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Abstract. Tracing products and processes across complex supply chain networks has become an integral part of current supply chain management practices. However, the effectiveness and efficiency of existing supply chain traceability mechanisms are hindered by several barriers including lack of data interoperability and information sharing, opportunistic behaviour, lack of transparency and visibility and cyber-physical threats, to name a few. In this paper, we propose a forensics-by-design supply chain traceability framework with audit trails for integrity and provenance guarantees based on malleable blockchain tokens. This framework also provides the establishment of different granularity levels for tracing products across the entire supply chain based on their unique characteristics, supply chain processes and stakeholders engagement. To showcase the applicability of our proposal, we develop a functional set of smart contracts and a local private blockchain. The benefits of our framework are further discussed, along with fruitful areas for future research.

Keywords: Supply chain · Traceability · Blockchain tokens · Smart contracts

1 Introduction

The Fourth Industrial Revolution is characterized by the convergence of various technologies, such as the Internet of Things (IoT) and blockchain, which are blurring the lines between the physical and the digital world. Such technologies may transform modern supply chain (SC) networks into complete digital ecosystems. SC digitization offers outstanding business speed, agility, and the development of traceability mechanisms (TM) that allow for an almost complete identification and recording of products and processes. It is worth noting that blockchain-enabled SC approaches coupled with IoT applications could improve the communication and the selective export of SC traceability data, enabling additional benefits to the logistics sector for data management and analytics [2].

SC traceability has attracted considerable attention in the last decade, particularly in safety-sensitive sectors, like food, pharmaceuticals and perishable agri-food products [1,11]. Traceability can be useful in product recalls, may improve process control and production optimization and reduce costs of liability claims and lawsuits. Moreover, traceability mechanisms build trust and foster the establishment of long-term relationships among disparate SC partners [27].

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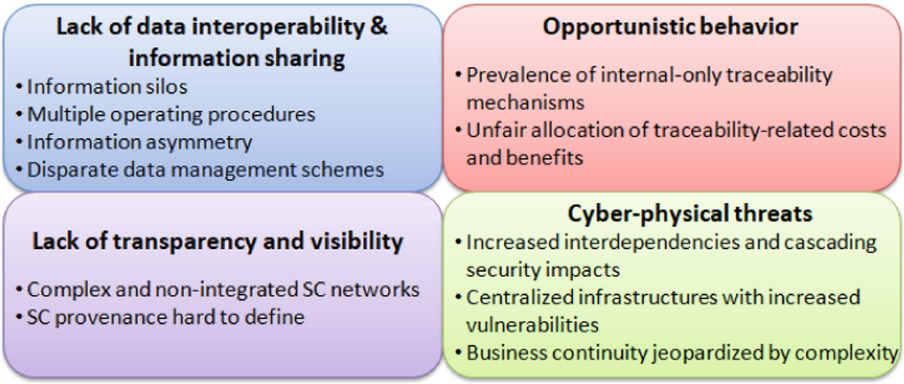


Fig. 1. Barriers hindering the development of TM in modern SC networks.

Blockchain is considered a foundational technology of the Fourth Industrial Revolution and is expected to play a crucial role in SC management [7]. In a nutshell, blockchain is a distributed and immutable data ledger, which enables the transfer of a range of assets among non-trusted parties securely and inexpensively without third-party intermediaries [7]. By providing trust in distributed environments, blockchain has the potential to offer full transparency and visibility within the SC, build confidence in legitimate operations, safeguard products quality and reduce administrative costs. Further benefits from the adoption of blockchain applications in SC traceability may relate to data interoperability, greater access to finance, auditability, integrity, and authenticity. Two features within the blockchain technology are of paramount importance: smart contracts (SmCs) and tokens. SmCs are agreements among mutually distrusting participants that may be executed in multi-peer environments and are automatically enforced by the consensus mechanism of the blockchain without relying on a trusted third party [10]. SmCs enable computations within the blockchain; thus, they operate as a decentralized virtual machine. Tokens are digital entities that may be used as a digital representation of physical assets (ingredients, subproducts, etc.) for tracing these assets individually. SmCs and tokens pave the way for the development of multiple new application scenarios in SC traceability, like product certification, deep traceability and cross-business tracing of products and services [7].

