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Physical Internet Based Ontology for Supporting Traceability in Logistic IoT

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Abstract: : Information integration and sharing in a standardized manner is crucial to enable visibility, coordination and synchronization of supply chain activities, i.e., traceability within and across several companies. Product traceability is an essential tool fully integrated in supply chain management which should not only allow identifying, tracing and tracking but also ensuring product safety and quality. It helps to utilize the resources optimally and makes reliable the information and physical flows, accelerates the transmission of information on these flows, allows accessing a detailed knowledge of the product movements, and leads to the more effective management of the supply chain. However, several difficulties hinder product traceability implementation and make it a challenging task, including diversity of stakeholders, semantic differences between the involved actors, and lack of a shared language leading to confusion and misunderstandings, which make information exchange difficult. Highly expressive systems and techniques are therefore required. The latter must be characterized by the ability to exchange relevant data between stakeholders in a timely, meaningful and coherent manner. In this paper, we propose the development of an Ontology-based traceability system. The ontology is based on an architectural model for the physical Internet using computing resources such as Cloud computing, Fog computing and Internet of Things (IoT). The proposed system provides a shared and common language which improves information exchanges among all stakeholders in supply chains. To evaluate its consistency and efficiency, we carry out several queries dealing with different scenarios of product traceability. The validation results indicate that the developed ontology has the expressivity needed to represent all the knowledge related to the product traceability domain, enabling interoperability among different actors.

Keywords: Supply Chain Management, Logistics, Traceability systems, Physical Internet, Internet of Things, Cloud and Fog Computing

1. INTRODUCTION

In recent years, Supply Chain Management (SCM) has undergone a remarkable evolution at several levels such as production chain, storage policies, and particularly the transportation of goods both within and across several companies. SCM becomes a central element in business; it ensures the proper management, coordination and integration of physical and information flows and controls these flows in order to satisfy the customer, i.e. deliver the right product to the customer in the right place, at the right time, at the right price and at the lowest cost, and with the best quality. For that, integration and sharing of data and knowledge in a standardized manner along the supply chain is crucial to enable not only identifying, tracking and tracing but also guaranteeing product safety and quality, i.e. product traceability.

Product traceability is a fundamental tool fully integrated in SCM. It makes reliable the flows, accelerates the transmission of information on these flows, allows accessing a detailed information of the movements, and leads to the more effective management of the supply chain. However, due to industrialization and globalization, the diversification of distribution circuits and the development of ever more numerous and sophisticated products, SCM has become more complex, adding many intermediate steps between production and the consumer, and highly interdependent. In fact, supply chains have evolved and gone from simple local and linear chains to become networks of supply chains extended throughout the world, resulting in the notion of Supply Network. This new concept in SCM has developed intense exchanges of products and information within and across the companies, and has given rise to new requirements in order to ensure traceability and control costs.

However, several difficulties hinder traceability implementation and make it a challenging task including diversity of stakeholders, semantic differences between the interacting stakeholders, and lack of a shared language, leading to confusion and misunderstandings. Highly expressive systems and techniques are therefore required. The latter must be able to exchange relevant data between stakeholders in a timely, meaningful and coherent manner.

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In order to streamline and implement product traceability, we propose an ontology-based approach to implement an efficient and effective traceability system capable of transmitting accurate, up-to-date, complete and consistent product information, and would facilitate real-time tracking and tracing the route of products throughout the supply chain. It would support the continuous information monitoring of product traceability and record and associate the corresponding information with product movements. A link with their components is then established in order to be able to react as quickly as possible and at the lowest cost in the event of a crisis. To ensure this traceability, the product must be provided with an identifier, a reader must be able to interpret this identifier, and the information thus created must be put into context by an information system. The resulting system would place particular importance on the collection and processing of data from sensors and RFID chips, the orchestration of the various data collected by IoT technologies and the translation of this data into relevant information for decision-making for a communicating, integrative, flexible and collaborative supply chain.

In this way the development of an Ontology as a tool to model traceability and rules within product chain to provide a shared and common understanding, to improve information exchanges among all stakeholders in supply chains, and to control the flow of transported goods using computing resources such as Cloud computing, Fog computing and Internet of Things (IoT). To this end, we develop an ontology that represents the knowledge related to the product traceability in an interconnected supply chain considering the concepts of the Physical Internet (PI) and a Fog computing architecture associated with a Cloud to collect information and record product events from any point in the supply chain. That way, the proposed system will ensure the main traceability functions, including product identifying, tracing and tracking, and thus achieve efficiency and sustainability goals. It will provide unprecedented visibility across the entire supply chain, allowing different stakeholders to monitor and adjust distribution and transportation processes on the fly. It can significantly reduce operating costs and increase productivity.

To evaluate the system consistency and efficiency, we interrogate the developed ontology with several queries that the user can express whether he is a customer, a supplier or a manager dealing with different scenarios and problems in terms of the condition, location and traceability of their products. The validation results indicate that the ontology has the needful expressivity to represent all the information related to the product traceability domain, enabling interoperability among different actors and allowing for integrating the heterogeneous data adopted by each actor involved in the supply chain.

The remainder of the article is as follows: in section 2 we briefly introduce the research methodology for the design and development of the ontology-based traceability system. Section 3 presents background concepts of supply chain management (SCM) and traceability in SCM, we also introduce the notions of Internet of Things (IoT), Cloud, and Fog computing. Section 4 provides a comprehensive literature review on existing traceability systems. We define the research context of setting up Physical Internet (PI) to address product traceability and transportation in section 5. Next, we describe the ontology approach to the design and development of a traceability system using the PI paradigm in section 6. Section 7 is devoted to the system evaluation. Finally, the findings are summarized and some clues of future work are provided in section 8.

2. RESEARCH METHODOLOGY

In this research we employ a four-phased iterative research methodology for the design and implementation of our system. It is summarized as follows:

In the first phase, the literature review that we have carried out in this research takes stock of the state of the art of traceability in a Supply Chain Management vision which favors an inter-organizational perspective. We employed the literature to design and develop the ontology engaging domain experts and users.

