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Classification Model Of Supply Chain Events Regarding Their Transferability To Blockchain Technology

Fabian Dietrich[1,2], Eldin Mehmedovic[1,2], Ali Turgut[3], Louis Louw[2], Daniel Palm[1,4]

[1]ESB Business School, Reutlingen University, Alteburgstr. 150, 72762 Reutlingen, Germany
[2]Department of Industrial Engineering, Stellenbosch University, 145 Banghoek Rd., 7600, Stellenbosch, South Africa
[3]Steinbeis Innovation gGmbH, Alteburgstr. 150, 72762 Reutlingen, Germany
[4]Fraunhofer Institute for Manufacturing Engineering and Automation, Alteburgstr. 150, 72762 Reutlingen, Germany

Abstract

The blockchain technology represents a decentralized database that stores information securely in immutable data blocks. Regarding supply chain management, these characteristics offer potentials in increasing supply chain transparency, visibility, automation, and efficiency. In this context, first token-based mapping approaches exist to transfer certain supply chain events to the blockchain, such as the creation or assembly of parts as well as their transfer of ownership. However, the decentralized and immutable structure of blockchain technology also creates challenges. In particular, the scalability, storage capacity, and the special requirements for storage formats make it currently impossible to map all supply chain events unrestrictedly on the blockchain. As a first step, this paper identifies important supply chain events for different use cases combining blockchain technology and supply chain management. Secondly, the supply chain events are classified in terms of their expected technical properties and their relevance for the respective use case. Finally, the identified supply chain events are evaluated regarding their transferability to blockchain technology and a classification model is introduced.

Keywords

Blockchain; Supply Chain Events; Supply Chain Management; Classification Model

1. Introduction

To overcome the challenges in supply chains, such as increasing transparency, traceability, security, etc., the potential of blockchain technology has been proven in recent years [1]. The blockchain technology represents a distributed electronic register to store and retrieve information permanently, transparently, and in a trustworthy manner without the need of accessing a central instance [2,3]. Information is stored in so-called 'blocks'. Thereby the blocks and thus also the information in the blocks are encrypted with so-called 'hashes' [4]. Hashes are an encryption and can be seen as a kind of fingerprint or identification of the individual block. When a new block is created in this chain, a new hash is generated for the emerging block. In addition to its own hash, a block always includes the hash of the previous block. Therefore, the individual blocks are connected in a linear sequence to form a secure chain [4]. Another significant feature of blockchain technology is the decentralised network whereby every network participant has access to the complete blockchain [3]. When a new block is created, this information is sent to all participants in the network, so each of these participants verifies the newly created block and confirms the conducted changes in this block [5]. The blockchain technology is thus a decentralised database that can hardly be manipulated and is accessible to every participant in the network [4]. With the implementation of smart contracts, the technology became relevant for application areas beyond the financial sector [6]. Smart contracts are prefabricated program codes that specify the contract terms of the respective contract partners in advance and are triggered when the contract terms are fulfilled [6]. The mentioned characteristics of the blockchain in combination with smart contracts can be used for example to overcome challenges of supply chains [7,8] to increase their transparency, traceability, automation, and immutability [1]. A major challenge, however, is the simultaneous use of the three properties: decentralisation, security, and scalability. For example, increasing the degree of decentralisation and security of a blockchain system automatically reduces its scalability. This current correlation is also known as the blockchain trilemma [9]. In order to circumvent the scalability problem, it requires to divide supply chain scenarios into supply chain events (SCEs) to differentiate them individually when transferring them to a system such as blockchain technology [10]. The "Event Product Code Information Service (EPCIS) enables different applications to create and share event data with visibility, both within an enterprise and across enterprises [11]". Each event is described with the four dimensions of the generic 'EPCIS-Event'. These four dimensions are the object(s) or other entity(ies) that are the subject of the event, the date and time, the location where the event occurred and the business context [11]. In summary, the generic EPCIS-Event describes "what, when, where and why" happens. The 'what', in turn, is differentiated into the four core event types Object Event, Aggregation Event, Transaction Event and Transformation Event [11]. According to GS1, the definitions of these core SCEs are as follows [11]:

