An Ontological Approach to Defining and Systematizing Traceability Terminologies

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Short Paper

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This paper outlines a structured ontological approach to defining and systematizing numerous product traceability terminologies in novel token-based and traditional enterprise systems (ES). It will aid researchers and manufacturers in regulated industries in defining syntactical and semantic standards for objects and events in the traceability domain. In this paper, a design science research method supports the development of a backward-forward-enterprise ontology (BFEO) artifact that helps to design and manage the complexity of multi-organization enterprise networks. This paper compares and evaluates this ontological artifact against several ontologies, offering further development opportunities. Finally, traceability professionals and various developer communities can adopt and further develop the ontology using simple development tools.

Keywords: Ontology, Blockchain, Enterprise Resource Planning, Traceability, Token

Introduction

For over a decade, manufacturers have used a variety of quality-assurance techniques and traditional ES, such as manufacturing execution systems (MES) and enterprise resource planning (ERP) systems, to facilitate traceability within complex centralized databases (Kuhn et al., 2021; Pytel et al., 2020). Regulatory changes, extended traceability requirements, and a heightened awareness of collaboration in supply networks have all motivated both researchers and practitioners to explore the use of novel token-based traceability concepts on blockchain (Dietrich et al., 2021; Sunyaev et al., 2021; Zamfir, 2020). Early attempts to combine MES, ERP systems, and complex use cases point to challenges for mapping product flows into a blockchain (Kuhn et al., 2021; Pytel et al., 2020). Due to the novelty of these efforts, both researchers and practitioners lack the necessary experience to manage integration across corporate borders, which is why early trial-and-error approaches can lead to misconceptions and misunderstandings during the adoption phase (Rogers, 2010). According to the authors, this inexperience increases the likelihood that the dissemination of the technology can fail. However, unambiguous terminology can serve as a foundation on which to generate and exchange data across multiple ES and organizations (Psarommatis et al., 2023). Terminologies describe activities and responsibilities, making each employee’s work standardized, transparent, and traceable within a manufacturing facility. Clarifications and ontological concepts can help to effectively explain data structures and map different blockchain types, such as Hyperledger Fabric and Ethereum (Hector & Boris, 2020). Our research goal is to combine the old enterprise-system-based world of product traceability with the new world of token traceability. We want to develop an ontology to address this technological contradiction. Therefore, in this paper, we explore, define, and systematize product and token traceability terminologies.

Method

In this study, we use the design science research method to develop an artifact, in line with Vaishnavi and Kuechler (2015) (see Figure 1). The *awareness* of the problem refers to the need for clear terminologies to conceptualize data structures for product flows across corporate borders. For this purpose, we use an ontological approach to design our artifact. Ontologies offer structured means of capturing the complexity of information systems (IS) and creating a shared understanding between multiple actors (Hector & Boris, 2020; Kim & Laskowski, 2018; Pizzuti et al., 2017). We employ *data collection* and *suggestions* from experts to identify classes, objects, and relations, avoiding a siloed approach and development from a single perspective (Psarommatis et al., 2023). The *development* follows the procedure for developing ontologies, in line with Noy and McGuinness (2001). The *evaluation* process entails communicating with experts and conducting criteria-based evaluations of ontologies (Raad & Cruz, 2015). Finally, we summarize our results and demonstrate the need for further development of the artifact.

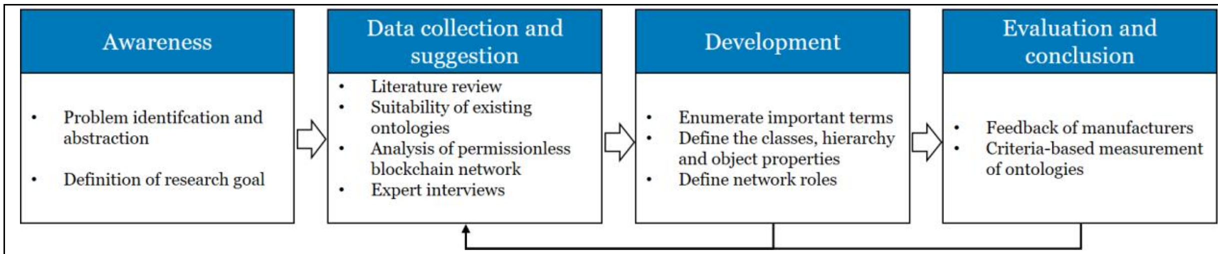

Figure 1. Research Methodology Based on Vaishnavi and Kuechler (2015)

