/Products	Initiative/Project/Company involved	Objectives
Agri-food	AgriOpenData (Galvez *et al.,* 2018)	Allow quality and digital identity to be certified
Agri-food	Supply Chain Traceability System for China Based on RFID & Blockchain Technology (Galvez *et al.,* 2018)	Trusted information throughout the agri-food supply chain
Beef	"Paddock to plate" project, BeefLedger; JD.com (Kamilaris *et al.,* 2018)	Food traceability
Beer	Downstream (Kamilaris *et al.,* 2018)	Food traceability
Chicken	Gogochicken; Grass Roots Farmers Cooperative; OriginTrail (Kamilaris *et al.,* 2018); ZhongAn (Ciaian, 2018)	Food traceability, food safety concerns of urban consumers
Coffee	FairChain coffee: Bext360 in partnership with Moyee Coffee (Ciaian, 2018)	Traceability, transparency of the value added
Fish	Provenance (Galvez *et al.,* 2018)	Auditable system
Fresh food	Ripe (Galvez *et al.,* 2018)	Enabling data transparency and transfer from farm to fork
Fruits	FruitChains (Galvez *et al.,* 2018)	Public, immutable, ordered ledger of records
Grains	AgriDigital (Kamilaris *et al.,* 2018)	Financial
Large enterprises	IBM (Galvez *et al.,* 2018)	Food tracking project
Mangoes	Walmart, Kroger, IBM (Kamilaris *et al.,* 2018)	Food traceability
Olive oil	OlivaCoin (Ciaian 2018; Kamilaris *et al.,* 2018)	Financial, Small farmers support
Orange juice	Alber Heijn & Refresco (International Supermarket News 2018)	Show customers how and by whom products are made
Pork	Walmart, Kroger, IBM (Kamilaris *et al.,* 2018)	Food traceability
Pork	Arc-net (Galvez *et al.,* 2018)	Brand protection and security through transparency
Scotch Whisky	CaskCoin (Ciaian, 2018)	Investing in maturing Scotch Whisky
Soybean	HSBC & Cargill; ING & Louis Dreyfus Co. (Hochfelder, 2018)	Help authenticate products as well as eliminate the "paper trail" of verification at every stage of the supply chain
Sugar cane	Coca-Cola (Kamilaris *et al.,* 2018)	Humanistic
Turkeys	Cargill Inc., Hendrix Genetics (Ciaian, 2018; Kamilaris *et al.,* 2018)	Food traceability, animal welfare
Wine	Chainvine (Galvez *et al.,* 2018), Winecoin (Ciaian, 2018)	Increase performance, revenue, accountability, and security

5 Comparison of functionality of traditional vs. blockchain-based traceability systems

Consider the question “What is a steak dinner?”. Is it still a steak dinner if you serve fries instead of a baked potato? Is it still a steak dinner if you serve it with pepper sauce or bearnaise sauce? Is it still a steak dinner if you serve it on paper plates rather than on proper dinner plates? Most people would say yes to all these questions; it is still a steak dinner, even if you change the context and the serving options. You cannot, however, take away the steak; then you would no longer call it a steak dinner.

The challenge when analysing blockchain is that the term is traditionally associated with one, or a very limited set of “serving options”. A block is a just set of recorded transactions, and a blockchain is just a chain of such blocks, linked in way so that each block refers to the previous block in a way that makes it impossible to change any part of the previous block (or rather, it would be immediately discovered if you made a change). For a computer scientist, a blockchain is simply a data structure similar to a linked list, where hashes rather than pointers are used to refer to the previous link in the chain. This is the “steak” analogy; if you do not have this data structure, then what you have should not be called a blockchain.

What then are the “serving options”? Any article on this subject will tell you that blockchain implementations are online, distributed (multiple copies of the database / the blockchain exist), that there is a consensus mechanism to decide how to synchronise these multiple copies, and that there is a signing process which uses public and private keys to ensure identification and to enable encryption. This is all true for bitcoin, which, as previously indicated is a public blockchain, but is it necessarily true for all block chain implementations, including hybrid blockchains and private blockchains? The answer, at least in principle, is no; all these additional attributes traditionally assigned to blockchain implementations are just implementation choices. Other implementation choices could have been made, and the underlying data structure would still be a blockchain. A programmer on a standalone offline computer could write a blockchain implementation based on a single version of the blockchain, with no consensus mechanism needed, no signing process needed, and no encryption needed. In principle this should be called a blockchain, because the underlying data structure for the implementation as well as the data recorded would be identical to a (single copy of) an online public blockchain, implemented in the traditional way with a consensus mechanism, a signing mechanism, and encryption using public and private keys.