- *Object Event*. "The Object Event represents an event that has happened to one or more physical or digital objects".
- *Aggregation Event*. "The Aggregation Event represents an event that has happened to one or more objects that are physically aggregated (physically forced to be in the same place at the same time)".
- *Transaction Event*. "The Transaction Event represents an event where one or more objects are associated or disassociated with one or more identified business transactions".
- *Transformation Event*. "The Transformation Event represents an event in which input objects are fully or partially consumed and output objects are produced, such that any of the input objects may have contributed to all of the output objects".

This paper aims to classify SCEs regarding their transferability in a blockchain technology context. First, challenges when transferring SCEs to blockchain technology are presented to raise problem awareness and explain the rationale of the research. Secondly, the classification model is developed based on the fundamental structure of blockchain architectures in supply chain management and relevant data quality dimensions. Finally, a classification model is proposed and the results are discussed.

2. Related works and rationale of the research

Especially when mapping supply chains with complex products on the blockchain, a transfer of different SCEs is necessary [1,12]. To enable a holistic mapping, GS1 defines generic EPCIS-Events consisting of Object Events, Aggregation Events, Transaction Events, and Transformation Events [11]. With its special decentralised and immutable structure, the blockchain technology poses special requirements for the transfer of SCEs, which have not yet been uniformly clarified in research. Holtkemper [12] considers the storing of SCEs with (large) files on the blockchain practical at certain stages in the supply chain. Even though Holtkemper [12] considers the storage of files generally to be possible, he points out that due to the increasing storage capacity of the blockchain transferring certain files to different storage systems could be reasonable. Hepp et al. [13], on the other hand, point out that blockchain's structure has such a limiting effect on the transfer of SCE-Data, that certain files and transactions cannot be stored on the blockchain. In addition, Hepp et al. [13] indicate that the localisation of the data to be stored has an impact on the data integrity and transparency of the overall system. To clarify this matter, this paper develops a classification model of SCEs regarding their transferability to blockchain technology. In order to develop the model, data quality dimensions of SCEs are identified and evaluated in a blockchain technology context. The proposed classification model is intended to serve as a foundation for evaluating supply chain use cases in terms of their sense and feasibility with the adoption of blockchain technology.

3. Development of a classification model

In this chapter the development of the classification model takes place. First, the fundamental characteristics of blockchain architectures in supply chain management are described. Subsequently, this chapter discussed the data quality dimensions to be considered when transferring SCEs to blockchain technology. Finally, the results are summarised in a classification model.

3.1 Blockchain architectures in supply chain management

A holistic supply chain mapping has to include the mapping of the four supply chain core events (Object, Aggregation, Transformation and Transaction Events) [11]. As the evaluation of blockchain publications in supply chain management shows, most of the research deals with mapping approaches based on simple supply chains [1]. This includes the mapping of subsets of the existing event categories mentioned above, but not a holistic mapping of all core events in one architecture [1]. For this to be possible, it requires to connect physical assets to unique identifiers or 'digital profiles' on the blockchain [14], which is also known as 'tokenising of assets' [15]. Fundamentally, one can distinguish between two types of tokens, fungible token and non-fungible token [22]:

- Fungible token (FT): Different units of a FT are interchangeable and have no unique properties.
- Non-fungible token (NFT): Each unit of a NFT is unique from another, allowing the tracking of their ownership.

Based on these technical properties, FTs are particularly suitable to represent cryptocurrencies while NFTs, as the term 'non-fungibility' suggests, are intended to identify unique digital or non-digital assets [16]. This makes the adoption of NFTs suitable for mapping assets throughout supply chains on the blockchain [17]. For the holistic mapping of complex supply chains two different token-based approaches exist.

