■特別寄稿論文

Ontology-aware Model-driven Architecture A Resource-Event-Agent implementation for the Blockchain

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Abstract : *This paper discusses the potential impact of ontology and model-driven architecture on decentralized ledger technology. It argues that an ontology-aware model-driven architecture approach could facilitate interoperability between blockchains and help build more resilient economic networks. More precisely, this paper advances the idea of an implementation of the resource-event-agent (REA) ontology in the MERODE model-driven design environment as an approach to develop blockchains for open value networks. In addition, this paper lists four potential application domains of such a REA-MERODE blockchain. First, it discusses how this approach could benefit the sharing economy. Second, it considers the potential impact on collaboratives of independent workers. Third, it examines the potential benefits of this approach to wood traceability, and fourth and finally, the potential benefits to vaccine traceability.*

Keywords : *Decentralized ledger technology, Value Network, Ontology, Model-driven architecture*

1. Introduction

The Covid-19 crisis exposed the vulnerability of the global economy (Fernandes, 2020). Both the peer-to-peer Blockchain technology and the peer-to-peer economy are believed to offer a resilient alternative to the current global economy that centralizes production and wealth in a limited number of geographic regions (Maupin, 2017, Davis, 2016).

Where blockchain technology seems to be application-domain agnostic and seems to support interoperability, applications appear to suffer from a stovepipe architecture. For example, Beefledger[1], Provenance[2], Walmart's[3] and LVMH's[4] traceability blockchains are not mere

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interface configurations of the same underlying traceability blockchain, but entirely independent projects.

This paper advocates the use of ontology and model-driven architecture to reduce the number of stovepipes. The ontology-aware model-driven architecture (hereinafter, MDA) approach for decentralized ledger systems presented below aims at developing a unifying theory for blockchains that is capable of supporting value networks such as Provenance and Beefledger. Therefore, this paper focuses entirely on the Resource-Event-Agent (hereinafter, REA) ontology, although other ontologies could be useful in this or other domains. While the advocated approach aims at being generic, this paper focuses entirely on the MERODE MDA approach as it has solid theoretical foundations in category theory, desirable characteristics for smart contracts (e.g. deadlock and infinite loop detection) and a code generator that is currently being transformed in an Ethereum smart contract generator (De Sousa et al., 2020).

The second section discusses the value of ontology in general, and more specifically the value of the REA ontology for describing value networks. The third section presents the ontology-ware MDA approach this paper advocates introducing MDA in general and MERODE more specifically. The fourth section lists potential applications of the proposed REA-MERODE approach, where the conclusion discusses the general applicability of ontology-ware MDA.

2. Ontology

An ontology is an explicit (preferably formal) specification of a tacit (preferably shared) conceptualization, that uses concepts, the potential relationships between these concepts and axioms that apply to these concepts and relationships to describe a domain of interest such that the universe of discourse defined by the concepts, relationships and axioms fits the underlying conceptualization of the domain of interest (e.g. business) in the best possible way (Guarino, Oberle and Staab, 2009). Such a specification can range from an informal glossary to a computer-readable frame (Lassila and McGuinness, 2001). A conceptualization is an individual's perception (i.e. a mental model) of a domain of interest. A specification of a conceptualization can be used to reach agreement on a shared mental model of the domain of interest within a group of relevant stakeholders. This shared understanding has been found to facilitate information retrieval, system operability, conceptual modeling and domain understanding (Roa, Sadiq and Indulska, 2014).

The concepts, relationships and axioms that build an ontology could be explained building, for example, an ontology of chess[5]. To play the game of chess, you should know the concepts: board, rank, file, square, piece, knight, queen, rook, bishop, etc. These are examples of concepts that belong to a chess ontology. These concepts relate to each other, although not every concept needs to relate to every other concept. For example, A board is composed of ranks and files. A rank and a file define a square. King, rook, bishop, etc. are pieces. One piece can take another piece. The board composition, the classification of the pieces and the taking of a piece by another piece are examples of relationships that are part of a chess ontology. Concepts and relationships are insufficient to truthfully portray the complexity of chess as not every move is legal. For example, a king can only move one square at a time; a rook can move any number of squares along a rank or file but is unable to jump over any other piece.