Establishing sound TM at a system level, however, remains a challenging task. As illustrated in Fig. 1, there are several barriers hindering the establishment of robust TM in SC networks. In particular, current SC networks are overwhelmed by information asymmetry, multiple operating procedures, and disparate data management schemes. As a consequence, traceability-related information lives in most of the cases in silos, where each participant has its internal TM and, inevitably, stores its unique traceability records. In addition, not all the collaboration models in SC are based on a "win-win" philosophy, and the prevalence of internal-only TM across SC networks unavoidably gives rise to opportunistic behaviours. Past experience has shown that the financial burden of implementing traceability may be borne by the processing firms (upstream SC members), while gains are reaped by firms in the distribution businesses closer to the end customer (downstream SC members) [22]. In addition, vast amounts of products are distributed/consumed globally with little knowledge regarding their origins, their manufacturing processes involved, and their storage/transportation conditions. Last but not least, SC networks are faced with both physical as well as digital threats, particularly due to: (a) the high and disparate number of participants from different sectors (e.g., industry, transportation, Information Technology-IT, government), with increased interdependencies and cascading security impacts; (b) the high volume of data that need to be managed and exchanged which often is based on centralized systems vulnerable to failures and attacks [28].

The literature related to blockchain tokens for SC traceability is extremely limited [18,30,33]. In addition, essential aspects of SC traceability, like the adoption of different granularity levels have received limited attention so far [13]. The primary goal of this paper is to address such issues. In particular, we propose a structured approach based on blockchain tokens and the usage of SmCs to define various granularity levels in SC traceability. The overall framework captures the multiple needs for precision in SC traceability (depth and breadth) by taking into account the products' unique characteristics, the various SC processes and the various stakeholders involved. Due to the adaptability and customized nature of the blockchain tokens, the proposed framework allows us to represent the entire granularity scales easily and elegantly across the entire SC and, therefore, create an accurate digital representation of the overall SC ecosystem. Moreover, the mutable characteristics of the blockchain tokens enable us to create practically infinite product definitions within the same structure, thus enhancing scalability and performance, a technical aspect which hasn't been addressed so far. Since the proposed framework is based upon the distributed and immutable nature of the blockchain, strong integrity guarantees and provenance regarding the SC traceability processes and the relevant data are provided.

The remainder of the paper is organized as follows. In Sect. 2, we provide an overview of the literature relevant to blockchain-enabled TM, with a particular focus on token-based approaches in SC traceability. In Sect. 3, we describe the proposed blockchain management framework for SC traceability services based on tokens. In Sect. 4, we showcase the applicability of the proposed framework based on a set of experiments. Finally, in Sect. 5, we review the main results and discuss future research directions.

2 Literature Review

The lockchain technology has been recently used for the development of SC traceability applications in various sectors [21]. For example, blockchain-enabled applications have been proposed for tracking gems [6], in the mining industry [24], for tracking medicines and pharmaceuticals [34], in animal product

SC traceability systems [25], for tracking electronic products [17] and in textile industry [14]. The main focus of the available blockchain-based traceability literature has been on the food supply chain [4,15], particularly, in agri-food SC management [5,8,12,32], for ensuring food provenance [23], in meat traceability [29] and in the coffee SC [31]. Apart from specific sectors, certain studies address issues of food security and safety [19] or define different granularity levels in food tracking [13]. It is worth noting that the blockchain-related traceability literature is extremely limited in scope, and the available frameworks present limited applicability (mainly because they do not take into account the invited scepticism related to blockchain's scalability and the high-energy use).

The use of blockchain tokens in business-oriented applications has received limited attention so far. For example, blockchain tokens have been mainly used as a financial engineering instrument [26], particularly for raising funds and engaging stakeholders [9]. Some token-based applications in the health care domain have also been proposed in the literature [20]. Regarding SC traceability, very few studies make use of blockchain tokens for tracking and tracing products [18] or for establishing ingredient certification schemes for commingled foods [30]. Arguably, the most relevant research is the one presented in [33]. The authors propose a blockchain-based approach for tracking manufactured goods based on tokens. The amount of tokenized goods that are required for minting a new token is defined by specific "token recipes", which resemble the bill of materials. It is worth noting that our token-based approach is significantly different from the approach presented in [33], particularly in the way tokens are defined (we make use of a set of adaptable/mutable tokens). In addition, our approach enables the development of TM with a high level of granularity.