Over the course of this study, we conducted three design cycles. The first cycle entailed analyzing and synthesizing traceability terminologies in the context of blockchain-supported supply network traceability use cases. The evaluation and feedback from manufacturing experts revealed that the first version of the artifact must consider supply network roles in a manufacturing environment. Furthermore, it revealed that terminology definitions in the literature have many shortcomings, as they rely on something other than actual technical blockchain implementations. Therefore, in the second cycle, we analyzed terminologies in an inductive manner consistent with a permissionless blockchain network. In the third cycle, we extended the data-collection process by conducting interviews with experts in four manufacturing facilities to define traceability roles. Finally, 14 traceability specialists and software developers evaluated the resulting ontological artifact.

Data Collection

Literature Review

The terminology employed by many industrial standards, including ISO 9001, ISO 22005, GS1 EPCIS, EU law, and traditional ES, results in researchers and practitioners struggling to easily understand the concept or directions of traceability (Islam & Cullen, 2021; Pytel et al., 2022). However, the distinction between “backward” and “forward” (BF) traceability is well-known in the manufacturing and food industries, justifying the analysis of terminologies in the scientific literature as a first step (Islam & Cullen, 2021; Jansen-Vullers et al., 2003). Following such a first step enables us to define the fundamental terms for a cross-organizational traceability analysis that is not reliant on a centralized authority (e.g., GS1, software provider), ERP, or blockchain (Pytel et al., 2023). To capture the current state of traceability terminologies, we searched for scientific literature in line with vom Brocke et al. (2015), using several scholarly databases (viz., Ebsco, ACM Digital Library, ScienceDirect, AISeL, IEEE Xplore, and Springer Link). We did not limit the search by publication year and included only articles relevant to supply networks. Even though DLTs would be a more appropriate search term from a technical perspective, we searched "blockchain," as it returned more results. Exclusion criteria applied to papers not written in English, papers that consider only one direction—backward *or* forward—and papers that only mention the BF concept in their conclusion. "We used the following search: "forward traceability” AND “backward traceability” AND blockchain. The search turned up 17 unique papers. We first selected 12 based on their titles and abstracts. Ultimately, 12 publications remained after a closer examination of the material. Table 1 presents the final list of papers alongside the following information: (1) the authors’ domain, (2) whether the authors discuss the directions of backward and forward (3) the author's distinction between track and trace (t+t) to refer to the directions of forward and backward, respectively, and (4) the employed organizational traceability standards.

	Domain	BF	T+t	Standards Used
(Al Barakati & Almagwashi, 2020)	Food and Manufacturing	Yes	No	
(Liu et al., 2019)	Food	Yes	No	
(Behnke & Janssen, 2020)	Food	Yes	Yes	
(Tagarakis et al., 2021)	Food	Yes	Yes	GS1 Standards
(Islam & Cullen, 2021)	Food	Yes	No	GS1 EPCIS, ISO, EU
(Freitas et al., 2020)	Food	Yes	No	
(Ling & Wahab, 2020)	Food	Yes	No	
(Yadav et al., 2022)	Food	Yes	No	
(Zhou et al., 2022)	Food	Yes	No	
(Schuitemaker & Xu, 2020)	Manufacturing	Yes	No	GS1 Standards
(Pytel et al., 2023)	Manufacturing	Yes	No	GS1 EPCIS
(Zhang et al., 2020)	Construction	Yes	No	

Table 1. Traceability Terminologies and Concepts in Blockchain-Supported Use Cases

The review reveals an emphasis on the food industry, with manufacturing and construction receiving significantly less attention. Only two authors distinguish between terms, with "trace" referring to backward traceability and "track" referring to forward traceability (Behnke & Janssen, 2020; Tagarakis et al., 2021). Instead of choosing a relationship to t+t, Schuitemaker and Xu (2020) set the two traceability directions based on a "traceable unit" (TRU) for the manufacturing domain. The authors only briefly discuss the integration into emerging technologies. Focusing on stronger technology, Liu et al. (2019) briefly describe manufacturing and food characteristics. The authors position backward and forward within the concept of "ownership," a component of emerging ES rather than traditional ES (Kuhn et al., 2021; Pytel et al., 2020). In summary, the fragmented traceability domain keeps open concepts—such as TRU, ownership, and t+t—that should accrue to BF traceability. This presents challenges for multiple manufacturers trying to achieve a shared understanding of data-mapping requirements and the integration of their ES.