These are examples of the axioms of a chess ontology.

Together the concepts, relationships and axioms, which are all referred to as universals, define a universe of discourse. A perfect ontology defines a universe of discourse (e.g. all possible chessboard layouts) that matches the underlying reality (i.e. the ontology does not allow for any illegal layout or move and is able to portray all legal layouts or moves).

Unfortunately, many ontology specifications (e.g. the meta-model of a domains-specific modeling language) exhibit ontological deficiencies (Recker et al., 2011). A first ontological deficiency is *construct deficit*, which indicates that the specification lacks a concept that is present in the conceptualization. For example, a chess instructor might prefer to not to explain "castling" at first not to overwhelm a novice player. Consequently, the novice player's knowledge of the game (i.e. the universe of discourse) is incomplete as the novice is unaware of certain moves. A second deficiency is construct excess, which implies that the specification contains an irrelevant concept. For example, a novice player might inadvertently believe that the concept "chess master" is relevant to the game. A third deficiency is construct redundancy, which signals that the specification contains two or more universals that map to the same universal in the underlying conceptualization (i.e. synonymy). For example, a novice player might think that "row" and "rank" have a distinct meaning, while they are synonyms. A fourth and final deficiency is construct overload[6], which conveys that a single specification universal maps to two or more conceptualization universals (i.e. homonymy). For example, a game can end in a "draw" either by "agreement", "stalemate" or "dead position".

2.1 Value Networks

A *value network* (hereinafter, VN) is a network – defined by Allee (2008) as any set of roles and interactions – of collaboration spaces in which people participate in both tangible and intangible exchanges (e.g. of goods, services and rights) to achieve economic or social benefit. Such value networks can either be open or closed and either internal-facing or external-facing. In closed value networks a relatively stable set of actors plays a relatively stable set of roles. In open value networks actors can assume and abandon roles in the network at low or no cost, which allows for frequently changing role assignments and a high actor churn-rate. Internal-facing networks focus on the interpersonal relationships that shape their own internal working, where external-facing value networks seek collaboration with other organizations in their business ecosystem.

Moore (1998) defines such a *business-ecosystem as "an extended system of mutually supportive organizations; communities of customers, suppliers, lead producers, and other stakeholders, financing and trade associations, standard bodies, labor unions, governmental and quasi-governmental institutions, and other interested parties. These communities come together in a partially intentional, highly self-organizing, and even somewhat accidental manner."* Within these business-ecosystems he distinguishes between the extended enterprise and the core business (Moore, 1996). Where the *business- ecosystem* involves investors, labor unions, trade associations, competing organizations, government agencies and other regulatory bodies, other stakeholders and the extended enterprise; the *extended enterprise* involves direct customers, customers of customers, suppliers of suppliers, suppliers of complementary products, stan-

dard bodies and the *core business*, which includes core contributors, distribution channels and direct suppliers.

2.2 Introduction to REA

The Resource-Event-Agent (hereinafter, REA) ontology (McCarthy, 1982) has been shown to possess the ability to unite financial with non-financial value streams and to serve as a conceptual foundation for blockchain implementations (Gal and McCarthy, 2018). REA has a conceptualization for describing an organization's metabolism (i.e. the value chain (McCarthy, 2003)) from the inside, and a conceptualization for describing the business-ecosystem (e.g. supply chain, external-facing value network) that supports the organization from the outside. The former conceptualization is called the dependent or trading- partner view and was first documented by W. E. McCarthy (1982). The latter conceptualization is called the independent (and sometimes helicopter) view, which represents the perspective of any third party (i.e. a party not taking part in the economic exchange) in the business-ecosystem (e.g., investors, the government, the market, a random observer) and was first documented by Haugen (2007), together with the International Organization for Standardization. (ISO, 2007)