3 The Proposed Framework

In this section, we provide the details of our framework for the blockchain-based SC. First, we present the details and equivalences of our framework in terms of physical to digital world transformation. Second, we define the actors/resources of our framework and define a set of bill of materials containing their possible values. Third, we provide a formal definition of elemental and compound tokens, both enabling mutable characteristics.

3.1 Tokenization of the Bill of Materials

For developing the token-based traceability framework we apply a bill-of-materials approach. A *bill of materials* (BOM) is a hierarchical list of raw materials, components, and assemblies required to manufacture a product [16]. By implementing a BOM checker we ensure that each component (at the lowest level of analysis) of a product is digitally represented by a token. The procedure is depicted in Fig. 2a. First, the bill structure checker receives a set of input tokens and checks their pedigree structure as well as their ID, to avoid token reuse. Note that the BOM of tokens information and the IDs that have been used are stored off-chain (by using decentralized permanent storage solutions, such as IPFS [3]). Next, the bill structure checker controls whether the pedigree tokens are included in the BOM of the token that we want to create. Finally, the checker creates the new token if and only if all the pedigree tokens are valid and in the bill structure.

In our approach, we apply a relaxed policy in terms of the BOM structure. We consider a product to be valid only if it contains at least one product of the corresponding BOM (and none out of it). Nevertheless, we can apply restrictions at the BOM structure level, in terms of minimum materials and quantities needed to pass the checker. This also enables the possibility to implement quality thresholds in the token design.

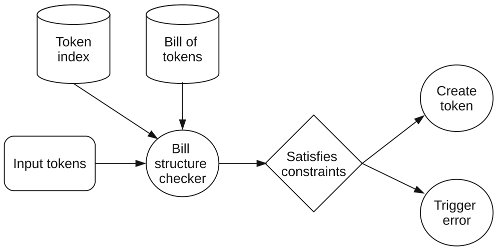
3.2 Main Actors and Resources

In what follows, we describe the characteristics of the main actors/resources of the framework, namely the products, the stakeholders and the processes. Moreover, we provide a generic BOM structure for each of them and describe their main properties.

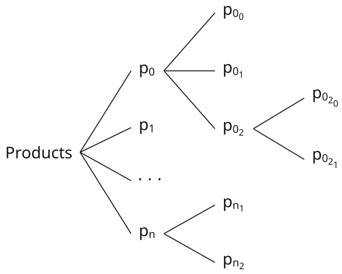
Product: A product can be defined as an article or substance that is a result of a process. Moreover, a product can be quantified and shared (in a physical and/or digital manner). An example of a BOM structure of a product (with each corresponding pedigree, represented as a child leaf in the tree structure) is depicted in Fig. 2b. Note that a BOM structure may be adapted/modified according to each product specifications and characteristics. We further classify products into *primary* or *secondary* products. The latter are the result of the combination of different raw materials, which could belong to diverse categories or subcategories. In addition, a secondary product p_i may contain or be the result of a set of sub-products (semi-finished etc) so that $p_i = (p_0, p_1, ...p_n)$. Note that, for the sake of clarity, we use p to refer to any kind of product. Depending on the product specification and its BOM structure (see Sect. 3.1), a secondary product p_i may contain zero, one or n different products (i.e. a specific sauce may not contain all the ingredients if a customer is allergic).

Process: A process can be defined as a series of physical, chemical, mechanical or digital operations that aim to transform or preserve a physical or digital element. For example, we may define a set of processes pr such that $pr = (pr_0, pr_1, ..pr_n)$ where pr_0 may correspond to a mixing process, pr_1 a grilling process, etc. In this context, we can define different bills of processes considering their characteristics and the activity that we are performing, such as transportation processes, packaging processes, chemical processes, etc.

Stakeholder: We define a stakeholder as an independent user or party involved in a process. Similarly to the processes, we can define a bill of stakeholders if necessary, depending on the level of analysis needed by our system.



(a) Workflow of the bill structure checker.



(b) Generic bill of products

Fig. 2. Bill of materials checker and a generic example.