In phase two of this research, the design of a technological solution best suited to the objectives set to meet regulatory requirements and ensure complete monitoring of product traceability was elaborated. Thus we formulated an initial ontology for product traceability based on fog computing in the context of physical internet.

In phase three, we achieved the development and refinement of the ontology. Generic and specific-purposed ontology concepts were identified and developed, and implicit and explicit relationships between concepts are elicited. At this point the generalizability of the developed ontology is emphasized. We implemented the ontology structure and knowledge using some dedicated tools such OWL-DL language, PROTEGE, RDFS, SPARQL.

In the fourth phase, we validated the ontology and evaluated the performance and efficiency of the system by carrying out a traceability simulation and sample queries.

In the following section we present background concepts of supply chain management (SCM) and traceability in SCM, and the notions of Internet of Things (IoT), Cloud and Fog computing.

3. PRELIMINARIES

A. *Supply Chain Management*

There is no single definition for the supply chain, In [1] the following definition is given: "The supply chain is a network of connected and interdependent organizations that cooperate and work together to control, manage and improve physical, information and financial flows from suppliers to end customers”: 1) Physical flow is concerned with the materials transportation throughout the supply chain, taking into account the time and place constraints; 2) information flow guarantees the sharing of data between the different links in the supply chain, such as product traceability, customer demands, and interactions between distributors, retailers and the end customer; while 3) financial flow relates to the financial management of companies: sales of products, purchases of components or raw materials, as well as production tools. SCM can be considered from different points of view (company, customer, or supplier) and it can be more or less extensive (centered on the company alone, extending from the supplier to the customer or from the supplier to the customer). In the case of supply chains of modest size, the company is seen as a succession of functions which can be assimilated to a supply chain of functions or an internal supply chain. Supply Chain Management (SCM) represents a performance tool for the company that brings together the approaches and functions needful to meet the triple objective of improving service levels, reducing costs and creating value, by managing relations, both upstream and downstream, with suppliers and customers [2][3].

The reality of the exchanges between the actors of the Supply Chain no longer really constitutes a chain in the linear sense of the term, since the same supplier refuel different retailers and a retailer distributes to several customers. This is how networks appeared instead of chains, and from there was born the concept of the logistics network or Supply Network.

B. The Concept of Traceability

Logistics management for flow control is inseparable from traceability, which makes these flows visible. The term traceability is defined as ”the ability to study in detail the history of a given activity or process”. Traceability enables to track an entity qualitatively and quantitatively in space and time by means of recorded identifications [4][5]. The term ”entity” can be a process, a product, a person or an organization. When relating to a product, traceability can refer to direct properties of the product and/or its associated ones such as product condition (temperature, humidity, etc.) throughout the supply chain, batch numbers, the origin of materials and parts, the history of processes applied to the product, the distribution and location of the product after delivery [6], enabling both suppliers and customers to track the goods throughout the chain and locating them along their route, using various means of identification such as batch numbers or various associated data. For companies, traceability is an obligation; it allows avoiding major problems for sectors in which production defects can have serious consequences for people in terms of health and safety. In information management, setting up a traceability in supply chain consists in systematically associating an information flow with a physical flow; the objective is to be able to find, at any time, the conditions (location, temperature, humidity, etc.) relating to batches or groups of products throughout the supply chain based on one or more identifiers [7][8]. Product Traceability has the function of identifying the products and to inform the management structure on the product conditions. Two types of traceability can be distinguished: 1) logistics traceability or ”tracking” which means the quantitative monitoring of products; and 2) product traceability or ”tracing” which refers to the quality monitoring of products. Overall, it allows linking a product to its environment (history of raw materials and manufacturing, destinations, etc.) through actions of reading, marking and registration, and thus creating informational links [6].

C. The Internet of Logistics Things

In recent years, due to the enormous technological progress, IoT technology expands and becomes completely integrated into our lifestyles. More and more everyday objects and sensors are connected to the Internet. This allows providing new functionalities to users. These objects have very different characteristics. Some are mobile (robots for example), others are controlled by a human user or only interact with other connected objects (Machine-to-Machine or M2M communications) [9]. The IoT theory supports the idea that today any object can be connected to the Internet. In other words, this concept means that ”the internet can extend to objects and places in the real and physical world” [10][11]. IoT is a network of networks that allows via standardized and unified electronic identification systems, and wireless mobile devices, to directly and unambiguously identify digital entities and physical objects. Thus, we will be able to retrieve, store, transfer and process the related data without discontinuity between the physical and virtual worlds [12][13]. IoT applications can respond to needs of SCM for material goods, documents or immaterial exchanges, in particular: identifying and recognizing a product based on tangible elements; verifying the characteristic elements for product authentication, verifying the integrity of both the products and containers, and enabling traceability and regulatory control. The IoT generates a very large volume and a variety of data that must be processed and analyzed by a Cloud computing infrastructure for example.

D. Cloud computing

Many objects connected to the Internet require low-latency computing and large storage space so they can make decisions quickly. For example, for an autonomous and connected car, the data transmitted from its sensors must be processed as quickly as possible so that the car can react and avoid an accident. However, for cost reasons, these objects very often have limited computing and storage capacity and do not have the necessary resources to process the data they collect.

The commonly used solution is to utilize an external infrastructure such as Cloud Computing [14]. These processing centers are generally connected directly to the

Internet. Large vendors distribute data centers around the world to provide access to systems in less than 50 ms from any location. The user can access to services on demand, set up and manage the configuration remotely by means of a command console.

The integration of the Cloud has offered several advantages, particularly in the field of product traceability in supply chains [15]. However, due to their centralized architecture, Cloud Computing infrastructures are not adapted to the needs of the Internet of Things as the location of the data centers, far from users and connected objects, decreases the latency time [16]. This makes cloud computing ineffective in a number of use cases for which the response time is crucial and the data produced by the IoT is various and speedily generated. Furthermore, with few data centers, the number of objects connected to each center is ever increasing. This overloads the network, particularly at the links level that converges on these infrastructures, and makes it difficult to scale up. For all these reasons, other solutions are explored, including fog computing.