This is what makes it difficult to compare blockchain-based traceability system with a traditional electronic traceability system, which normally uses a relational database as the underlying data structure. Strictly speaking, the only difference between the two systems is the structure of the underlying database, and that means that while inherent differences between the implementations exist, these differences are fairly small and relate to the immutable, inherently consistent nature of the blockchain data structure. This is, however, not how blockchain implementations are usually described or analysed. Rather than comparing blockchain against non-blockchain implementations, most analyses compare online against offline implementations, or distributed against centralised, single copy implementations, or encrypted against non-encrypted signatures.

As an example, a statement that is repeated in many articles on applications of blockchain in the food industry is the following "*In a Walmart blockchain project, it took 2.2 seconds to trace mangoes to the farm. Without blockchain, this would take the retailer 6 days, 18 hours and 26 minutes to identify the original farm*" (Collak 2018). Let us accept the first statement, that using a traceability system based on blockchain technology it took 2.2 seconds to trace mangoes back to the farm. However, the second statement is clearly untrue, and cannot serve as a basis for evaluating the relevance of the blockchain solution. It might be true that in the (apparently very inefficient) previous traceability system it took more than 6 days to trace the mangoes back to the farm, but that has nothing to do with the system being based on a relational database (or whatever kind of database) rather than blockchain; it is related to the change from fragmented, non-integrated, possibly partly manual data to online, distributed, harmonised, and connected data.

As part of the comparison of blockchain-based vs. traditional electronic food traceability systems, it is worth enumerating some of these "serving options" in Table 6.

Table 6 Attributes and implementation options for traditional vs. blockchain-based traceability systems

	Traditional electronic traceability system	Electronic traceability system based on blockchain technology
Underlying database	Relational database (usually)	Blockchain
Immutable database?	Possible by setting 'append only' flag on database, but very unusual	Yes
Single copy of database?	Normally, yes. Traditional databases often use client-server network architecture, where a single, master copy of the database is stored on a centralised server.	No, normally multiple copies (but strictly speaking this is an implementation option)
Consensus mechanism?	Needed if there are multiple copies of the database, unusual	Yes (but strictly speaking this is an implementation option)
Online? Cloud-based?	Not uncommon for large companies, and for modern chain traceability systems	Yes (but strictly speaking this is an implementation option)
User authentication	In a client-server implementation, the server authenticates a client's credentials	Based on cryptography with private keys and public keys (but strictly speaking this is an implementation option)

So, what does this mean? Should we compare a blockchain implementation to a "bad" traditional traceability system, to an average one, or to one that is as similar to a blockchain implementation as possible, with all the same implementation options?

There is no clear answer to this question; it depends on what you want to measure, and it depends on what you want to achieve by making the comparison. If you want to argue for the desirability of blockchain solutions, you compare blockchain solutions to fairly bad traditional traceability systems, like in the Walmart example. A better approach is to analyse the attributes and implementation options separately and indicate pros and cons of each.

Suitability of database

A traditional database can store anything, and it is normally state-based, i.e. it stores the current state or value of the data. A blockchain stores transactions, and as transformations in a (food) supply chain are similar to transactions, the blockchain is well suited for storing data related to food (or product) traceability.

Data quality and veracity

Ensuring quality and veracity of recorded data is a significant challenge for both types of systems; there is a risk of 'garbage in, garbage out'. Accidental errors in recorded data are likely to be equally frequent in the two types of systems. Deliberate fraud, however, is probably less likely (but certainly still possible) in a blockchain-based system, as the person committing the fraud will know that if fraud is discovered in a blockchain-based system, the provider of the fraudulent statement can be unambiguously and quickly identified, and this obviously increases the risk of being caught.

Immutability, integrity and transparency

In a traditional database, data elements can be overwritten, although it is not uncommon to keep a version log, indicating who did the overwriting, when, and where. The data recorded in a blockchain is immutable by design, which means that we know that recorded data has never been overwritten. Thus, a traditional database has no built-in integrity; it stores the latest recorded (or claimed) state of each data element independently. In a blockchain implementation, the state of each variable is not stored; instead all the transactions that led up to this state is stored. Using a feed silo as an example, in a traditional database the current amount and type of feed would be stored (probably also the previous feed transactions to and from the silo). In a blockchain implementation, the current amount of feed would not be stored; only the entire list of transactions to and from the silo. In a traditional database, the current feed level recorded in the database would be an unsubstantiated claim. In a blockchain implementation, the current feed level would be calculated by going through all the recorded transactions, thus providing more transparency and integrity to the stated feed level value.

Confidentiality

While a blockchain implementation, especially a private blockchain, can provide data confidentiality, that is not what it was designed for. In a blockchain implementation, confidentiality and tiered data access protocols are designed externally, and on an ad-hoc basis. Blockchain scores highly on transparency, and in this context transparency and confidentiality are to some degree mutually exclusive qualities; if you score well on one, you cannot really score well on the other.