3.3 Mutable Tokens

Our framework considers two types of tokens, namely elemental and compound ones. Elemental tokens store the information of basic primary products and their corresponding processes and stakeholders. The information of the primary products corresponds to a unique and integral element, which does not contain other tokens or products in its pedigree structure. The compound tokens inherit the properties and features that elemental tokens have and an additional pedigree structure, which contains information of the pedigree tokens used to create them. More concretely, the pedigree set contains a collection of 2-dimensional tuples in the form $(id, quantity)$, which store a token ID and the quantity of such a token, which is a physical subset of the corresponding product (e.g. one tomato or 0.5 L of milk). Therefore, compound tokens may contain a combination of compound or elemental tokens that contain the pedigree information not only of each inner product but also of all the processes and the stakeholders involved. Without loss of generality, a token t_i is defined as follows:

$$t_i = [(id, token\{(t_0, q_0), (t_1, q_1), ..., (t_n, q_n)\}, processes(pr_0, pr_1, ..., pr_n),$$
$$stakeholders(s_0, s_1, ...s_n), data]$$

Note that for elemental tokens, the pedigree structure corresponds to the source materials (i.e. primary products, as defined in Sect. 3.2). The contents of both types of tokens are described in Table 1. There is an additional field of information, where one can store the timestamp of the token creation, as well as supplementary descriptions.

Figure 3 shows an example of a pedigree structure. This structure follows the bill requirements in a cascade fashion (i.e. each corresponding token follows its own bill of tokens, processes and stakeholders), enabling quality inspections and auditability. The term *mutable* indicates that the contents of the pedigree structure can be different between the same type of tokens, enabling different combinations provided that each BOM is respected. Therefore, we do not need to define a new type of token for each possible combination during the design phase, as discussed in Sect. 3.1. An example is depicted in Fig. 4. A vegetarian salad

Table 1. Contents of each type of token. Note that the information presented in each field relates to the possible values of the bill of each category, as defined in Sect. 3.2. For instance, a compound token can only be created using the set of tokens defined in its bill structure.

Type	elemental/compound
Identifier	a unique alphanumerical identifier
Pedigree	source materials/pedigree structure
Processes	list of processes involved
Stakeholders	list of stakeholders involved
Other	Additional information, timestamps

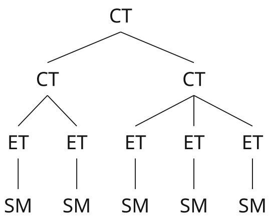


Fig. 3. High-level abstraction of a token pedigree tree. CT stands for compound token, ET for elemental token and SM for source material.

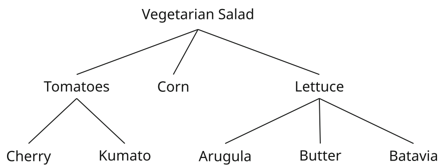


Fig. 4. Simple example of a vegetarian salad's BOM.

may contain lettuce, tomatoes and corn or any combination of such elements. However, it cannot contain chicken since it is not in its BOM. Note that for the existing mechanisms, the more the possible combinations, the less the resulting scalability, since the system needs to store variations (e.g. possible combinations and quantities of tokens to create a vegetarian salad) as a new token with a specific BOM. Nevertheless, our token definition solves this drawback by design, enhancing the scalability and performance of the system. Moreover, every token is linked to its pedigree using unique IDs.

4 Experiments

To showcase our method, we provide a use case scenario. Our example is based on the case presented in Fig. 4, which we now extend. Therefore, our final product is a vegetarian salad, consisting of multiple products, as seen in Fig. 5.

In this case, we consider that tomatoes, lettuce, onion, dried fruits and dressing (including oil) have a specific BOM. For example, the BOM of onions contains two possible onion varieties (vidalia and shallot). In this regard, the set of tokens and compound tokens needed to create the selected vegetarian salad is depicted in Fig. 6a. In the case of source materials, we specify the name and the ID of a product in the pedigree field. In addition, we specify three units of $et1$.

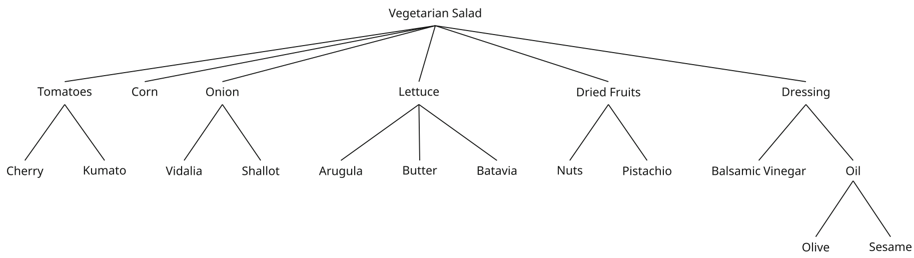


Fig. 5. The complete BOM of a vegetarian salad. Note that each component is digitalised as a token.