Suitability of Existing Ontologies

Ontologies offer a potential way to capture real-world complexity in the form of classes, objects, and relations (Noy & McGuinness, 2001). There are four types of relevant ontologies (Guarino, 1998). The *top-level ontology* presents fundamental concepts that typically do not depend on a particular problem or domain and entail a high degree of abstraction. Ontologies for tasks and domains have a moderate level of granularity. *Domain ontologies* explain a general domain and deal with more specialized topics and ecosystems. *Task ontologies* are independent of a domain and describe general ideas linked to activities or tasks. The most specific notions are *application ontologies*, which combine domain and task ontologies. They define "roles" that specify domains and tasks in creating real-world applications. In general, ontologies should represent all of a domain's information but limit it to the visible problem or objective at hand (Calvanese et al., 2016). Before creating a new ontology, Nguyen et al. (2019) advise researchers to assess the suitability of existing ontologies. Table 2 lists existing ontologies relevant to the objective of traceability.

Notably, there may not be a single "correct" ontology of a domain or application; designs can vary depending on the relevant domain and technology (Noy & McGuinness, 2001). The analyzed ontologies offer different approaches for the design of classes, objects, and constraints, utilizing various modeling techniques and ontology-development tools (e.g., Protégé). Notably, none of the ontologies regards "backward and forward" as a central traceability concept. Only GS1 EPCIS is considered for use in holistic technology integration; however, there has yet to be a specific conceptualization for blockchains (GS1 US, 2020; Rejeb et al., 2020). Therefore, we opted to specialize the BFEO—a domain-type ontology for manufacturing—with assistance from Protégé.

	Ontology Type	**Domain**	**Technologies**	**Tools**
(GS1 AISBL, 2022; GS1 US, 2020)	Domain	Generic	ERP, Unspecified Blockchain	No
(Pizzuti et al., 2017)	Application	Food	Generic IS	Protégé
(Kim & Laskowski, 2018)	Application	Generic	Ethereum	Protégé
(Wessel et al., 2021)	Application	Manufacturing	ERP, MES	No
BFEO	Domain	Manufacturing	ERP, Hyperledger Fabric, Ethereum	Protégé

Table 2. Overview and Comparison of Product Traceability-Related Ontologies

Analysis of a Permissionless Blockchain Network

As a further inductive approach for identifying potential relevant terminologies, we have analyzed an open blockchain network and the flow of products (BlockBar, 2023). The BlockBar platform is a marketplace based on the Ethereum blockchain, which uses an ERC721 token. Due to its non-fungible nature, the extent to which the ERC721 token would have a real impact in complex manufacturing environments remains unclear. However, it is applicable to a 1:1 data mapping of serialized and final products (Dietrich et al., 2021; Westerkamp et al., 2020). We analyzed 9,352 transactions executed between the first minted NFT on the BlockBar platform on October 4th, 2021 and December 20th, 2022. We downloaded the data from etherscan.io in CSV format. The flow of products is illustrated below in Figure 2, in which edge thickness is directly proportional to the number of tokens transferred. Simplifying this representation, the basis for the generation of the node labels in the oriented graph is the Ethereum 40-hexadecimal addresses. The thickness of the edges is computed as the logarithm five base functions of the actual number of tokens transferred. Since the representation of the original graph with over 9,000 transactions is not readable, we only filtered in the edges that transferred at least five tokens.