The constructs of REA were augmented with axioms for the dependent view to create the actual REA ontology. The first REA axiom, which is also called the stock-flow axiom, stipulates that *"At least one inflow event and one outflow event exist for each economic resource; conversely inflow and outflow events must affect identifiable resources."* (Geerts and McCarthy, 2000) It requires that an agent possess a resource before he can use or sell it. The second REA axiom, which is also called the duality axiom, stipulates that *"All events affecting an outflow must be eventually paired in duality relationships with events affecting an inflow and vice-versa."* (Geerts and McCarthy, 2000) It requires exchanges to be fair. The third REA axiom, which is also called the participation axiom, stipulates that *"Each exchange needs an instance of both the inside and outside subsets."* (Geerts and McCarthy, 2000) It requires that every exchange involves two trading-partners, one that is defining the semantics of the dependent view (i.e. the inside) and one that is not (i.e. the outside). REA links internal-facing value networks to external-facing networks respectively with inside and outside participations (i.e. the associations between an economic event and an economic agent).

Finally, the REA^2 ontology (Laurier et al., 2018) unites the dependent with the independent view demonstrating by means of an operationalized mapping that the three perspectives on an economic exchange (i.e. buyer, seller and third party) are information equivalent despite being semantically different.

3. Model-driven Architecture

The Object Management Group (OMG) advocates model-driven architecture (MDA) as an approach to facilitate interoperability both within and across (technology) platforms by modeling the business logic separate from the application logic (OMG, 2020).

MDA distinguishes between computational-independent (CIM), platform-independent (PIM) and platform-specific (PSM) models. A CIM is also known as a domain model, which does not show any characteristics of the future system. It is very similar to an ontology. A PIM, on the other hand, is computer-dependent considering the logic of a type of technology but does not

consider the characteristics of a (vendor-specific) computer platform. A set of technology/vendor-specific transformation rules should then be able to transform the PIM in a PSM, which can subsequently be transformed in (executable) code. (Gaševic, Djuric and Devedžic, 2006, p. 111)

3.1 An introduction to MERODE

The MERODE (i.e. Model-driven, Existence-dependency Relation, Object-oriented Development) methodology (Snoeck, 2014) relies on the concept of existence dependency for its static platform-independent conceptual model (i.e. the Existence Dependency Graph (EDG)).

MERODE is currently supported by the Merlin online CASE (i.e. Computer-Aided Software Engineering) tool, which can be used for building the MERODE compliant PIM (i.e. the EDG), checking the business logic of the PIM (e.g. through the detection of infinite loops and deadlock in the lifecycles of objects) and for generating executable Java code, which implies that the PSM is tacit in MERODE. Figure 1 summarizes MERODE's MDA stack.

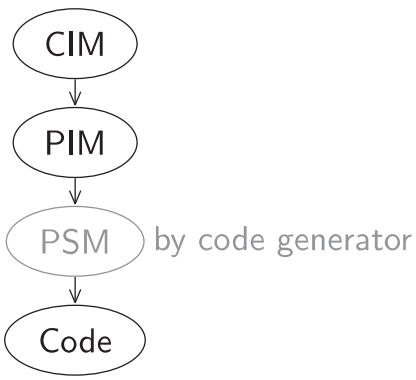

Figure 1 MERODE's MDA stack.

3.2 REA-aware MDA for the blockchain

Where Merlin currently only supports the generation of Java-code, and web-services an Ethereum smart contract generator called B-MERODE is currently being developed (De Sousa et al., 2020). Consequently, when developing ontology-aware blockchains, Merlin could still serve as a PIM editor, but its Java-code generator would be replaced by the B-MERODE code-generator for Ethereum. Where the OMG's definition would only require the CIM to be preserved, the B-MERODE approach would also preserve the previously validated PIM changing only the PIM-to-code transformation rules.