E. From Cloud Computing to Fog Computing

As applications implementing the distributed services of the IoT are increasingly used, cloud computing can no longer meet all this demand, particularly applications that are sensitive to latency. In order to overcome these limitations, the ideal solution is to bring the processing closer to the IoT devices by applying another paradigm called "fog computing" [17] which represents an extension of cloud computing.

Fog computing has been defined as a platform that provides computing, storage, and networking services between end devices and traditional cloud computing, usually located at the edge of the network. The Fog extends the Cloud to get closer to IoT devices. The devices, called fog nodes, can be deployed anywhere with a network connection: in a factory, on top of a utility pole, along a railway track, in a vehicle or on an industrial platform. Any device with computing, storage, and communications connectivity can be a Fog Node. Examples: industrial controllers, switches, routers and servers [18].

Fog provides resources to the various underlying IoT nodes. Compared to the traditional Cloud, the Fog is a micro-data center (Micro data center) with low capacities and resources compared to a Cloud data center. The Fog also includes one or more gateways that contribute to smarter data communication, according to application requirements [19]. Since Fog nodes are often in close proximity to IoT endpoints, analysis and response are much faster than from a centralized cloud hence fog computing low latency. As opposed to batch processing, such in the case of cloud-based, fog-based applications involve real-time interactions and responses [16]. Fog computing could improve the performance of different applications such as SCM. It brings processing closer to the location of data, making it advantageous to support for mobility and make decisions closer to the data source without needing to process some data in the cloud.

4. LIERATURE REVIEW

Traceability systems are technical tools intended to help the company to comply with defined objectives. They will be used to determine the history and/or location of a product and all of its components. These systems are useful especially in perishable products such as foods and pharmaceutical products, in particular to ensure compliance with the cold chain, as well as the expiry dates relating to the various products [20].

Implementing a traceability system means mapping the route followed by a product and developing recording instruments. From a user perspective, traceability can be defined as tracking products qualitatively and quantitatively in space and time. From an information management point of view, implementing a traceability system in a supply chain requires systematically establishing a direct correspondence between physical flows and information flows. It is a first principle, common to all traceability systems.

The traceability system includes a set of procedures that help to know the location of a product during the supply chain at each moment and to retrace its route and know its destination location through reading, marking and recording actions, and to create informational links. Proper use of this information allows managing a posteriori and sometimes a priori the risks, quality and condition of the product. The traceability system must therefore ensure the synchronization of product flows with associated information, but this is only effective when the traceability bases are provided in real time, hence the essential use of efficient tools.

A traceability system is composed of:

1) A Hardware Platform It consists of a Material Handling System (MHS) with tools for physical identification of products, for example by **R**adio **F**requency **Id**entification (RFID), a read/write equipment, barcodes labels or electronic chips. This identification allows to associate an identifier with each traced product in order to be able to track it and distinguish it unequivocally in the workshop and in stock;

2) A Software Part It is made up of recording tools for acquiring, controlling, processing and storing data flows in the database allowing links and archive information, and communication tools made up of associated input/output interfaces through which the traceability data of a product is accessed at any time and exchanged within the system [8].

Numerous tools and software have emerged to make it easier the control of the product flows. We distinguish two families of systems: the first consists of using personalized spreadsheets (with automatic calculation or statistical processing of data) whose users secure the formulas themselves and make regular backups. The second family corresponds to marketed software packages offering the integration of traceability information, of which six main types are identified. Among these tools, we can cite ERP (Enterprise Resource Planning), SCE (Supply Chain Execution), MES (Manufacturing Execution System), AOM (Advance Order Management), APS (Advanced Planning System), WMS (WareHouse Management System), TMS (Transport management System), CRM (Customer Relationship Management) and software packages dedicated to traceability.

Several software packages dedicated to traceability have been developed addressing logistics traceability. These systems can be classified into two categories: classic systems and the IoT-based systems.

In the first category, a traceability system in the meat industry is proposed [21]. The system identifies the products by a unique RFID sequential number or barcode. Data is transferred from combined barcode and RFID readers to a traceability database.

In [22] a traceability system in the cold chain of fish is described. This system used smart RFID tags to identify products and multiple sensors to capture real-time information about temperature, humidity, and light.

In [15], the authors have defined three levels of traceability: traceability of physical flows, traceability of processes, and traceability of services. They also propose an IoT-based bacterial contamination traceability framework in the supply chain and a Bayesian causal network model to link the different layers of traceability. As for the second category, an IoT-based system for food monitoring during transportation is presented in [23]. The system ensures a continuous remote monitoring and real-time collection of data which are sent automatically to the Cloud.

In [24] the authors proposed a food traceability system using Cyber-Physical System (CPS), Value Stream Mapping (VSM), EPCglobal and Fog computing. The solution proposed in this work aimed to improve the efficiency of the traceability system with the object of removing poor quality products from the supply chain using value-based processing.

It is important to note that ERP, SCE, WMS and TMS support flows from the moment products are packaged and ready to ship. As a result, they trace the packaging more than the product, with flows sometimes leading them to separate the products and/or repackage them, making logistics traceability data unusable in the event of a quality crisis. Often, the support for traceability is constituted by the link between the manufacturing and stocks. Therefore, coupling between the ERP and the MES or the dedicated traceability software package is essential. Generally the ERP intervenes upstream of production, with the reception of the material, and downstream through the process of packaging, palletizing, storage and delivery. The ERP manages the commercial reference. Typically the MES is inserted between upstream and downstream since it manages the manufacturing reference and components as well as the monitoring of production at workshop level.

Most of these tools struggle to adapt to the new challenges of today's traceability such as demand uncertainty, coordination and overall governance of the supply chain, collaboration of actors, intelligent and dynamic control, the semantics of the data exchanged between the actors, the flexibility of the traceability in order to better meet the requirements of customer demand. They generally store their data in a distributed database, available for all actors of the system. These systems often present problems, such as: Security: access, control, authentication and authorizations, heterogeneity of the protocols, data inconsistency, response delays, lack of visibility and limited communication with other partners. They are characterized by the use of IoT and RFID. However, many issues need to be addressed to process and analyze the large amount of data relating to objects generated from the various sensors and the large volume of data generated by the IoT at a level lose to users and connected object.