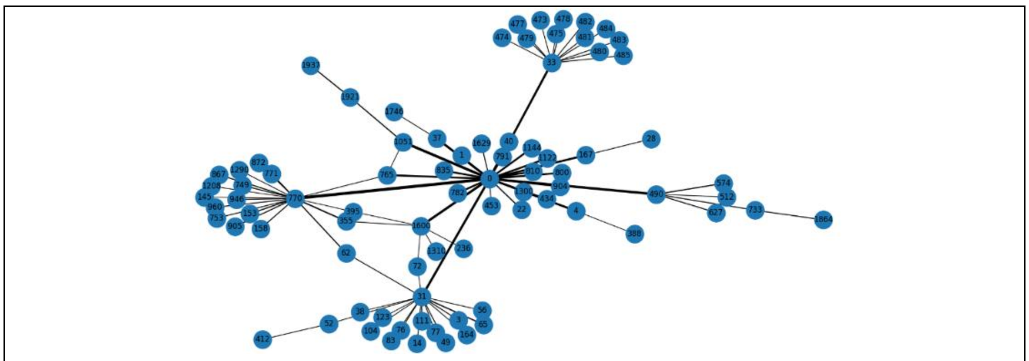

Figure 2. 0x0 Addresses and Flow of Tokens in a Blockchain Network

As a result of this network analysis, we included object attributes like *amount* and *token ID*, which can represent a serialized product movement in traditional ES and blockchains in a 1:1 relationship (Kuhn et al., 2021). The terminology of movements reveals that token events (e.g., transfers, sales) can differ from process-oriented ES events (e.g., source, make, deliver) (Pytel et al., 2022). Furthermore, the concept of ownership represented by addresses and address names (e.g., Johnnie-walker.eth, Hennessy-cognac.eth) can serve as a concept for mapping unique ES IDs (e.g., USID-ERP1.eth, USID-ERP2.eth) into a network (Pytel et al., 2022), representing a traceability role that both reads and writes data.

Design and Development

Representing knowledge in IS necessarily entails the development of human-understandable representations, rules, and relations. IT and domain terminologies can differ on a fundamental level, requiring more than a technical understanding of traceability in ES or a particular application to construct ontologies for a domain (Calvanese et al., 2016). Designing a comprehensive representation of knowledge requires a significant degree of expertise, especially in the context of a regulated manufacturing environment (Calvanese et al., 2016; Pytel et al., 2022). Although the development process begins in its most abstract form with the definition of different types of things and classes, it ultimately aims to reflect the real-world structure and the current stage of technological advancement. Using objects and relations, it describes the domain of interest in depth (Chandrasekaran et al., 1999). In the section that follows, we systematize the collected data, beginning with a "top-down" approach and continuing with a "bottom-up" approach, in line with Noy and McGuinness (2001). The top-down approach represents the early enumeration of important terms that we mapped onto classes. Related object properties then provide more attributes that relate to different classes. In the bottom-up approach, we used research prototypes (Kuhn et al., 2021; Pytel et al., 2020), the object attributes of network analysis, and technical documentation (Le Hors et al., 2021; Radomski et al., 2018). In the second iteration, we included expert interviews to add additional classes to the top-down approach. The integration of ownership concepts and token events led to the addition of attributes and relations to the defined classes.

Enumerate Important Terms

Backward traceability describes a "where-from" path in which output objects (e.g., finished products) serve as a starting point for the tracing analysis of input objects, such as raw materials. **Forward traceability** describes a "where-to" path in which input objects (e.g., raw materials) serve as a starting point for the analysis of output objects, such as finished products (Jansen-Vullers et al., 2003). Instead of looking back, this is a forward analysis that enables the identification of output objects. **Backward and forward traceability** defines the absolute traceability path that recalls require; however, it does not relate to the objective of a real-time application. Therefore, the terms relate to the terminology "trace." **Forward-tracking** describes an objective beyond recall situations entailing the analysis of defective inputs or outputs. Supply network actors have additional interest in the location, timestamp, and state of an object when it comes to order processing (partially or finally confirmed) or object state (OK or not OK) (Kuhn et al., 2021). These dynamic attributes depict specific physical movements or machine-related events. The term refers to the terminology "track" and satisfies the objective of a real-time application. **Object property** specifies physical or digital object ownership associated with a network entity and a TRU. A relationship connects an object property with at least one class. The term "TRU" often serves as an abstract concept for describing identifiable products, quality certificates, or humans (Jansen-Vullers et al., 2003; Kim & Laskowski, 2018; Pytel et al., 2022; Schuitemaker & Xu, 2020). Consequently, a token comprises the object attributes of a TRU (e.g., TokenID, serial number) to represent a unique asset in a network, offering a history of value creation and a traceability path through multiple related owners (e.g., ES of organizations). While the literature defines a token as an asset or asset type and a sequence of characters (Sunyaev et al., 2021), we define a token as a TRU encoded with organizations' history, movements, and evolving composition. **Event types** serve, in a traceability model, to distinguish between static and dynamic events (Kuhn et al., 2022). Static events refer to an object attribute's general (independent of temporal) behavior. Conversely, dynamic events refer to fine-grained changes to object properties that enable the description of an object's state as part of a sequence with timestamps. According to Pizzuti et al. (2017) and Pytel et al. (2020), the term "activities" describes high-granular logistic and machine-related events. Nevertheless, the BFEO exclusively uses "event types." A **role** describes a physical (human) or virtual (ES) object's participation in a traceability network system (Pytel et al., 2022). The active engagement and assumption of responsibility for running a network or transferring tokens are "internal roles." Conversely, "external roles" entail mere participation in a network without taking on responsibilities (e.g., transport service provider, private customer that only can read data).