The first approach aims to map SCEs in individual smart contracts based on the non-fungible ERC-721 token standard [18]. Each SCE, except Transaction Events, is represented by a smart contract on the blockchain network. Transaction Events are already embedded into the ERC-721 token standard and do not require the deployment of own 'transaction' smart contracts. The other SCEs are represented by individual smart contracts and their creation can be connected to certain conditions. This means that the creation of a token can be dependent on another token, but the tokens themselves, however, are not logically coupled [19]. This architecture with individual smart contracts without logical coupling enables a fast implementation but merely a static mapping of supply chains on the blockchain [20]. Consequently, dynamic adjustments in the supply chain or product structure lead to a redeployment of all smart contracts which are affected directly or indirectly (smart contracts with defined dependencies on each other). This makes it difficult to maintain the architecture in supply chains that place high demands in terms of continuous flexible adjustments [20]. In addition, the lack of logical coupling complicates considerably the auditability of the individual tokens [19].

The second approach aims to map all SCEs holistically with functions embedded into one smart contract [20]. The individual SCEs can be both, dependent on each other through defined conditions and logically coupled with each other on an application level. With the help of an embedded authority concept, dynamic adjustments in the supply chain or product structure can be conducted without the need of redeploying a new smart contract on the blockchain network [20]. This allows the mapping of supply chains that place high demands in terms of continuous flexible adjustments. However, this approach considerably increases the planning effort before the deployment of the smart contract. Due to the immutability of the blockchain, eventualities regarding the structure and the supply chain events must be defined in advance and embedded into the source code [20]. Figure 1 shows the fundamental architecture with one supply chain smart contract in a decentralised blockchain network.

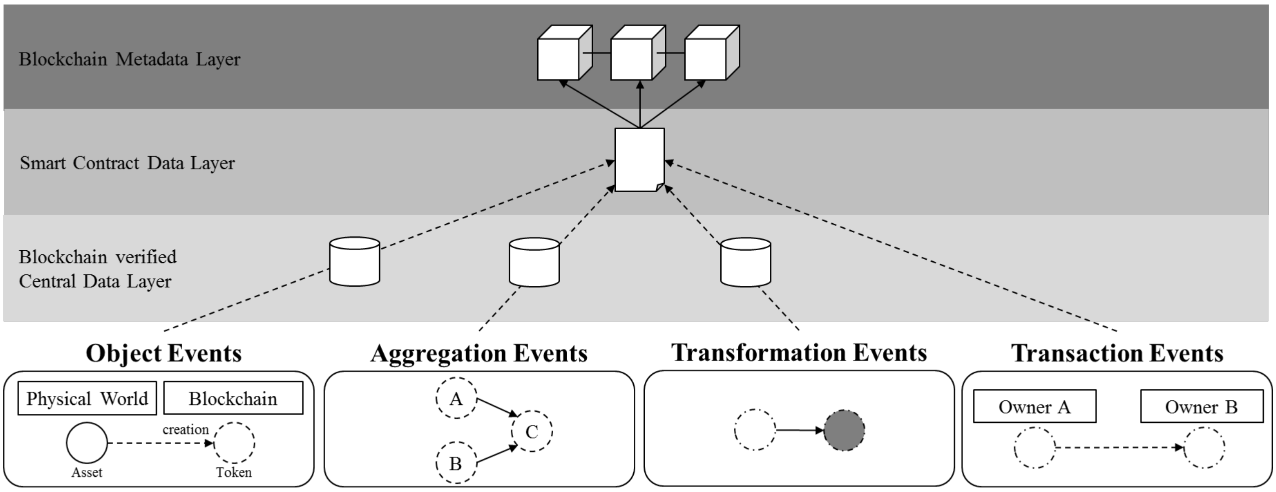

Figure 1: Fundamental architecture with one supply chain smart contract in a decentralised blockchain network