Likewise, these tools must deal with risk management and decision-making at the local and global level for decentralized logistics traceability and the interoperability of logistics networks with the constraints of heterogeneity of norms and standards. Finally, a dedicated traceability solution must offer powerful tools, not only for managing reports, but for navigating traceability data. A solution which collects in detail, but which renders the data in a way that is too partial or complicated, will not reveal the full power of good traceability management. In fact, most tracking systems are a mixture of paper and electronic barcode and newer radio frequency identification (RFID) systems.

The advent of the physical internet concept and its combination with SCM has raised some logistical challenges and given a new vision for companies while keeping product traceability with a gain in transportation costs. We define in the sequel the research context of setting up PI to address product traceability and transportation.

5. THE RESEARCH CONTEXT

The deficiencies observed in supply chains and transportation systems on a global scale have a negative economic, environmental and social impact: ever-increasing freight transportation costs, greater number of accidents, pollution, poor time management as well as the deterioration of the transporters working conditions. Setting up Physical Internet (PI) would address these shortcomings. However, there are still no universal standards in global logistics regarding, for example, container dimensions or

EDI (Electronic Data Interchange) messages. Nevertheless, PI requires some rules which, if specified and generalized, should become acceptable standards in the future. For the purpose of this research, we consider the following PI context:

A. Physical Internet (PI)

The concept of Physical Internet (or PI) is presented for the first time about ten years ago by CIRRELT [25]. PI was defined as "an open global multimodal logistics system based on universal physical, digital, and operational interconnectivity of logistics networks, achieved through the encapsulation of standard dataset, collaboration protocols, modular containers and intelligent interfaces for increased efficiency and sustainability [26].

PI allows delivering, producing, moving, storing, and using physical objects around the world in an economically, environmentally, and socially efficient manner, and ensures universal logistics interconnection at the physical, informational and operational level. For that, it is based on three key elements that have the purpose of achieving these functions: PI-containers, PI-hubs and PI-Protocols [27].

1) PI-containers

In logistics, the physical flow is used to transport products or materials from manufacturers to consumers. The physical internet would not handle bulk freight, pallets or non-containerized goods. The products must be stored and handled in boxes or packages (in the Physical Internet these are the PI-containers). It has been mentioned that in logistics vacuum and packaging take up a lot of space, PI-containers have been designed to remedy this situation.

PI-containers would be standard sizes or modules, eco-friendly (made from eco-friendly materials), smart (RFID and GPS trackable and able to interact with the network), secure, nestable to create units larger and, in most cases, able to be compacted to optimize storage and improve return efficiency. The PI-containers would come in various sizes and shapes and could be assembled and disassembled.

There are three types of PI-containers [26]: 1) Transport containers (T-containers): are the entities transported by the different types of vehicles (trucks, trains, ships, etc.). A T-container can contain several H-containers. Their dimensions are studied in order to optimize their filling rate [28]; 2) Handling containers (H-containers): contain physical goods and/or PI-containers of smaller sizes. Their size is modular and allows them to fit in a T-container; and 3) Packaging containers (P-containers): are used to directly contain physical goods. They are sized to adapt in a modular way to H-containers.

2) PI-hubs

PI-hubs are the routing centers responsible for receiving, storing, and sending PI-containers. PI-hubs are the core of fast, efficient and reliable multimodal transport, allowing easy transfer of Pi-containers between different modes of transport. They adopt the same function as that of digital internet routers by ensuring that each received PI-container is routed to the next destination on time and correctly. PI-hubs may be of input/output or transit type. The input/output PI-hubs are nodes that allow suppliers to put their products in the chain or from which customers receive their ordered products. As for transit PI-hubs; they only allow the transit of products from PI-hub to PI-hub to their destinations.

PI infrastructure is made up of a set of interconnected PI-hubs. Interconnection is one of the most important characteristics of PI. Its purpose is to make PI network open, global, efficient and sustainable, while being flexible, i.e. it allows modification if a new organization is added to the network [16].

3) PI-protocols

The physical Internet is modeled on classic Internet protocols. The circulation of information packets (data for the classic Internet, goods for the PI) from the sender to the recipient is automatically organized and carried out by the system. This allows optimal use of the capacity available on the network without any human intervention. Like the TCP/IP protocols of the digital Internet, the PI-protocols are standard rules allowing the control and the management of the operations of the physical Internet network. By analogy to the Open Systems Interconnection (OSI) model used in the TCP/IP protocols of the digital internet, the Open Logistics Interconnection (OLI) model was introduced. The OLI model consists of the following seven layers: physical, link, network, routing, shipping, encapsulation and web logistics [29].

B. Identification Technologies

In automatic identification technologies, several solutions are used such as barcodes, RFID tags (Radio Frequency Identification), QR code or matrix codes, etc. [30][31]:

1) The Barcode

is an information coding system, represented by a succession of bars and spaces of different widths, the juxtaposition of which represents numeric or alphanumeric data. The marking of this coding can be done using different techniques: inkjet, laser engraving, thermal printing, etc. This type of coding must be associated with an optical reading device such as: pencil, laser gun or scanner.

2) The QR Code (Quick Response Code or Datamatrix)

is a two-dimensional barcode (or matrix code) made up of black modules arranged in a square with a white background. The name QR stands for "Quick Response" because its data content can be decoded quickly. Intended to be read by a QR code reader, a mobile phone, or a smartphone, it has the advantage of being able to store more information than a barcode.

3) Radio Tag or RFID Smart Tag (Radio Frequency Identification) tag

is the most commonly used solution today. Unlike the barcode which must be placed in the axis of a laser, reading the RFID tag only requires the presence of the tag in an electromagnetic area. RFID technology consists of three key elements: An RFID label or tag (an electronic chip) for storage and calculation, an antenna to receive signals for communication, and decoders integrated into a computer system to read RFID tags via radio signals. The information is contained on the tag and can be used for inventory tracking and product traceability.