Trust

Trust is not a trivial attribute to evaluate in this context, because the different implementations treat the concept of trust differently. In a traditional traceability system, you are asked to trust the owner of the system and the database, and if anything turns out to be wrong (false claims, food fraud etc.), the reputation of the owner of the database (and in practise, the brand) suffers. Blockchain was designed to work without trusting any particular organisation; the trust in the veracity of the data would be supplied by the design of the blockchain system. While this in itself is a useful attribute, it is not really how trust in the food sector works. To remove the need to trust any organisation and to democratise the responsibility for data veracity is relevant in a purely virtual system, but that is not what the food sector is. Brand owners will still need to be trusted, both to provide data, but most of all for producing safe, nutritious, and high-quality food. While using a blockchain-based system provides no disadvantage in relation to trust, the inherent blockchain quality of “not needing to trust any single organisation” is not really applicable in the food sector.

Speed and efficiency

Obviously, this integrity comes at a great cost. A blockchain implementation will always be slower than a traditional implementation, because in addition to supporting the functionality that a normal database supports (writing and reading data) it also needs to verify signatures / identities using cryptography, and it needs to execute a consensus algorithm to determine which blocks gets added to the blockchain during the next update. This is in addition to the inefficiency related to the built-in redundancy in the blockchain, where there are multiple copies of the database, and where all transactions since the creation of the blockchain is stored and accessed.

Robustness

The redundancy has an upside, which is robustness. Robustness is an indication of how sensitive the data and the database is to mistakes, errors, or incidents, including things like power-outs, hacking, server crashes and malfunctioning software or hardware. In a traditional system robustness is provided by external processes, and these may vary; significant amounts of data may be lost if something goes wrong and the protective measures are not in place. In a blockchain-based system, a degree of robustness is inherent in the system, both for the state of the data, which can be recreated by traversing the recorded transactions, and for the database, which is normally online, and duplicated many times.

Interoperability

In principle, interoperability, i.e. how well different systems exchange information, could be seen as independent from the traditional / blockchain choice. In practice, however, this is not the case. As indicated above, a traditional electronic traceability system has a large number of implementation options, and the relational database can be structured in many different ways. At least for now, blockchain implementations are more homogenous, in that they all store transactions rather than data element values, they are all online, they are all immutable, they all employ cryptography for verifying identity etc. The fact that blockchain systems are more homogenous makes them more interoperable, and in fact many of the reported blockchain success stories are based on the improvement in operability and data sharing along the supply chain rather than on any of the blockchain attributes in itself. For traditional traceability systems to become (more) interoperable would depend on widespread adoption of standards both for Electronic Data Interchange (EDI) and for data content; unfortunately, there are too many competing standards in this area, so the current level of interoperability is fairly low. In this report, we highlight improved interoperability as the most important benefit of using a blockchain-based electronic traceability system in the food industry. This benefit is not, strictly speaking, based on any particular characteristic of the blockchain structure or database; it is based on the fact that interoperability between blockchain implementations are simpler, because blockchain implementations are more similar than traditional electronic traceability implementations which can be built on a wide range of operating principles, system architectures, and database types.

6 Cost, benefits, and practical considerations relating to blockchain-based systems

To evaluate costs, benefits, and to consider some practical considerations, we have evaluated how a blockchain-enabled food traceability system may be used in supply chains for food products in general, and in the supply chains for red meat, and for herbs and spices in particular. We have also indicated how authorities seeking to get access to food item properties and to verify the veracity of the associated claims may utilise a blockchain-based system.

6.1 Food product supply chains in general

Based on the evaluation criteria identified in the previous section, the overall comparison of a traditional traceability system with a blockchain-based system is indicated in Table 7. Red colour indicates a disadvantage or an existing challenge, light green colour indicates a small advantage for the system type in question, and deep green colour indicates a significant advantage.

Table 7 Costs and benefits of blockchain-based systems in the food product supply chains in general

Comparison criteria	Traditional electronic traceability system	Electronic traceability system based on blockchain technology
Suitability of database	Records (claimed) variable states, versatile	Records transactions, well suited for recording transformations
Data quality and veracity	Data provider must check and vouch for data quality and veracity	Data provider must check and vouch for data quality and veracity, but fraud frequency may be lower, as risk of getting caught is higher
Immutability, integrity and transparency	Data elements can be overwritten; needs additional recording (transaction log or similar) to document this	Only the transactions are recorded, which means a higher level of integrity and transparency of the claimed values
Confidentiality	Easy to integrate tiered levels of access	Can be done, but to some degree it goes against the philosophy of what a blockchain implementation is meant to support
Trust	Based on trust in the food business and the brand	Still based on trust in the food business and the brand, but trust may be higher because of higher degree of data integrity and transparency
Robustness	Duplication, back-up, and other means of providing robustness must be provided by external processes	Robustness and duplication of data is built into the system
Speed and efficiency	As good as you can get	Significant overhead related to duplication, error checking, consensus mechanisms, and calculating the state of variables based on transactions
Interoperability	There is a plethora of systems, implementations, and database structures, there are a number of standards for TRU identification and Electronic Data Interchange, and there are very few standards defining how the recorded data elements should be named and measured. This means that system interoperability (exchange of data) is a big problem.	Blockchain-based systems are less diverse; they all record transactions (transformations) rather than state values, and they are all immutable. Interoperability and data interchange between blockchain-based food traceability systems is easier than between existing systems, any many of the success stories reported is because a higher degree of interoperability has been achieved.