Figure 1 shows that in such architecture one can distinguish between three different data layers. The blockchain metadata layer provides the basis. Depending on the type of blockchain, private or public, either only selected participants have access to this data layer, or it is publicly accessible. The blockchain metadata layer includes the metadata of the network such as the time of transactions, the transaction initiators, or the type of transaction (financial transaction or smart contract interaction) [21]. The second layer consists of the smart contract data layer. This data layer contains the data to be stored within the smart contract. Only authorities with access to the smart contract have the possibility to access this information or add new information. From the perspective of transferring SCEs to the blockchain, this data layer represents the critical data storage. Unlike the metadata layer, the smart contract developer can determine the scope of data to be stored in this layer. However, they must adhere to the framework conditions of the blockchain metadata layer (see Section 3.2). Due to the limited scalability of blockchain technology, various approaches exist that extend the smart contract data layer with a blockchain-verified central data layer – so-called blockchain verified off-chain storages [21,22]. Such off-chain storage approaches store data in a content-addressable storage system, which stores files by their hashes. The respective hash is also stored in the smart contract on the blockchain and serves as a reference to the complete data set. Clients can then compare the hash resulting from the off-chain data with the hash stored in the smart contract on-chain. A modification of the data would result in another hash making it easy to verify the correctness of the off-chain stored data [22].

This raises the critical question of what data should or can be stored on-chain in the smart contract data layer and what data should be transferred to the blockchain verified central data layer. However, the type of SCE itself cannot determine this. For example, for some Object Events it is sufficient to add a simple identification number to the object when creating it; for other Object Events it is necessary to add an entire construction plan or a CAD drawing [12]. As a basis for such decisions, this paper considers an evaluation of SCEs based on different data quality dimensions.

3.2 Data quality dimensions

The mapping of core SCEs represents a transfer of data from multiple sources in a larger information systems context. When conceptualizing such larger information systems, Strong et al. [23] recommend a holistic view on data qualities (DQs). In this context, larger information systems "cover the organizational processes, procedures, and roles employed in collecting, processing, distributing and using data [23]".

Strong et al. [23] define four DQ categories: Accessibility, Representational, Contextual, and Intrinsic. The Accessibility DQ and the Representational DQ are technical in nature and must be ensured within the information system. The Contextual DQ and the Intrinsic DQ, however, must be ensured during the transfer of data into the information system. Transferred to the blockchain architecture presented in Section 3.1, the Accessibility DQ and the Representational DQ must be ensured within the blockchain technology and the smart contract, while the Contextual DQ and the Intrinsic DQ must be ensured when transferring SCE-Data to the blockchain and the smart contract.

Table 1: DQ categories and dimensions with blockchain relevance

DQ Category	DQ Dimensions
Contextual DQ	Relevancy, Value-Added, Timelessness, Completeness, Amount of data
Intrinsic DQ	Accuracy, Objectivity, Believability, Reputation
Blockchain Suitability DQ	Data Format, Transaction Frequency, Data Size

This paper extends the DQ categories by Strong et al. [23] with a blockchain specific DQ which aims to evaluate the suitability for storing data on-chain. Table 1 shows the DQ categories and dimensions with blockchain relevance. In this context, important DQ dimensions are represented by the data format (transactions, source code, or files) [12], the transaction frequency as well as the data size [13].

- *Data format*. Current blockchain platforms support the storage of transactions and codes, but do not support the storage of files [12]. Approaches exist that convert files into a blockchain transaction format, store them on-chain, and decode them to restore the file at any point [24]. However, if it is necessary that certain files remain in a certain format (e.g. PDF-files) throughout the supply chain, it is not suitable to store these files on-chain and a blockchain-verified off-chain storage is preferable.
- *Transaction frequency*. Blockchain platforms are inferior to central systems in terms of their transaction processing. For example, the main Ethereum network currently processes only 14 transactions per second [25]. Therefore, SCEs that require a higher scalability regarding the transaction processing, cannot be transferred to the blockchain network. If the transaction frequency of a single SCE is just below the transactions-per-second limit, it can theoretically be supported by the network, but could have a negative impact on the usability of the overall system. In this case, the overall transaction load of all SCEs must be aligned with the network capacity and considered in the decision whether events should be stored on-chain or off-chain. In this context, the threshold values differ depending on the blockchain platform used.
- *Data size*. The data size that can be transferred to the blockchain within one transaction is limited by the block size of the used blockchain platform [13]. Currently, the average block size of the Ethereum blockchain is around 50 KB. Similar to the transaction frequency, transactions with bigger data size must be evaluated regarding the holistic SCE context to determine whether the transfer of such events could have a negative impact on the usability of the overall system. Again, the threshold values also differ depending on the blockchain platform used.