C. Product Nature

We consider the food and pharmaceutical products. The latter are characterized by their sensitivity to climatic conditions and by an expiry date defined at the time of their manufacture. Thus, the temperature and the humidity rate parameters are controlled. These parameters must be captured each time the RFID is read and recorded in the event generated following this reading.

Based on the PI context we develop and design the ontology approach to set up a traceability system.

6. ONTOLOGICAL APPROACH TO PRODUCT TRACEABILITY

A. System Architecture

Our approach to develop a traceability system in interconnected supply chains which network structure extends on a global scale is an ontology-based. Fort that, we have considered the following concepts: PI as it adapts to the requirements of interconnected supply chains; RFID, a promising solution to meet the requirements of real-time traceability systems; OWL DL language [32] adopted for data representation, allowing efficient storage, processing and especially sharing and reasoning on the manipulated data; IoT to deal with connected logistical object, and Fog computing in order to share data and processing, to reduce the cloud overload, and to improve latency as the connected objects are closer to Fog than to Cloud.

At each level (Fog and Cloud), an ontology is developed and used:

- At each Fog an ontology is created (Onto-Fog) which represents and manages the events inside a fog (intra Fog). This ontology will be used to represent the paths taken by the products inside a fog; it provides local traceability.
- At the Cloud level, an ontology is also created (Onto-Cloud) which manages the events circulating between the fogs (inter Fog). This ontology represents a directory of the fogs with their PI-hubs, as well as the events generated by the reads RFID tags, capturing information on the conditions of the products whose destination is outside the fog in which they are located. This ontology will allow finding the global traceability of the products from the different local traceability of the product.

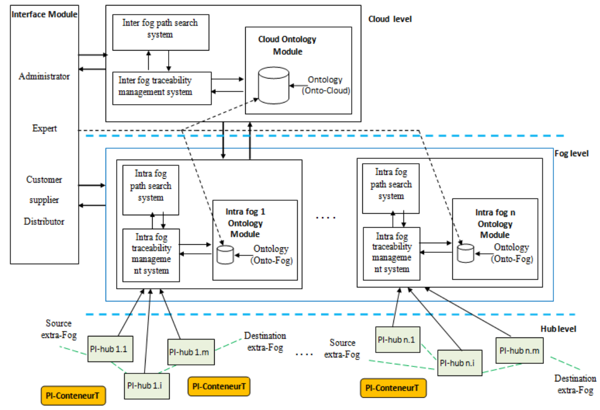

Figure 1. Functional architecture of the system

Each fog has a local fog traceability system that exploits the Onto-Fog ontology specific to this Fog while the cloud has a global traceability system which uses the Onto-Cloud ontology. The latter represents the meta-knowledge that allows forming the global path crossed by a product, from its local paths in the different fogs by which the product is routed. "Figure 1" depicts the functional architecture of the system that integrates the ontologies.

To construct the two ontologies, we adopted the widely used "METHONTOLOGY" method [33]. The ontology development methodology is usually composed of several strategies on defining classes and class hierarchy, defining properties and naming considerations. Three types of ontologies are generally developed: Domain, task and application ontologies [34][35]. Our approach to product traceability is supported by a domain ontology.

B. Ontology Specification

This step is essential for the construction of the ontology. It consists in organizing and structuring the domain knowledge, particularly, extracting the concepts, their attributes, the relationships between concepts as well as the instances of the concepts from the documentation of the logistics domain, cloud and fog computing, as well as that of the concepts of the Internet in logistics. At the end of this step, we obtain the conceptual model at a fog level (Onto-fog) (Figure 2) and that at the cloud level (Onto-cloud) (Figure 3).

1) The Onto-Fog Ontology

a) Concept Extraction: the following main concepts are extracted: PI-container, PI-Hub, Event, Product, and Supplier. The PI-container concept includes the following three types T-container, H-container and P-container. The

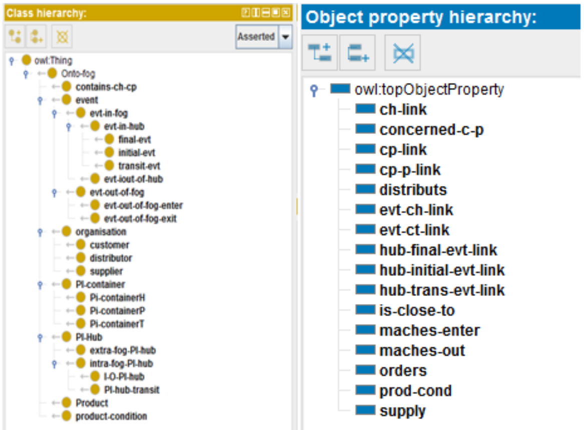

Figure 2. Onto-Fog ontology class hierarchy

PI-Hub concept includes the PI-Hub-extra-fog and PI-Hub-intra-fog. The latter includes the I/O PI-Hub and the transit-PI-Hubs.

b) Attribute Extraction: Each extracted concept is characterized by its attributes. For example, the product concept is characterized by its identifier (an EPC - Electronic product code - which uses RFID technology. It is made up of four parts: 1) The header specifying the EPC format used by the tag; 2) A unique number assigned to the manufacturer of the product; 3) The product class identifier; and 4) The serial number assigned by the manufacturer to each product.

A PI-hub has as an identifier, a designation, an address, as well as a capacity. As for the event concept, at each time an RFID tag is read, an event is generated. Its attributes: an identifier, designation, date and time of the read.

c) Concept Relations Extraction: we were able to bring out the relations between the concepts. For example, as RFID tag reads can be made for products located in either T-container or H-container, each event generated following an RFID read is associated with 1 or 0 T-container. On the other hand, each generated event corresponds to at least one H-container.