Type	ID	Pedigree (ID,quantity)	Proc.	Stake.
SM	213	cherry	1,2	1
SM	111	corn	1,2	1
SM	576	nuts	1,2	2
SM	4676	pistachio	1,2	2
SM	2667	balsamic vinegar	2,4	3
ET	et_1	$(213, 1)$	-	1,5
ET	et_2	$(111, 100)$	-	1,5
ET	et_3	$(576, 5)$	-	2,6
ET	et_4	$(4676, 10)$	-	2,6
ET	et_5	$(2667, 1)$	-	2,5
CT	ct_1	$\{(et3, 1), (et4, 1)\}$	5	4,7
CT	ct_2	$\{(et_1, 3), (et_2, 1), (ct_1, 1), (et_5, 1)\}$	5	8

(a) Set of tokens of a vegetarian salad.

ID	Description
1	Collection
2	Sanitisation
3	Dehydration
4	Aging
5	Mixing

(b) Processes.

ID	Description
1	Manufacturer A
2	Manufacturer B
3	Manufacturer C
4	Manufacturer D
5	Deliverer A
6	Deliverer B
7	Deliverer C
8	Manufacturer E

(c) Stakeholders.

Fig. 6. An example list of processes and stakeholders.

Thus, this salad will contain 3 cherry tomatoes. Note that the elemental tokens may contain not only a unit of a source material but a set of them. Moreover, a compound token can contain several units of an elemental token, as in the case of the cherry tomato (see the pedigree of ct_2 in Fig. 6a). Lists of possible processes and stakeholders are described in Figs. 6b and c. Finally, all the tokens contain their creation time, as well as additional info, if required. Note that further information of the processes can be specified in the smart contract, such as temperature or delivery time requirements in a transportation process. Nevertheless, the addition of other parties such as insurance and quality inspection organizations that may trigger self-executing penalties for misbehaving is left for future work.

An overview of the framework, from the creation of the primary goods until the generation of the final product is depicted in Fig. 7. First, we create the set of SmCs and fill them with the corresponding information (e.g. stakeholders, processes). Next, all the primary products are collected and transformed into an elemental token. Thereafter, compound tokens are created which contain all the pedigree information. Finally, the vegetarian salad is created using a combination of such tokens. At each step, the operations are translated into the blockchain by using specific functions. All the procedures are checked by the bill structure, which guarantees the validity of each token's contents, enabling features such as quality, provenance and auditability. As previously mentioned, this framework also enables mutable tokens so that similar products can be defined without the

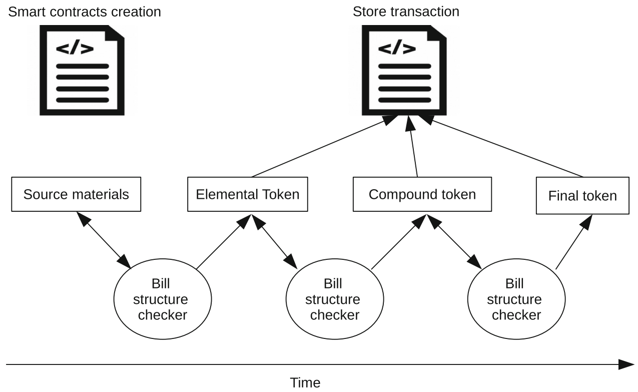


Fig. 7. An overview of the operations performed in our framework.

need to create a specific token in each case. Note that this is critical in contexts where each product may contain a wide variety of combinations, such as in the food industry. Further restrictions can be implemented in terms of quantities so that strict quantity policies can be implemented. It should be noted that we kept the example simple to ease its adoption, considering this functionality as a product-specific feature.