The findings regarding the Blockchain Suitability DQ together with the DQs listed in Table 2 are transferred to a 3-level blockchain-related model (see Figure 2). The Contextual DQ ranges from irrelevant to relevant for the respectively considered use case. In between are SCE-Data, which are not relevant for the actual use case but potentially offer added value to the considered use case (e.g. detailed shipping information). The Intrinsic DQ ranges from poor quality to high quality, whereby the lowest DQ is for example represented by manual data input and the highest DQ can be provided by so-called blockchain oracles. “A blockchain oracle is a mechanism that fetches data from the external world to include it in the isolated execution environment of a blockchain. [...] Blockchain oracles are needed to bridge blockchains and the external world because of unique characteristics of blockchain [26]". Therefore, blockchain oracles act as trusted intermediary service between blockchains and a variety of independent data sources [27]. In between, 'normal' IoT (Internet-of-Things) devices that can transfer their data automatically to the blockchain provide a medium Intrinsic DQ. Figure 2 shows a summary of the findings with a three-level subdivision of the DQ categories. The results of this chapter are summarised and discussed in a classification model in Section 3.3.

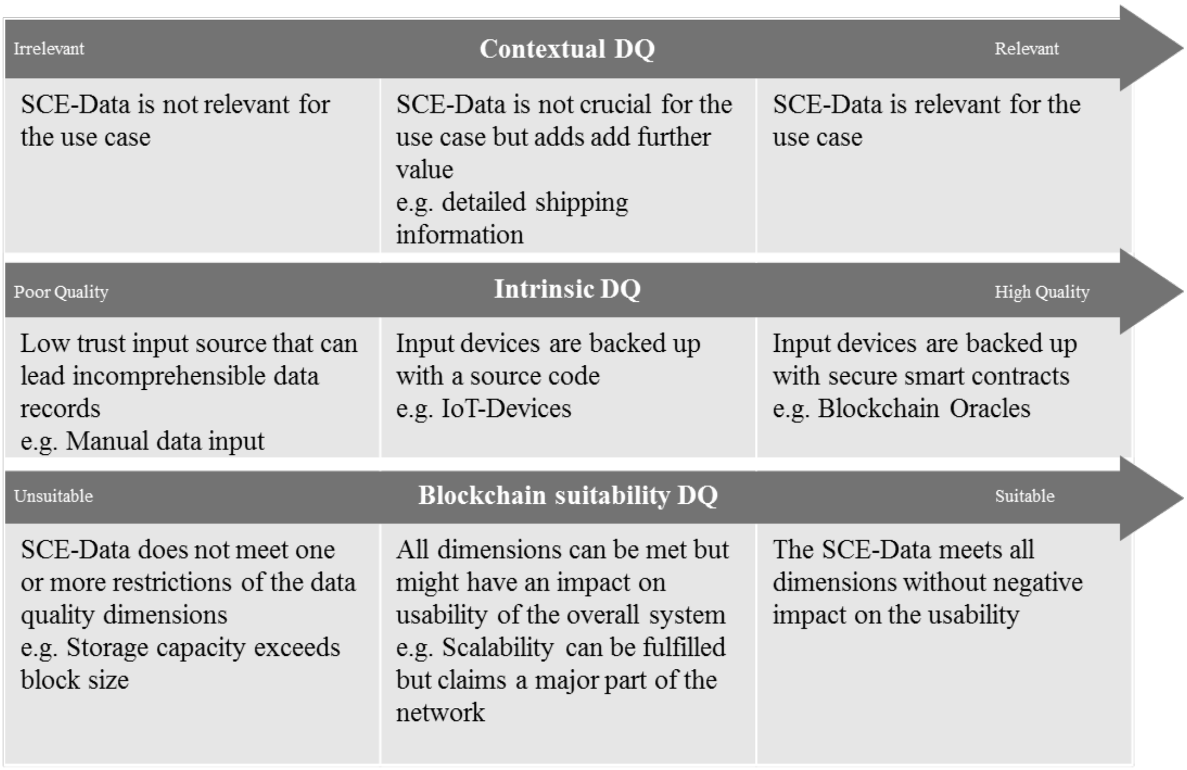

Figure 2: Three-level subdivision of the DQ categories with blockchain relevance

3.3 Classification Model