2) The Onto-Cloud Ontology

this ontology represents meta-knowledge relatively to onto-fog. It mainly consists of a directory of PI-hubs related to the fogs to which they belong. It represents also events relating to products which rout through more than one fog. These events are sent by the fog source of this product. The cloud in turn sends an event to the destination fog, informing it of the upcoming arrival of an extra-fog product.

The ”initial fog” and ”initial PI-hub” information is also sent to the destination fog. Product condition information remains at the fog level. As a result, the event that is sent to the cloud only contains the identifiers of the product, and of the T-container, the H-container and the P-container in

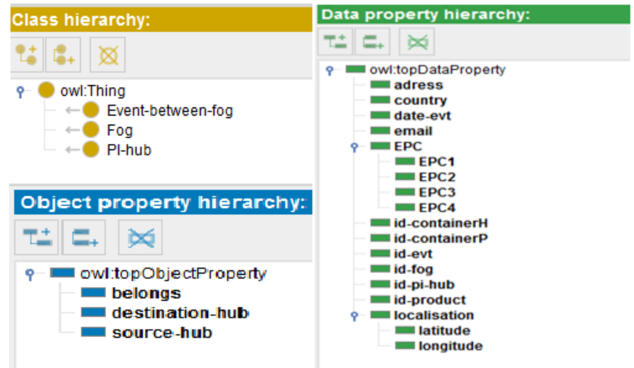

Figure 3. Onto-Cloud ontology class hierarchy

```
</owl:DatatypeProperty>
<owl:TransitiveProperty rdf:ID="is-close-to">
  <rdfs:domain rdf:resource="#contains-ch-cp"/>
  <rdfs:range rdf:resource="#contains-ch-cp"/>
  <owl:inverseOf rdf:resource="#is-close-to"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#SymmetricProperty"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:TransitiveProperty>
<owl:FunctionalProperty rdf:ID="ch-link">
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
  <rdfs:range rdf:resource="#Pi-containerH"/>
  <rdfs:domain rdf:resource="#contains-ch-cp"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="concerned-c-p">
  <rdfs:domain rdf:resource="#product-condition"/>
  <rdfs:range rdf:resource="#Product"/>
  <rdf:type rdf:resource="http://www.w3.org/2002/07/owl#ObjectProperty"/>
</owl:FunctionalProperty>
<owl:FunctionalProperty rdf:ID="cp-p-link">
```

Figure 4. An Excerpt of the Onto-Fog ontology OWL file

which the product is located.

A product that enters the supply chain is put in an I/O Pi-hub, which represents the initial PI-hub of this product. The PI-hubs, through which this product is routed, represent the transit PI-hubs for this product. The PI-hub, from which this product is delivered to the customer, represents the final PI-hub for this product. This way of modeling allows us to retrieve the product path from the initial PI-hub to the final PI-hub.

C. Ontology Formalization

We have chosen to formalize the ontology using OWL-DL language. OWL-DL is expressive enough to syntactically represent several formalisms. Moreover, it has a semantics that supports the expression of axioms. Semantic web tools such as reasoners and inference engines are also used to perform reasoning, which ensures consistency as well as inference of knowledge. Finally, we used the PROTEGE tool [36] for the creation of ontologies. Figure 4 and Figure 5 depict the two generated corresponding OWL files.

D. ONTOLOGY-BASED REASONING

The PI-containers are modular and standardized. They can also be assembled and disassembled. This facilitates their handling (loading, unloading) as well as saving space in transportation containers. In this context, we considered that during any loading or unloading, the H-containers

```
<owl:Ontology rdf:about=""/>
<owl:Class rdf:ID="Event-between-fog"/>
<owl:Class rdf:ID="PI-hub"/>
<owl:Class rdf:ID="Fog"/>
<owl:DatatypeProperty rdf:ID="C-EPC">
  <rdfs:domain rdf:resource="#Event-between-fog"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="C-tieme-event">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#time"/>
  <rdfs:domain rdf:resource="#Event-between-fog"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="C-id-product">
  <rdfs:domain rdf:resource="#Event-between-fog"/>
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="C-EPC2">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#string"/>
  <rdfs:subPropertyOf rdf:resource="#C-EPC"/>
</owl:DatatypeProperty>
<owl:DatatypeProperty rdf:ID="C-id-containerT">
  <rdfs:range rdf:resource="http://www.w3.org/2001/XMLSchema#int"/>
  <rdfs:domain rdf:resource="#Event-between-fog"/>
```

Figure 5. An Excerpt of the Onto-Cloud Ontology OWL file

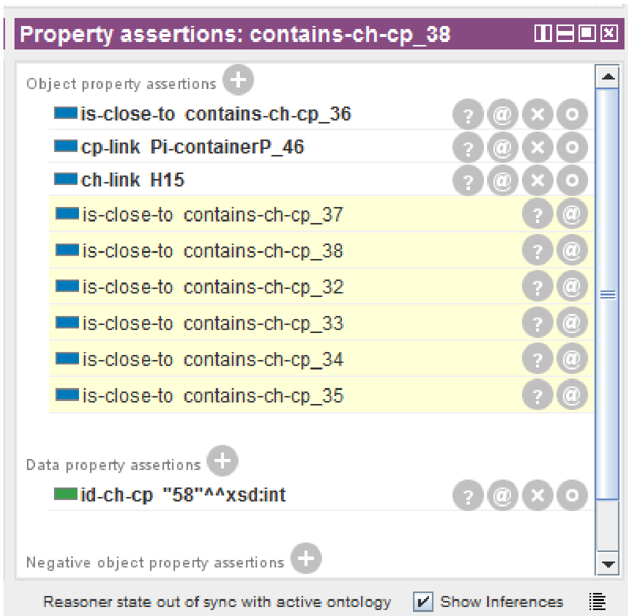

Figure 6. 1st instance infered of the class ”contains-ch-cp” related to the object property ”is-close-to”