Define the Classes, the Class Hierarchy, and Object Properties

The creation of classes is well-known among software developers on account of object-oriented programming. However, the creation of technical coding classes differs from the creation of ontology classes. The latter is focused not on methods but on structural properties, with classes describing the very concept of a domain (Noy & McGuinness, 2001). Summarizing important terms categorizes them as classes (yellow), data objects (blue), and relations. Protégé designed (Stanford University, 2023) and GitHub shared the results of the domain ontology publicly, where researchers and practitioners can access it (*GIT BFEO*, 2023). This repository will also house any additional information that the upcoming token-based enterprise applications generate. Since t+t utilizes terminologies across several fields, they provide the most basic explanation of a traceability IS and act as top-level classes. As the previous section on key concepts established, "Backward and Forward Traceability" and "Forward Tracking" provide more descriptive ideas regarding the objectives of a product's direction and act as a subclass. The basis for the input-output traceability subclass is the concept of complex product compositions whose terminologies stem from the input/output relations of mapping product structures in token-based prototypes (Kuhn et al., 2021; Pytel et al., 2020; Westerkamp et al., 2020). Finally, we included "Roles" from four expert interview transcriptions, as traceability data can be tailored to different roles (internal or external).

We utilized the Protégé tool's OntoGraf option to showcase potential interactions in a traceability example. Figure 3 illustrates how an ES (e.g., ERP SystemID) stores the data of four TRUs (e.g., serialized Product A-D). A traceability analysis (e.g., Output_Product_Traceability) of all TRUs could be conducted for internal traceability roles (e.g., employees that need information about product structure at different phases). Specific requests for external traceability roles (e.g., private customer) can be made to read specific predefined requests for traceability information, which can be valuable for customers (e.g., confirmation that all safety-relevant products have been correctly tested through the tracing analysis of related TRUs and quality events). Traces for different roles are created manually in the current stage, though they may be automated in the future.

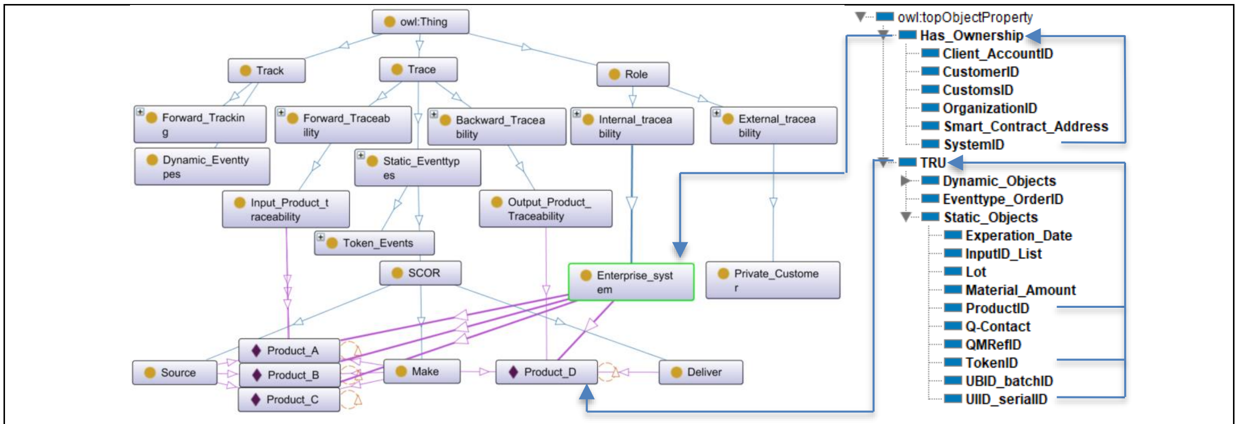

Figure 3. Classes and Data Objects of BFEO

Classes and data objects in the BFEO can capture syntactic and semantic structures of ES, products, and their related events. Furthermore, relationships among TRU, t+t, and ownership offer visual support and a more structured approach through the use of the BFEO. The data objects describe a possible mapping for several blockchain types, including Ethereum and Hyperledger Fabric, which rely on different data structures (Hector & Boris, 2020). Human-understandable language can also avoid misunderstandings between different developer teams via helpful comments attached to data objects: "We do not have wallet addresses in Fabric, and users need to know their account ID to transfer tokens" (Le Hors et al., 2021).