The findings of Chapter 3 form the basis for the three-dimensional classification model of supply chain events regarding their transferability to blockchain technology. Figure 3 shows the proposed classification model. In this model, the z-axis represents the Contextual DQ, the x-axis the Intrinsic DQ, and the y-axis the Blockchain (BC) Suitability DQ. The first number (1 x x) indicates the Contextual DQ, whereby irrelevant SCEs are rated with a '3' and relevant SCEs are rated with a '1'. These SCEs have add either low or high value to the respective use case. The second number (x 1 x) indicates the Intrinsic DQ, whereby poor quality SCEs are rated with a '3' and high quality SCEs are rated with a '1'. These SCEs determine the integrity of the input data and therefore affect the integrity of the overall system.

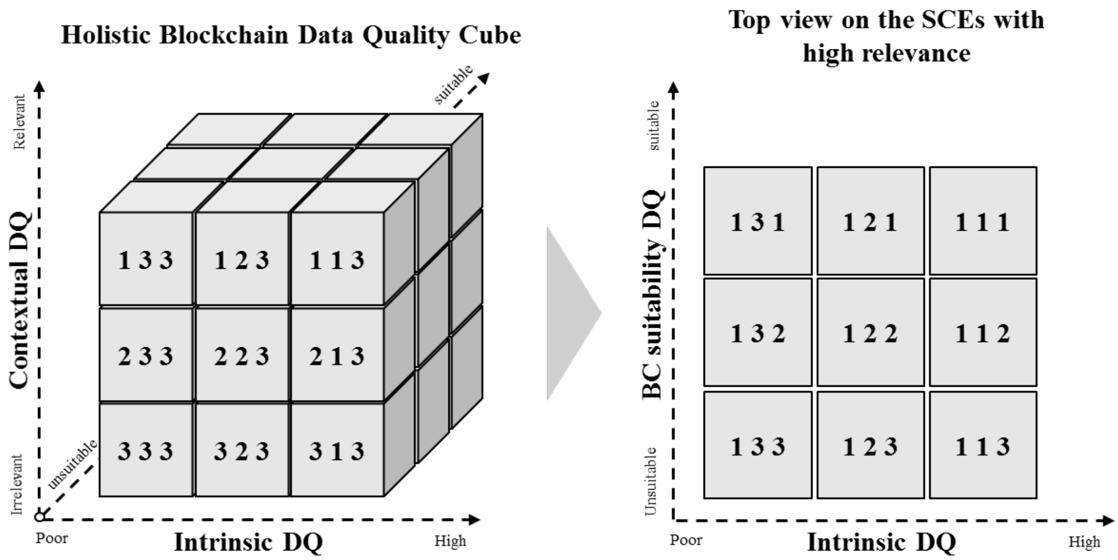

Figure 3: Classification model of SCEs regarding their transferability to blockchain technology

The third number (x x 1) indicates the BC Suitability DQ, whereby unsuitable SCEs are rated with a '3' and suitable SCEs are rated with a '1'. These SCEs determine the data transparency of the system. SCEs with are unsuitable for on-chain storage must be stored in blockchain verified off-chain storages and therefore indicate a low data transparency. In reverse, SCEs that are suitable for an on-chain storage increase the data transparency of the system. As the model shows, the SCEs events with low use case relevance, poor Intrinsic DQ, and unsuitable for an on-chain storage (3 3 3) represent the worst classification. The counterpart is represented by SCEs with high use case relevance, high Intrinsic DQ, and high suitability for storing them on-chain (1 1 1). Such SCEs add high value to the respective use case, guarantee a high data integrity, and offer a high data transparency.