We implemented a set of three SmCs, each one devoted to managing the different resources of our framework (see Sect. 3.2). We use a smart contract to define the stakeholders' functions, another one to manage the processes and their characteristics and another one devoted to product and token creation and management, which checks the information of the other two (utilizing the *call* function) to ensure that the operations are legitimate. More concretely, we use `truffle`[1] and `ganache-cli`[2] to create a local Ethereum blockchain and deploy the SmCs, for which the code is shared in GitHub[3]. The interactions between the different actors can also be stored. Secure access policies manage everything, defining what information is visible by whom using the *require* clause of `solidity`. For the sake of clarity, an excerpt of the most relevant functions implemented in the token management SmCs, as well as a description, is provided in Table 2. In our implementation, we consider that only the creator of a token has permission to add contents to it (e.g. pedigree or processes). Nevertheless, this constraint can be relaxed so that a subset of stakeholders may have permissions over each token. In terms of costs, although writing in the blockchain needs the use of GAS, reading operations are free. Therefore, to minimize the costs, other solutions based on private blockchains will be explored in the future (such as Hyperledger).

[1] http://truffleframework.com.
[2] https://github.com/trufflesuite/ganache-cli.
[3] https://github.com/francasino/tokens.

Table 2. Functions available in the tokens' SmCs and their characteristics.

Function	Input	Output	Description
constructor	-	True/False	Creates and initializes structures
addToken	`id_token`, name, timestamp, pedigree [], processes [], stakeholders[]	True/False	Adds a token to the system
addPedigree	`id_token`, `id_pedigree`, quantity, timestamp,	True/False	Adds a pedigree tuple to a token
addPedigreeElemental	`id_token`, `id_product`, quantity, timestamp	True/False	Adds product tuple to an elemental token
addProduct	`id_product`, name, timestamp,	True/False	Adds a product to the system
addProcess	`id_token`, `id_process`	True/False	Adds a process to a token
addStakeholder	`id_token`, `id_stakeholder`	True/False	Adds a stakeholder to a token
changeStatusToken	`id_token`, boolean	True/False	Change status of a token
getToken	`id_token`	Object	Returns a token object and its contents
getPedigreeToken	`id_token`	List	Returns a token pedigree structure with the corresponding ids
getProcessToken	`id_token`	List	Returns list of processes used in a token
getStakeholderToken	`id_token`	List	Returns list of stakeholders involved in a token
getNumberOfTokens	-	Integer	Returns the number of available tokens, for statistics
updateNumOfProcesses	address	Integer	External update to avoid non-existing ids
updateNumOfStakeholders	address	Integer	External update to avoid non-existing ids
retrieveHash	`id_token`	Hash	The hash of the information of a token
triggerFunctions	-	Alert	Set of functions called after specific operations

5 Discussion and Conclusions

In this paper we have proposed a new blockchain-based framework for SC traceability. Based on a BOM approach we have created a digital representation of all the materials, sub-assemblies and intermediate assemblies of a product by using tokens. This digital representation is complemented by the provision of various granularity levels in the SC traceability processes. Contrary to the existing token-based traceability literature, we use mutable tokens so that similar products can be defined without the need to create a specific token in each case. To achieve our objectives we have used blockchain and SmCs as the building blocks of our framework. In particular, we have used blockchain as a distributed tamper-proof chain-of-custody mechanism and SmCs as an automation mechanism for managing SC stakeholders and processes as well as for token creation.

The proposed framework offers several benefits in terms of improved SC process management, security and resilience. The decentralized and secure nature of blockchain safeguards the accuracy, trustworthiness, timeliness, and usability of the exchanged traceability records. Keeping permanent traceability records on the blockchain creates an undeniable (and potentially unavoidable) transparency in SC where blockchain-certified traceability of products from source to store may be achieved. Checking for compliance by external stakeholders is further enhanced by the usage of SmCs that (a) improve the creation of highly robust audit trails and (b) render the overall process fully automated. By using tokens, each logistics unit obtains a digital representation on the blockchain and it may be individually traced by any stakeholder as it goes through the various SC processes. Moreover, to the best of our knowledge, this is the first work that proposes the use of malleable/mutable tokens, which enable better scalability and avoid asset redundancy, since one token may contain different pedigrees if defined in its BOM. Despite the benefits of our approach, our solution needs to be further refined to enhance its possibilities towards more complex scenarios. Therefore, various issues still need to be addressed such as: (a) large scale application of the proposed framework (with a multitude of SC stakeholders, processes and relevant products) for assessing its scalability and (b) combination of the proposed framework with various SC optimization approaches.

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