There are minor costs and benefits related to the first five comparison criteria, as indicated by the light green shading (green indicates a potential benefit). As indicated above, the two criteria where the difference between the traceability system is biggest is “Speed and efficiency” which strongly favour a traditional system, and “Interoperability” which strongly favour a blockchain-based system.

When deciding between a traditional implementation of an electronic traceability system and a blockchain-based one, it is important to determine which system qualities are most important. If database transparency, integrity, and robustness is important, then a blockchain solution can be very relevant. On the other hand, if speed and data confidentiality are considered to be the most important system attributes, a traditional electronic traceability system is probably better.

The relevance and utility of improved interoperability should not be underestimated. While interoperability is technically possible for traditional traceability systems, it is difficult to get a large and diverse group of companies to agree on what standards and data formats to use. It is probably easier to get a large and diverse group of companies to agree to all use blockchain-based systems, and then significantly improved interoperability will be a much-desired side effect of that decision.

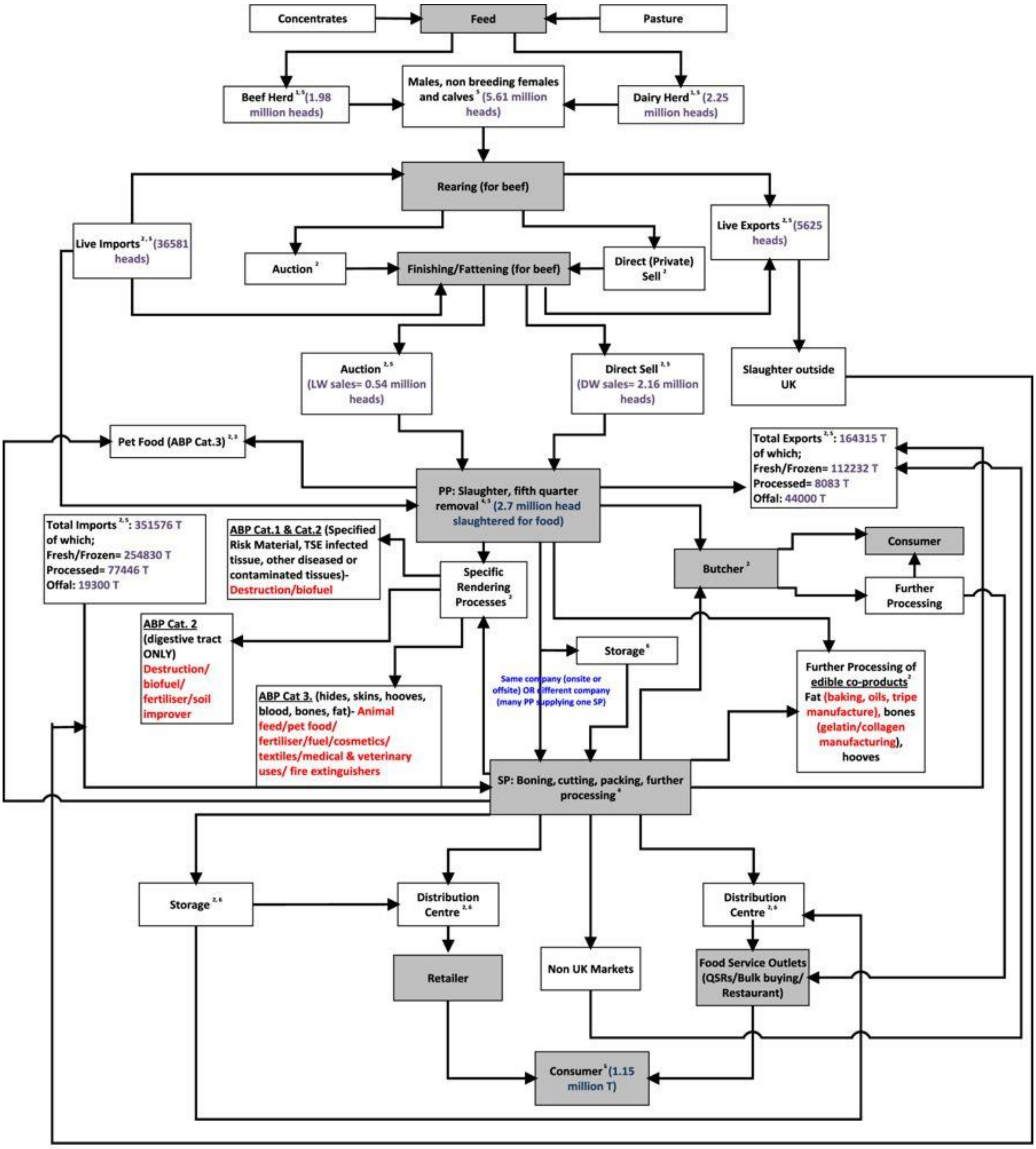
6.2 Red meat supply chain example

The food industry is generally vulnerable to crime and of the most vulnerable sectors within this industry are the meat, fish, olive oil and spice industries (Silvis *et al.* 2017). The European Horsemeat Scandal of 2013 highlighted vulnerabilities within the beef supply chain. This scandal resulted in product recalls, serious effects on the sale of ground beef, and huge economic losses for defrauded companies. Widespread media coverage of the event contributed to further damage to consumer trust and brought into question the integrity of the beef supply chain. Such scandals have increased awareness of food fraud, causing it to become a major concern for the food industry, its products, reputation, and consumers.

According to recent research, in the UK beef supply chain (Figure 5), in the period 1997–2017, counterfeiting[2] and adulteration[3] were the biggest threats. In the same supply chain, primary processing, secondary processing, and rearing were the most vulnerable areas. The greatest proportion of incidents occurred during primary processing, which will go on to affect subsequent parts of the beef supply chain. The greatest range of fraud types occurred in secondary processing, and rearing had the third most recoded incidents.

[2] All aspects of the fraudulent product and packaging are fully replicated, including property infringement, copies of popular food produced without the same food safety assurances (e.g. health certificates or documentation are be fraudulent, missing or otherwise improper; product is produced without inspection, and/or legal testing such as for Bovine spongiform This includes illegal slaughter of livestock).