4. Discussion

The proposed model enables a classification of SCEs regarding their transferability to blockchain technology. According to Strong et al. [23], it is essential that an information system consists of a high Contextual DQ and that the stored data provide an added value for the respective use case. Due to the scalability problems of blockchain technology described in Section 3.2, the Contextual DQ becomes even more important, as data without benefit for the respective use case would burden the overall system with unnecessary data traffic. For this reason it is recommended, to first of all filter the SCEs with high contextual DQ when applying this model to a certain use case (1 x x). As Figure 4 indicates, the top layer of the Blockchain Data Quality Cube represents such SCEs. In a second step, the selected SCEs with high relevance can be evaluated regarding their Intrinsic DQ. As described in Chapter 1, the blockchain technology provides a trustworthy, secure, and immutable data storage. Regardless of the Blockchain Suitability DQ, Blockchain projects that mainly consist of SCEs with poor intrinsic DQ (x 3 x) can severely compromise the integrity of the overall system. Therefore, the colour scheme of Figure 4 emphasises all SCEs with a poor Intrinsic DQ. Derived from this, supply chains with low Intrinsic DQ SCEs can be advised to raise the Intrinsic DQ of particularly critical SCEs (for example, by introducing RFID readers or Blockchain Oracles). Finally yet importantly, the selected SCEs can be evaluated regarding their Blockchain Suitability DQ. In particular, SCEs that require low data sizes and infrequent transaction rates are suitable for an on-chain storage. SCEs that do not meet one or more requirements regarding the DQ dimensions described in Section 3.2 are unsuitable for an on-chain storage and must be transferred to a blockchain-verified off-chain storage.

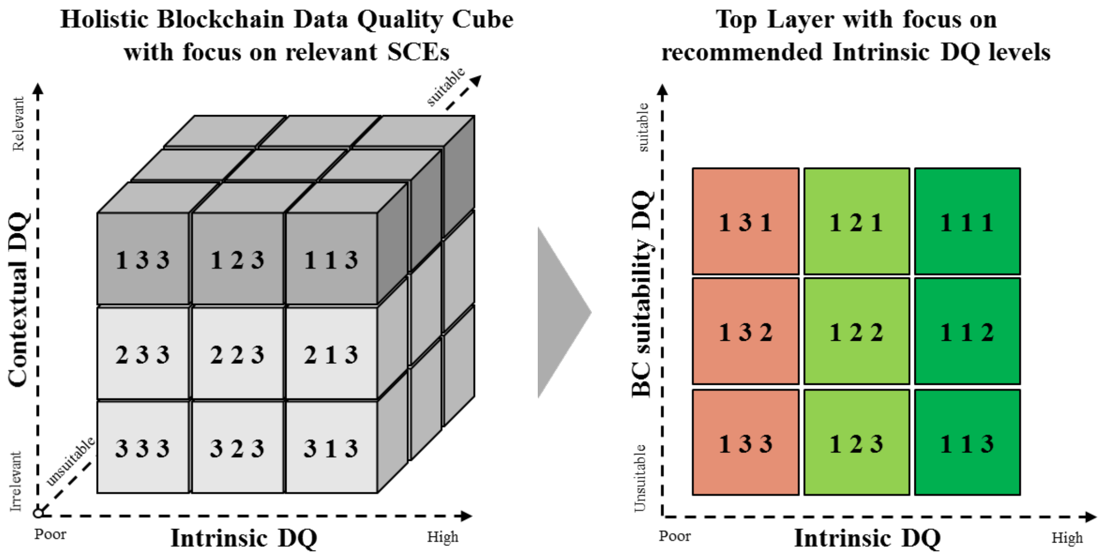

Figure 4: Blockchain Data Quality Cube with evaluation regarding recommended implementation approach

As mentioned in Section 3.1, transferring SCE-Data to an off-chain storage decreases the data transparency of the overall system. Supply chains with many ‘level 2’ Blockchain Suitability DQ Events (x x 2) must be further evaluated regarding the scalability of the overall systems. Although the SCE-Data sets are transferable to the blockchain technology, they could have a negative impact on the usability of the overall system. In such a case a multi-stage evaluation process could be considered, whereby the proposed classification model can be applied again to all SCEs with ‘level 2’ classification (x x 2). These can then be compared among each other and be evaluated based on their Contextual DQ, Intrinsic DQ and Blockchain Suitability DQ.