Laurier et al. (2021) have developed an EDG for the REA^2 (Laurier et al., 2018) ontology from which an executable Java application has been generated with Merlin. Once the B-MERODE code generator is operational, it should be able to transform the REA^2 EDG to an REA^2-compliant Ethereum blockchain.

This approach, in which REA or an alternative ontology serves as a CIM, the REA^2 EDG or EDGs of alternative ontologies serve as PIMs and different code generators (e.g. Merlin for Java, B-MERODE for Ethereum), should then allow for transforming these EDGs to applications using different technologies while preserving the business logic, which is expected to facilitate inter-technology (and inter-blockchain) interoperability.

We expect the ontology-aware MDA approach above to reduce the complexity and increase the ease of use of blockchain technology. Using MERODE, a mathematically well-founded MDA approach, we hope to increase performance and scalability of blockchains through decomposition and interoperability. By using ontologically well-founded definitions of the concepts in smart contracts and blockchains, we also hope to improve interoperability. Additionally, ontologically well-founded smart contracts and blockchains should reduce human error

through an improved understanding of the blockchain and smart contract code. Moreover, the MERODE approach should contribute to formal verification of smart contracts and blockchains, both at design-time (e.g. identifying infinite loops and deadlock) and run-time (e.g. operationalizing the REA axioms as in Laurier et al. (2021)). As MERODE also checks for infinite loops, it should be able to reduce blockchain's vulnerability to recursive calls (e.g. the DAO attack).

4. Blockchain

Blockchain[7] is a peer-to-peer network-based technology for distributed and decentralized databases that stores information blocks as ordered lists to solve the problem of maintaining the order of transactions, while the committed blocks are immutable to avoid the double-spending problem. (Casino et al. 2019, Nakamoto et al. 2008)

In her 2015 book, Swan identifies three iterations in the use of blockchains. Blockchain 1.0 is related to decentralized currencies. Blockchain 2.0 stands for the application of smart contracts and all things concerning economic exchanges enabled by this technology. An example is that of crowdfunding, where a platform can issue blockchain-based shares, which once the project is successfully backed act as regular shares and give right to dividends. Blockchain 2.0 can also help promote smart property. If a series of assets are registered on a blockchain, ownership of the asset can simply be passed by transferring the asset's private key from an individual to another. Blockchain 3.0 encapsulates applications beyond the scope of currencies, economics, and markets, most often concerning justice and governments-related issues such as IP protection, identity verification, or decentralized governments services. Below, we list 4 potential blockchain 2.0 applications of the REA-aware B-MERODE application introduced above.

4.1 The sharing economy

The economy tends to evolve toward more openness and sharing, while focusing on local economic development (Albinsson and Perera, 2012). This calls for a technology able to incorporate these new values in its design, in order to organize economic exchanges between individuals in a decentralized network.

In decentralized ledger technology (e.g. blockchain) lurks the promise of empowering individuals (Pazaitis et al., 2017). Anyone can join a blockchain, so it is open and inclusive. Block chains are consensus-based, so there is no need for a centralized authority. The technology is open source, so anyone can encode a different set of rules into its design, and as the tendency is to remain local, this set of rules can change from one local blockchain to another depending on what set of values the community agrees upon. Moreover, it is code-based and thus standardized, which allows for automation (Seebacher and Schüritz, 2017).

Open value networks could considerably benefit from these characteristics. For example, blockchains could help reduce energy waste by enabling peer-to-peer trading to promote local energy markets (Cali and Çakir, 2019). Some individuals are producing energy for their households thanks to the installation of solar panels on their roof. Depending on the weather, the solar panels can produce too much or too little energy for one household. The excess energy can then either go to waste or be shared with a neighbor with an energy deficit. Cali and Çakir (2019) proposed a blockchain design which incentivizes the local government authority, the

traditional energy providers, the consumers, and the prosumers (i.e. producing consumers) to openly join. This example use of blockchain shows that the technology enables the sharing economy by making privately owned goods easily available for public use.