Evaluation

Since the design process involves several specialists, the development framework may vary significantly, and the design of ontologies can be highly subjective (Raad & Cruz, 2015). For instance, framework requirements can entail varying degrees of ES knowledge, laws, and experience in building a traceability path or assuring the quality of products in the case of an ontology for manufacturers. As previously stated, no single correct ontology exists for any given domain (Noy & McGuinness, 2001). The evaluation of an ontology, however, must ensure respect for criteria like quality and correctness (Raad & Cruz, 2015). The criteria that Raad and Cruz (2015) suggest using to determine which ontology is suitable for a given purpose are as follows: (1) accuracy, (2) completeness, (3) conciseness, (4) adaptability, (5) clarity, (6) computational efficiency, and (7) consistency. The ontology should conceptualize the design of a traceability system across multiple organizations in a way that covers the necessary concepts and terminology for manufacturers. Fourteen professionals and software developers with experience in ES traceability had to apply these criteria in semi-structured interviews. The interviewees received information about the problem statement, the objective, and the existing ontologies to understand the design and aims of the ontologies. The participants identified the GS1 EPCIS and BFEO ontologies as potential solution spaces. Common knowledge characterizes the evaluation, as none of the participants had any prior exposure to the two ontologies. The interviewees' capacity to work with the GS1 and BFEO ontologies was evaluated to measure efficiency. We asked the participants to assess a traceability example for products A–D both backward and forward. Two measurements were taken for each participant and ontology. All participants completed the BF analysis task using both the GS1 (median/average: 08:16 min/08:45 min) and BFEO ontologies (median/average: 03:30 min/03:52 min).

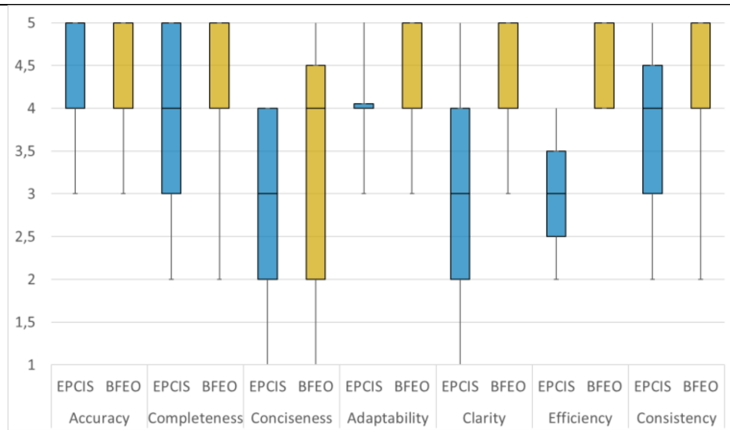

Figure 4. Comparison of GS1 EPCIS and BFEO Ontology

Examining the seven criteria suggests that both ontologies rank in the top third. According to the participants, the most significant distinctions between the two ontologies pertain to complexity, global and understandable terminology, and acceptance. The interviewees noted that the amount of information was much higher within the GS1 EPCIS ontology, making it more difficult to navigate. The GS1 EPCIS 2.0 standard boasts 229 pages in which it is challenging to identify and use relevant terminologies and details for traceability purposes (GS1 AISBL, 2022). These basic terminologies are clarified in the BFEO by the "Important Terms" section, which is short and tailored to the context of the manufacturing domain and to objects of traditional and emerging ES. While the BFEO appears to operate well, supply network actors may have more expertise with the GS1 EPCIS ontology, as its initial release took place over eight years ago (GS1 AISBL, 2022). According to the interviewees, the acceptance of one of the two ontologies is dependent on which domains will be addressed and which ES will be used to design a traceability IS. However, it is a matter of choice whether to adopt GS1 standards or to use the BFEO alongside a concept that represents TRUs as tokens, as additional development and integration into future applications can occur independently without the constraints of a centralized authority or community.

Conclusion

Future legal and traceability requirements may change, and cooperation across corporate borders requires a structured approach to develop a standardized language, avoid misconceptions, and manage the complexity of multiple organizations' heterogeneous ES. In this paper, we chose an ontological approach that selects and systematizes supply network and ES product flow traceability. As a result, we developed an initial version of a BFEO, which practitioners have evaluated. We consider this BFEO to be a modular framework that could be developed further for future use cases and roll-outs in order to manage variety in terminologies and avoid misconceptions between interdisciplinary teams. However, more research must be done on traditional and emerging ES to develop the ontology from a domain into a reusable and valuable application ontology that can aid in the development of novel product traceability use cases.

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