5. Conclusion

Token-based blockchain architectures enable a holistic mapping of supply chains on the blockchain. Thereby, SCE-Data can either be stored on the blockchain or in blockchain verified off-chain storages. The current limitations of blockchain technology in terms of its scalability have a significant impact when transferring SCEs to the blockchain. Based on the proposed model the authors recommend that the transfer should initially focus only on SCEs with high use case relevance. Here, the intrinsic DQ determines the integrity of the overall system and the Blockchain Suitability DQ determines the data transparency. Blockchain projects that mainly consist of SCEs with poor intrinsic DQ can severely compromise the integrity of the overall system and therefore, can be considered questionable. Regarding the Blockchain Suitability DQ, in particular SCEs that require low data sizes and an infrequent transaction rate, are suitable for an on-chain storage. Otherwise, the data must be stored off-chain. Thereby the block size and the transaction rate of the selected blockchain platform determine the limitation. SCEs with high resource requirements should rather be stored in blockchain verified off-chain storages. SCEs that require high resources but only occur infrequently, for example, can still be stored on-chain. The highest data transparency and integrity can be achieved in supply chains consisting of a large number of SCEs with blockchain suitable events and a high intrinsic DQ. The proposed classification model serves as a theoretical foundation for evaluating supply chain use cases in terms of their sense and feasibility with the adoption of blockchain technology. Further research is currently being conducted to examine the influence of the individual DQ categories on the feasibility of blockchain projects in an industrial scale. Furthermore, a prototype application is currently being developed to evaluate the practical feasibility of such blockchain-based SCE tracking system. In the proposed model, all DQ categories are assessed equally. Similar to the

Failure Mode and Effects Analysis (FMEA), a multiplication of the individual values can be taken into account. Derived from this, a different weighting of the individual DQ categories can possibly take place and a holistic feasibility framework for applying blockchain technology to supply chains can be developed.

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Biography

Fabian Dietrich (*1993) is Ph.D. Candidate (Industrial Engineering) at Stellenbosch University, South Africa and works as Research Associate at ESB Business School, Germany. He holds a M.Eng. (Industrial Engineering) from Stellenbosch University and a M.Sc. (Digital Industrial Management and Engineering) from the ESB Business School of Reutlingen University.

Eldin Mehmedovic (*1993) is currently pursuing a M.Eng. and M.Sc. double degree at Reutlingen University, Germany and Stellenbosch University, South Africa. His main research interests include blockchain applications in supply chain management in combination with Cyber physical Systems and IoT. In 2020, he received his B.Eng. from the Reutlingen University, Germany.

Ali Turgut (*1984) studied industrial engineering (B.Eng.) with a focus on supply chain management at the Esslingen University of Applied Sciences, Germany and the Kettering University, Michigan, USA. He is an employee in the area of innovation management at Steinbeis Innovation gGmbH and is completing a part-time master's degree in Digital Business Engineering (M.Sc.) at the Reutlingen University, Germany.

Louis Louw (*1974) has been an associate professor at Stellenbosch University since 2018. Previously Prof. Dr.-Ing. Louis Louw spent twelve years in industry as a business consultant and senior manager, before joining the university in 2014. His research interests are in the field of Digital Operations & Supply Chain Management, and he is a member of the International Association of Learning Factories.

Daniel Palm (*1967) is Professor for Supply Chain Management at the ESB Business School. Univ.Lektor Prof. Dr.techn. Dipl.-Ing. Daniel Palm is head of the teaching and research center for Value-Added and Logistics Systems at Reutlingen University and the Reutlingen Center Industry 4.0, RZI 4.0 - a cooperation of the Fraunhofer Institutes IPA and IAO as well as Reutlingen University.