[3] A component of the finished product is fraudulent (e.g. presence of illegal veterinary medicine, antibiotics or growth promoters; addition of an undeclared material for economic gain; undeclared substances to improve appearance or shelf-life of product (i.e. colorants)).


Concentrates
Feed
Pasture
Beef Herd 1,5 (1.98 million heads)
Males, non breeding females and calves 5 (5.61 million heads)
Dairy Herd 1,5 (2.25 million heads)
Rearing (for beef)
Live Imports 2,5 (36581 heads)
Live Exports 2,5 (5625 heads)
Auction 2
Finishing/Fattening (for beef)
Direct (Private) Sell 2
Auction 2,5 (LW sales= 0.54 million heads)
Direct Sell 2,5 (DW sales= 2.16 million heads)
Slaughter outside UK
Pet Food (ABP Cat.3) 2,3
PP: Slaughter, fifth quarter removal 4,5 (2.7 million head slaughtered for food)
Total Exports 2,5: 164315 T of which; Fresh/Frozen= 112232 T Processed= 8083 T Offal: 44000 T
Total Imports 2,5: 351576 T of which; Fresh/Frozen= 254830 T Processed= 77446 T Offal: 19300 T
ABP Cat.1 & Cat.2 (Specified Risk Material, TSE infected tissue, other diseased or contaminated tissues)- Destruction/biofuel
Specific Rendering Processes 2
Butcher 2
Consumer
Further Processing
ABP Cat. 2 (digestive tract ONLY) Destruction/ biofuel/ fertiliser/soil improver
Storage 6
Same company (onsite or offsite) OR different company (many PP supplying one SP)
ABP Cat 3. (hides, skins, hooves, blood, bones, fat)- Animal feed/pet food/ fertiliser/fuel/cosmetics/ textiles/medical & veterinary uses/ fire extinguishers
Further Processing of edible co-products 2 Fat (baking, oils, tripe manufacture), bones (gelatin/collagen manufacturing), hooves
SP: Boning, cutting, packing, further processing 4
Storage 2,6
Distribution Centre 2,6
Distribution Centre 2,6
Retailer
Non UK Markets
Food Service Outlets (QSRs/Bulk buying/ Restaurant)
Consumer 5 (1.15 million T)

[1] Head number only accounts for breeding females that are producing calves for beef production

[2] Action may occur via trader/buyer/wholesaler OR directly within or between companies or farmers at former stages, i.e. between rearing and finishing stages

[3] Some intermediate companies take ABP Cat.3 material directly for pet food manufacture

[4] Location of boning, cutting, packing operations and further processing is dependent on site capabilities and may occur on same site as slaughter

[5] Further information on quantities are available from AHDB Beef and Lamb Yearbook 2015 and/or HMRC import/export statistics 2014

[6] Distribution Centre/storage may be shared by several separate suppliers/companies

Arrows denote transport/movement of produce. This may occur via a haulage company or by a farmer at former stages, i.e. between rearing and finishing stages
ABP= Animal By Products
LW= Liveweight
DW= Deadweight
PP= Primary Processing
SP= Secondary Processing
QSR= Quick Service Restaurant

Figure 5 An example of a UK beef supply chain (Brooks et al. 2017).