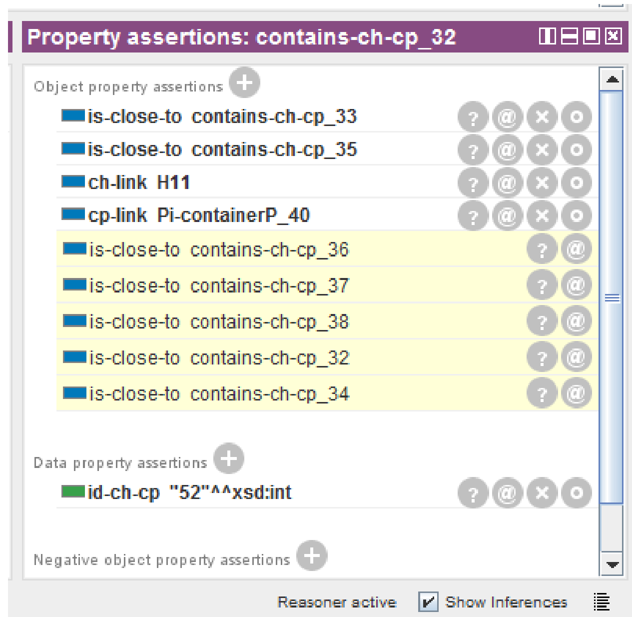

Figure 7. 2nd instance infered of the class ”contains-ch-cp” related to the object property ”is-close-to”

can be assembled or disassembled. In order to keep track of this assembly, we have provided in the ontology the relation ”is-close-to” between the instances of the class ”contains-ch-cp”. Each instance of the ”contains-ch-cp” class represents an H-container at a given time (Figure 6 and Figure 7). This container is constituted of P-containers, each of which contains a product. The relation (object property) ”is-close-to” represents in the ontology the link between two adjacent H-containers. This link can be detected following the container RFID read. We defined this object property as transitive. Therefore, running the Pellet reasoner infers all ”is-close-to” relationships between all H-containers that are assembled.

The figures Figure 6 and Figure 7 show an example of this reasoning: we considered 7 assembled H-containers; they correspond to instances 32, 33, 34, 35, 36, 37 and 38 of the ”contains-ch-cp” class. When reading RFID, each PI-container only detects its neighbor according to its size and position in the container. In the example, a container sometimes detects 2, 3 or 4 neighbors. After executing the Pellet reasoner, each instance is linked to all the instances (the seven) which form an H-container by assembly.

7. SYSTEM EVALUATION

Evaluation requires populating the ontology with real data then applying SPARQL [37] queries. Therefore to verify its consistency and its efficiency, we considered a fairly representative population of individuals. We carry out several SPARQL queries that the user can express and execute using the Pellet reasoner to deal with different specified use cases related to product traceability, condition and location. The results returned by these queries are used to evaluate the ontology.

A. *Traceability Related Queries*

The traceability of a product P consists in searching whether the product has entered the fog local supply chain. In this case, a corresponding event must be retrieved in the ”initial-evt” class. Otherwise, we search in the extra fog events, i.e. in the class ”evt-out-of-fog-enter”. If an event corresponding to this product is retrieved then we to search for the rest of the paths from the other events generated by the product reads. Below some query examples:

Q1: Give the path (the PI-hubs and date of passage) taken by the product P with id-p=2?

In response to this query, the product P with id = 2

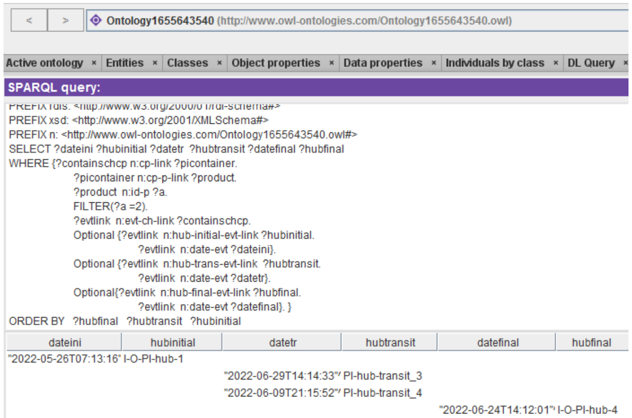

Figure 8. The path taken by the product P with id = 2

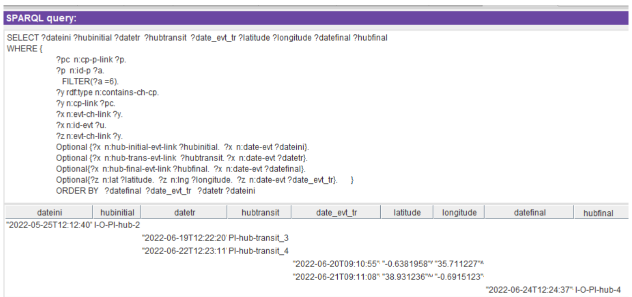

Figure 9. The trace of the product P with id = 6

is deposited and delivered at the same fog. His path is completely local as depicted in Figure 8.

Q2: Give the trace of product with id-p = 6?

We consider here that the hypothesis that the RFID tags can be read in real time. Therefore, events outside the PI-hubs are used and represented in the ontology. The RFID tag of the P6 product (id-p = 6) is read in the hubs through which this product is routed and also outside the PI-hubs. In response to this query, the complete trace of product 6 is given in Figure 9.

B. Product Condition Related Queries

Q3: What is the condition (temperature and humidity) of the product P with id = 6?

As depicted in Figure 10, we note that the condition of this product has deteriorated during its delivery. Indeed, its temperature exceeded the maximum temperature allowed during the 2nd event dated 06/19/2022. Also, the humidity level exceeded the maximum level indicated for this product during the 4th event on 06/21/2022.

Q4: Search for all expired products in the chain?

The list of all expired product is given in Figure 11.