However, the blockchain solution to the sharing economy does not come without challenges. Where blockchain could, for example, enforce the agreement between the owner of a property and its potential user without the use of a third trusted party thanks to a publicly available database, there would be a tension between the inherent design and value of the blockchain and individual privacy. Xu et al. (2017) propose a solution for this privacy issue through the use of cryptography.

4.2 Cooperatives of autonomous workers

Autonomous workers – workers who are not subordinated to the authority of an employer – have been growing in number in the last few years (+16,35% between 2008 and 2015) (Beuker et al., 2017) primarily due to companies' growing demand for flexibility, but also workers' aspiration for autonomy (Charles et al., 2018). Autonomous workers are particularly vulnerable to precariousness (i.e. job and revenue instability, absence of protection from injuries and equipment damage, etc.), as exemplified by a report commissioned by the EU Parliament (Koukiadaki and Katsaroumpas, 2017).

To reduce their vulnerability, some autonomous workers join cooperatives – i.e. organizations whose purpose is to offer services to its members, and that are owned and democratically managed by those members. Cooperatives of Autonomous Workers (CAW) enable their members to work autonomously on their entrepreneurial activity while benefiting from services of the cooperative, which are called "mutualized services" as they are jointly financed by all members of the cooperative. CAWs feature two types of services: (1) the access to a status of employee of the CAW (instead of freelancer or independent statuses), which gives workers an extended access to social rights such as unemployment, illness or retirement benefits and (2) the use of the CAW's mutualized assets, such as the tax identification number, which allows the worker to invoice clients and recover expenses from suppliers, but also more tangible assets such as an access to rooms, training, counselling or machines. There are hundreds of CAWs, mostly in Western Europe, and some of them gather more than 30.000 members.

CAWs could be seen as value networks as defined in section 2.1. Despite their taste for democracy and member involvement, however, Cooperatives of Autonomous Workers work in rather centralized ways: workers deal with the cooperative directly for all practical issues, and to express their requests, which puts the cooperative very much in the middle of the network (see Fig. 2, top). Blockchains could make these value networks less centralized (1) by fostering cooperation among members of the same cooperative, such that they exchange services (see Fig. 2, middle) and (2) by creating a network of CAWs, such that a person can be member of several CAW and benefit from a mix of services best suited for his or her situation and offered by a multitude of CAW (see Fig. 2, bottom).

The biggest obstacle to the development of decentralized CAW-member networks has been the CAWs' inability to create a clear, formalized and shared ontology (Desguin and Laurier, 2020). Such an ontology is expected to facilitate the development of a blockchain with the approach introduced above, which would help decentral-

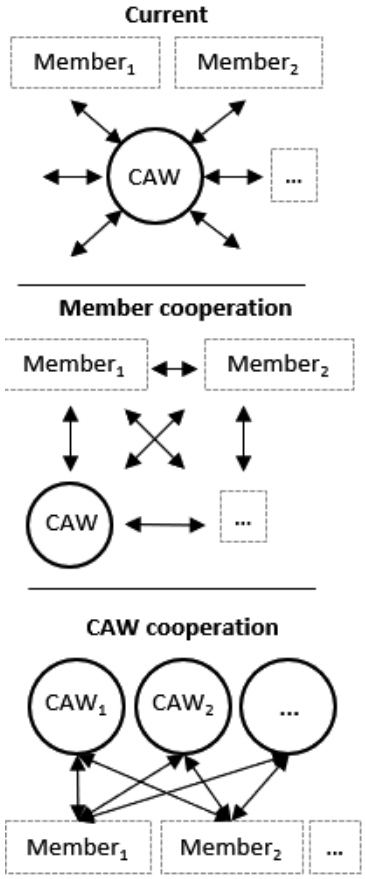

Figure 2 CAW-member network lay-outs

ize the data management.