In general, the pros and cons of using a blockchain-based traceability system for red meat are the same as for food products in general. While supply chains for red meat are quite diverse, they do tend to have some characteristics in common, mainly related to the type of commodity we are dealing. Examples of such characteristics, and what influence they might have on the choice of traceability system is indicated in Table 8.

Table 8 Particular costs and benefits of blockchain-based systems in the supply chain for red meat

Characteristic of the red meat supply chain	Relevance of blockchain-based implementation
Animals used for red meat production are often uniquely identified, and may be accompanied by a "passport" containing key data elements	Whatever the traceability system, there is no guarantee that the stated identifier is the actual identifier, or that the stated passport is the actual passport for the animal in question. However, in blockchain-based systems the integrity of the information once it has been recorded is assured, which is not the case for a traditional traceability system.
Animals used for red meat production are often linked with veterinary certificates that are meant to follow the associated red meat products as they move along the chain	Falsification of veterinary certificates is a common type of fraud, as is the practice of re-using / copying "good" certificates to replace "bad" or missing certificates. In a blockchain-based system, data on the certificate cannot be modified once entered, and re-use of certificates would be discovered in interoperable systems where a certificate ID exists, and data is exchanged.
While there are many food products with red meat ingredients (pies, pizzas, etc.), red meat is often the main product that the consumer buys The portion of red meat that in the end reaches the consumer is big enough to identify and trace in practice, should this be required	Bigger TRUs means fewer TRUs and more valuable TRUs where the transactions that produced them can be traced individually; this would fit well with a blockchain-based system, which in this case could also provide consumer access to the recordings in the database, should that level of transparency be desired

Veterinary certificates and laboratory reports are already being recorded in blockchain databases, even if the traceability systems in the associated supply chains are not blockchain-based. This protects against physical tampering of the certificate or report in question, as subsequent references to the certificate or report is required to link to the original recorded data, which in a blockchain database cannot be overwritten. This is useful if the provider of the certificate or report is honest and supports transparency; to protect against the certificates being used in a dishonest manner later on in the supply chain. As this type of implementation can be done and be useful on its own, it is likely to be (and to some degree it already is) one of the first successful applications of blockchain technology in the food industry.