4.3 Wood traceability

Unfortunately, the terms forestry and sustainable management are a sad oxymoron. A glance at the facts and figures about the world's forestry industry shows that there is still no sustainable global forest management. As indicated by Nellmann (2012), the issue of illegal logging remains highly problematic, especially for developing countries whose natural resources are exported illegally. According to Nellmann, 50-90% of logging activities in tropical forests are illegal. Globally, the illegal timber market accounts for 15-30% of the total market. This lucrative industry, valued at US$51-152 billion a year, seems uncontrollable, even in officially protected areas. These illegal activities also affect public confidence in government authorities, which are sometimes partly responsible, and compete unfairly with the legal forest sector.

This widespread illegal timber market does more than reducing essential revenues for developing countries and public confidence in government. This massive deforestation is also responsible for 17% of global carbon emissions. (Nellmann, 2012) In addition, tropical forests, the main victim of deforestation, perfectly capture carbon dioxide through photosynthesis. (Malhi et al., 1998) The rapid spatial reduction of these forests is therefore not only polluting but also hampers global efforts to mitigate global warming. Tackling this problem is therefore of crucial importance for the successful development of countries and the mitigation of climate change.

Many frameworks already exist to limit the extent of illegal logging. For example, the LEAF (Forest Law Enforcement Assistance Facility) initiative, coordinated by Interpol, aims to help countries address this problem, which is inherently international. (Nellmann, 2012) In addition, many types of certificates have been developed to assess the legality of wood-related operations at each stage of the value chain, such as the Forest Stewardship Council (FSC), LegalSource, Program for the Endorsement of Forest Certification (PEFC), etc. (Nellmann, 2012). Although these certificate systems are well organized and adopted globally or regionally, they face limitations such as their inability to report all timber harvesting or their inability to identify illegal activities. In general, these systems generally fail to effectively track wood products throughout the supply chain because they are slow, costly, unalterable and centralized. (Düdder and

Ross, 2017) What is needed is an incorruptible, decentralized, fast and inexpensive approach.

Academics have long studied the causes and consequences of illegal logging activities. In his book published in 2008, Luca Tacconi classified the different types of illegal logging, analyzing the extent of the phenomenon, its causes and its social, economic and environmental implications. His conclusions call into question the responsibility of states, which are often held co-responsible for this tragic situation. (Tacconi, 2008) Consequently, bypassing trusted third parties such as governments as is the case with blockchain, might be a desirable feature of an illegal logging nemesis.

Where Düdder and Ross (2017) highlighted the potential of the decentralized ledger technology to solve problems related to certification systems, others have explored its potential for improving supply chain management in general through decentralization (Baruffaldi and Sternberg, 2018).

4.4 Vaccine traceability

The pharmaceutical industry is confronted with many different logistics and supply chain management issues. Traceability is of paramount importance in the pharmaceutical sector. It is not only essential to ensure the quality of the product, but also to trace possible adverse reactions back to a given lot of drugs, its manufacturing, control, transport or storage. In the pharmaceutical industry traceability covers three stages. First, the identification of the source (i.e. supplier) and origin (e.g. chemical, microbiological, animal, human) of raw and starting materials. These materials must be tested and found compliant with compendial requirements. Second, traceability must be ensured in-house, throughout the entire manufacturing process, from starting materials through all intermediates to the final product. Third, traceability should be ensured downstream, from lot release by the company to patient administration.

Stage 2 traceability can be ensured through compliance with the requirements of the approved marketing authorization and with Good Manufacturing Practice, under the responsibility of the Qualified Person (QP).

Although less robust then the stage 2 traceability, the tracking of the raw and starting materials (i.e. stage 1) is also addressed by the pharmaceutical industry through procedures for vendor qualification and verification, supplier audits and approval. This exercise is also part of the regulatory requirements.