6.3 Herbs and spices supply chain example

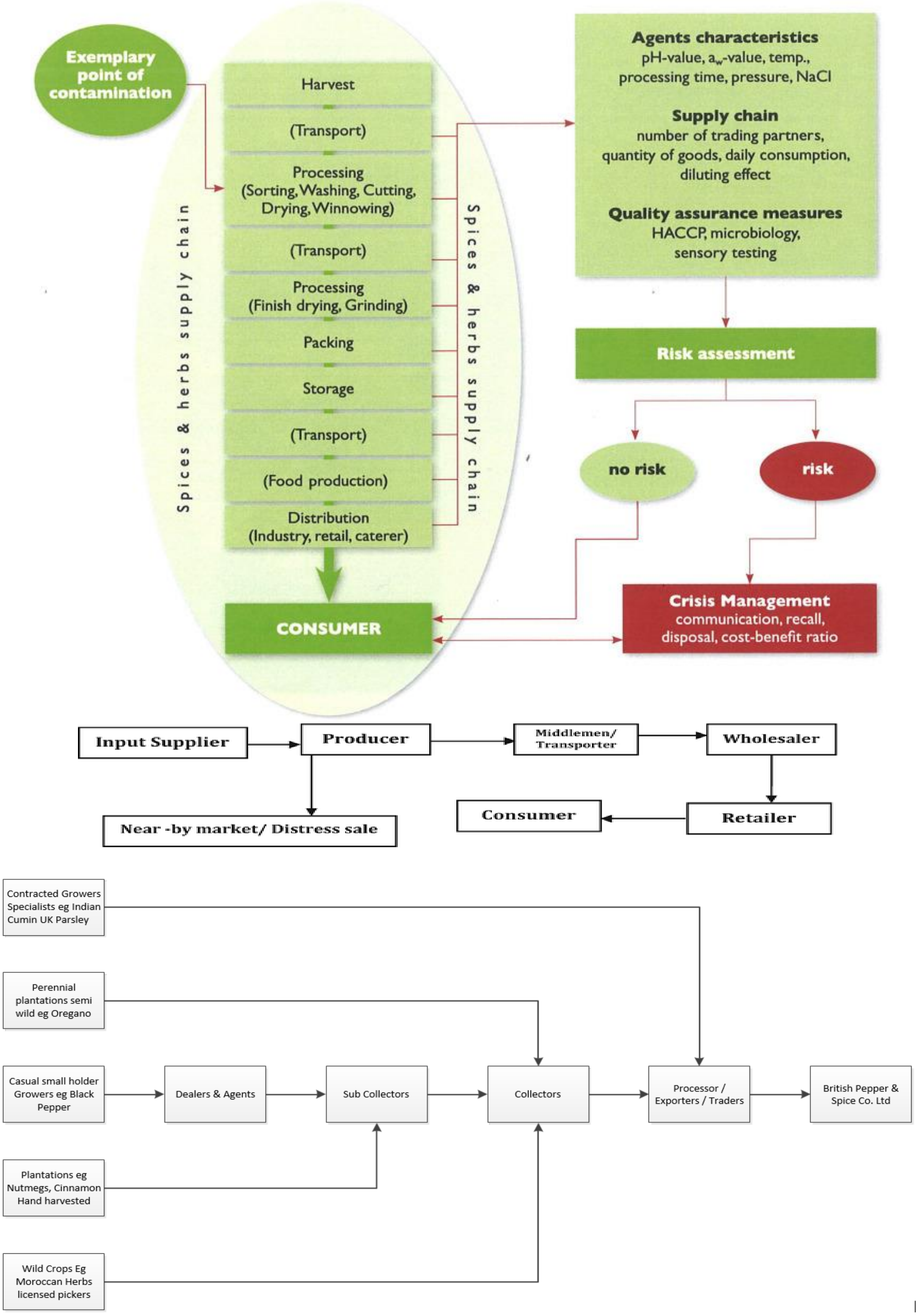

Exemplary point of contamination
Harvest
(Transport)
Processing (Sorting, Washing, Cutting, Drying, Winnowing)
(Transport)
Processing (Finish drying, Grinding)
Packing
Storage
(Transport)
(Food production)
Distribution (Industry, retail, caterer)
CONSUMER
Spices & herbs supply chain
Spices & herbs supply chain
Agents characteristics
pH-value, a_w-value, temp., processing time, pressure, NaCl
Supply chain
number of trading partners, quantity of goods, daily consumption, diluting effect
Quality assurance measures
HACCP, microbiology, sensory testing
Risk assessment
no risk
risk
Crisis Management
communication, recall, disposal, cost-benefit ratio
Input Supplier
Producer
Middlemen/ Transporter
Wholesaler
Near -by market/ Distress sale
Consumer
Retailer
Contracted Growers Specialists eg Indian Cumin UK Parsley
Perennial plantations semi wild eg Oregano
Casual small holder Growers eg Black Pepper
Dealers & Agents
Sub Collectors
Collectors
Processor / Exporters / Traders
British Pepper & Spice Co. Ltd
Plantations eg Nutmegs, Cinnamon Hand harvested
Wild Crops Eg Moroccan Herbs licensed pickers

Figure 6 Supply chain examples for herbs and spices (Székács et al. 2018) (Sharangi and Pandit 2018) (courtesy of British Pepper & Spice Co. Ltd., 2018)

Spices and herbs, which are consumed in small quantities, but used in a wide range of foods and food products, represent a unique segment within the food sector, which is associated with very complex distribution product chains. As such, specific concerns regarding food safety apply to these particular commodities (Székács *et al.* 2018). In general, herbs and spices represent an attractive category for potential offenders, because the products have a high value by weight and consumers have a limited capacity to detect adulteration (Silvis *et al.* 2017). Common authenticity issues associated with spices are the addition of lower value product foreign and product own material, which may include addition of unapproved 'enhancements', such as dyes to cover up the extension. Ground spices are particularly prone to adulteration, because the milling or grinding step changes the shape of both the spice and adulterant to a powder, which makes it difficult to detect adulterants in the final product (Silvis *et al.* 2017). A model of spices and herbs supply chain is exemplified in Figure 6.

In general, the pros and cons of using a blockchain-based traceability system for herbs and spices are the same as for food products in general. While supply chains for herbs and spices are quite diverse, they do tend to have some characteristics in common, mainly related to the type of commodity we are dealing. Examples of such characteristics, and what influence they might have on the choice of traceability system is indicated in Table 9.

Table 9 Costs and benefits of blockchain-based systems in the supply chain for herbs and spices

Characteristic of the herbs and spices supply chain	Relevance of blockchain-based implementation
Production planning for herbs and spices may be difficult; some crops are wild	Traditionally, initial data capture is more problematic for wild crops and wild captured fish; a blockchain database is more useful if the integrity of the initially recorded data can be assured
The herbs and spices supply chain is generally fairly long, with many intermediaries	Longer chains mean interoperability is a big problem and a central database system is not feasible; an argument for blockchain-based systems
Herbs and spices are often supplied by developing countries	Most blockchain implementations are technologically more advanced than the traditional systems, and would require infrastructure, processing capacity, online connection, etc.; it might be difficult to support a blockchain application in these situations
Herbs and spices are generally bulk products, and at some stages in the supply chain it is difficult to assign a physical identifier to the TRU	This is a challenge for both types of traceability systems, and it might be that the transactions cannot be recorded directly, which perhaps is a bigger problem in a blockchain-based system which is not designed to deal with data that we only know the current state of
For the final consumer, herbs and spices are often ingredients, and not the main product they buy	For complex products with multiple ingredients, traceability is a challenge regardless of what type of system is used. However, blockchain systems have the additional challenge of requiring all transformations to be recorded; that is not always feasible for complex products. Also, recording the large number of transformations involved in making a complex product will be more problematic in a blockchain-based system because of the data duplication and the corresponding speed penalty.

As indicated, the main advantage of blockchain-based traceability systems is the improved interoperability that is so problematic in traditional traceability systems. This argument holds for all food commodities, and improved interoperability is probably the most immediate benefit if one chooses a blockchain-based system (or rather, a set of blockchain-based systems that exchange data). With that said, the pros and cons of using a blockchain-based traceability system rather than a traditional one varies slightly with the commodity type, as indicated in the two examples above. A blockchain-based system is most suitable when there are clearly defined and identified TRUs, when these TRUs are of a size and value that makes it relevant to keep track of all the transactions that led to that TRU, and when the quality of the initial data capture is high, and easy to validate. Blockchain implementations deal slightly less well with bulk products, with products where the transactions are not recorded explicitly, or where the data is fuzzy. It is not that the blockchain system cannot handle these issues; it is more that the benefits one would normally get from a blockchain-based implementation are not as clear.

6.4 How authorities may use data recorded in a blockchain-enabled system

The costs associated with implementing and maintaining a blockchain-based traceability system largely fall on the food businesses; this includes the additional costs associated with a blockchain-based system as compared with a traditional system. Some of the benefits associated with a blockchain-based system are significant for the authorities, as indicated in Table 10.

Table 10 Costs and benefits of blockchain-based systems for authorities

Comparison criteria	Traditional electronic traceability system	Electronic traceability system based on blockchain technology
Suitability of database	Authorities can only access claims in relation to state of variables	Authorities can access the entire set of transformations that led to the current state, which makes it easier to see the origin of the stated claim
Data quality and veracity	Authorities need separate and external checks to test the data quality and veracity	Some degree of quality and veracity is provided by the blockchain-based system itself
Immutability, integrity and transparency	It is difficult for authorities to know if recorded data has been subsequently overwritten	The immutability of the database means that the authorities know that the data has not been overwritten
Confidentiality	Not an issue for authorities	
Trust	Not really an issue for authorities (except for trust in data quality and veracity, which is better in a blockchain-based system)	
Robustness	Not an issue for authorities	
Speed and efficiency	Not an issue for authorities	
Interoperability	Lack of interoperability makes it more difficult to identify discrepancies, and to do mass-balance accounting which is sometimes necessary to identify fraud	Better interoperability and better access to comparable data from different systems makes it easier to identify discrepancies, and to do mass-balance accounting

As indicated, the costs associated with blockchain-based systems (speed, efficiency, and confidentiality in particular) are not particularly relevant for authorities, whereas some of the benefits (recording of transactions and not only variable states, immutable database, interoperable systems) are significant for authorities. From this follows that authorities should be proponents of blockchain-based food traceability systems and should encourage FBOs to adopt them.

7 Conclusions and recommendations

The overall recommendation is that unless confidentiality or speed are of paramount importance, to base an electronic food traceability system on blockchain technology is a good solution. The main reason for this fairly clear conclusion is the question of interoperability and data sharing. While it is technically possible to achieve this between existing systems, in practice lack of interoperability has been one of the main bottlenecks preventing data access from farm to fork. Rather than continuing to hope for the widespread adoption of standards to support interoperability, it is probably more realistic to hope that many actors in the supply chain will adopt blockchain-based traceability systems, which in itself will increase interoperability.

It is worth emphasising that blockchain-based implementations will not solve all, or even most of the problems associated with traditional electronic traceability systems. This includes:

- Data quality and veracity — still a problem in blockchain-based implementations.
- Food fraud — still a challenge in blockchain-based implementation, although if food fraud is detected, it will be easier to identify who made the fraudulent statement.
- Need for standards – while standards for EDI are less relevant when using blockchain-based systems, standards that define what the recorded data elements and values mean (ontologies) will be needed more than ever. The increased interoperability will mean increased access to data recorded in a different part of the supply chain; a standard is needed to define what the data element names mean, and what the recorded values signify.

To avoid future disappointment, it is important that both food businesses and solution providers are aware that these challenges will continue to exist also in blockchain-based implementations, and in particular that the latter group tone down the current overselling of the technology and stops pretending that it is a panacea that will fix all our problems in this area.

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