By contrast, the traceability of the product after its release by the QP (stage 3) is no longer within the sole remit of the industry. The involvement of different stakeholders (e.g. institutions, countries) makes stage 3 supply chain management especially challenging. This is particularly critical for vaccines since:

(1) Most of them are sensitive to high or low temperature, or both.
(2) They are distributed worldwide including Low- and Medium-Income Countries (LMICs), in which the good distribution practices and the cold chain are not always ensured.
(3) They are intended for healthy subjects and as such, their quality and safety profiles need to be outstanding.
(4) Often, they are intended for infants, a vulnerable population vested with an important affective load.
(5) A lack of efficacy can go unseen for years since they have a preventive (and not a curative) effect.

It is estimated that vaccines save millions of lives each year (WHO, 2019). An improvement

of the supply chain will reinforce their impact on public health and could thus save even more lives.

Distributed ledger technology (DLT) has the potential to support all three stages of traceability in the pharmaceutical industry, which is expected to facilitate the tracing back of a pharmacovigilance signal (e.g. adverse effect following immunization, breakthrough) or a quality complaint to a vaccine lot, its distribution channels and conditions for distribution, its manufacturing process and control. Recently, Yong et al. (2019), suggested using the blockchain to ensure vaccine authentication.

5. Conclusion

This paper advocates the use of ontology-aware model-driven architecture for the blockchain. This argument is supported by the example of a blockchain 2.0 (i.e. related to business eco-systems) MERODE model-driven architecture application (i.e. B-MERODE) aware of the resource-event-agent (REA) ontology, and four potential use cases for such a REA-aware B-MERODE application.

This paper also argues that the use of ontology would facilitate semantic interoperability between blockchains and between blockchains and applications in other technologies and has the potential to reduce human error, in addition to the interoperability-enhancing and error-reducing potential of model-driven architecture.

As the paper focusses on the utility of ontology and MDA for blockchain 2.0 applications, it focusses on the REA ontology, which is appropriate for representing the transactions in a value network. Additionally, it lists four potential use cases for a REA-MERODE blockchain. The first potential use case is the sharing economy in which blockchain technology could make value networks more open and inclusive. The second potential use case is collaboratives of independent workers, in which decentralized ledger technology could eliminate the need for a central coordinating entity. The third potential use case is wood traceability, in which blockchains could allow for worldwide tamper-resistant supply chain certification schemes that bypass governments and other central authorities. The fourth and final use case is vaccine traceability, in which blockchain technology could support tracking and tracing individual vaccines in the diverse and complex supply chain that ships an individual dose of a vaccine from the controlled environment of the production unit to the person it will be administered to.

As many of the technologies discusses in this paper (e.g. decentralized ledger technology, B-MERODE) are still under development, and as the use cases listed are mainly cases we are currently working on, this paper does not aim at reporting on the outcomes of past research, but rather at sharing our vision for the future.

Endnotes

1) https://beefledger.io
2) https://www.provenance.org
3) https://www.hyperledger.org/learn/publications/walmart-case-study
4) https://www.ledgerinsights.com/lvmh-luxury-blockchain-microsoft-consensys/
5) This example is based on the Wikipedia page on chess: https://en.wikipedia.org/wiki/Chess
6) Note: The discussion above is itself a case of construct overload, at the ontological deficiencies as the original definitions of construct deficit, redundancy, overload and excess in Recker et al. (2011) pertain to modeling grammars and an underlying ontology (i.e. a formal specification), where the definitions above respectively concern explicit specifications and the underlying tacit conceptualization. However, as, to the best of our knowledge, the ontology literature lacks

the concepts to describe this mapping, we chose to overload Recker et al.'s definitions.

7) For an elaborate definition of the characteristics of blockchains, we refer to Viriyasitavat and Hoonsopon (2019).

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