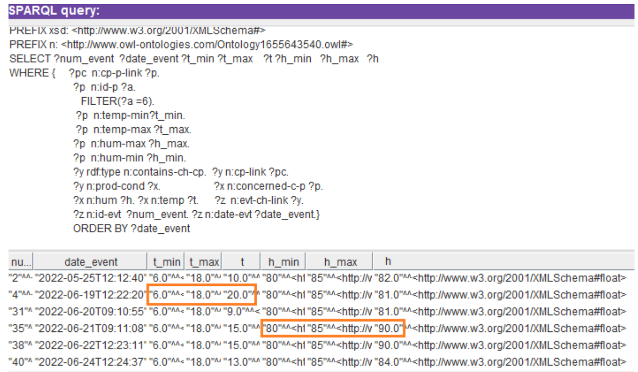

Figure 10. The condition of the product P with id = 6

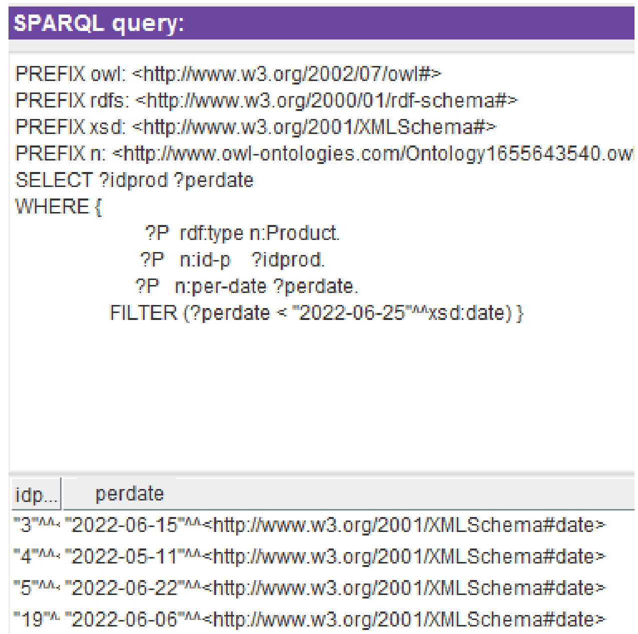

Figure 11. List of expired products

C. Location Related Queries

Q5: For each expired product, search its location in the chain?

This corresponds to the location of the last generated event that corresponds to this product. Figure 12 depicts the results for the latest hub of product P3 (id-p=3).

It is also possible to consider transit events (those generated between two successive PI-hubs in the path of a product. In this case, the query possibly returns the position of the event (latitude and longitude).

Q6: Search for products that have left the fog-1?

Products that leave the fog are those routed from a transit PI-hub to PI-hub in another fog. These products do

SPARQL query:

```
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX n: <http://www.owl-ontologies.com/Ontology1655643540.owl#>
SELECT ?product ?date_event ?hub
            WHERE {     ?pc n:cp-p-link ?product.
                        ?product n:id-p ?a.
                          FILTER(?a =3).
                        ?y rdf:type n:contains-ch-cp.
                        ?y n:cp-link ?pc.
                        ?x n:evt-ch-link ?y.
                        ?x n:date-evt ?date_event.
                        Optional {?x n:hub-initial-evt-link ?hub. }.
                        Optional {?x n:hub-trans-evt-link ?hub. }.
                        Optional{?x n:hub-final-evt-link ?hub. }.   }
ORDER BY DESC(?date_event) LIMIT 1
```

product	date_event	hub
P3	"2022-06-15T12:39:47"^	PI-hub-transit_6

Figure 12. The location of the product P with id = 3

SPARQL query:

```
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX n: <http://www.owl-ontologies.com/Ontology1655643540.owl#>
SELECT ?Idprod ?dateexit ?transit_hub ?extrafogdestination
        WHERE {
                ?x n:maches-out ?y.
                ?x n:hub-trans-evt-link ?transit_hub.
                ?y n:date-evt ?dateexit.
                ?y n:id-fog-destination ?extrafogdestination.
                ?x n:evt-ch-link ?z.
                ?z n:cp-link ?t.
                ?t n:cp-p-link ?u.
                ?u n:id-p ?Idprod. }
                ORDER BY DESC(?dateexit)
```

Idp...	dateexit	transit_hub	extrafogdestination
"18"^	"2022-05-29T18:44:12"	PI-hub-transit_6	"8"^^<http://www.w3.org/2001/XMLSchema#int>
"26"^	"2022-04-18T18:49:10"	PI-hub-transit_4	"13"^^<http://www.w3.org/2001/XMLSchema#int>
"23"^	"2022-04-18T18:49:10"	PI-hub-transit_4	"13"^^<http://www.w3.org/2001/XMLSchema#int>

Figure 13. List of products that have left the fog-1

not have end events in the current fog. In this case, the system sends a message to the fog which consists of the output event of the product fog. This message allows the cloud to keep track of the product moving from fog to fog. The trace of a product in a fog is supported by the system at the fog level.

We note that the products id-p=13 and id-p=26 have the same release date, because they are in the same H-container. They also have the same transit PI-hub and the same destination fog Figure 13.

Q7: What is the effect on the onto-cloud following the exit of products from a fog-1?

Onto-cloud lists all the product events that circulate between the fogs. By searching in the Onto-Cloud for products that have left fog-1, we find their traces: the source fog and PI-hub as well as the destination fog and PI-hub of each product Figure 14.

SPARQL query:

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX n: <http://www.owl-ontologies.com/Ontology1655202294.owl#>
SELECT ?Idprod ?source_fog ?source_hub ?destina_fog ?destina_hub
        WHERE {
                ?x n:source-hub ?y.
                ?y n:belongs ?source_fog.
                ?source_fog n:id-fog ?a.
                FILTER(?a =1).
                ?x n:source-hub ?source_hub.
                ?x n:destination-hub ?destina_hub.
                ?destina_hub n:belongs ?destina_fog.
                ?x n:id-product ?Idprod. }
```

Idprod	source_fog	source_hub	destina_fog	destina_hub
"18"^^<ht	Fog_1	transit_6	Fog_8	PI-hub_120
"23"^^<ht	Fog_1	transit_4	Fog_13	PI-hub_150
"26"^^<ht	Fog_1	transit_4	Fog_13	PI-hub_150

Figure 14. Traces of products that have left the Fog-1

To find the global trace of a product, the cloud just needs to request its local trace from each fog through which this product is routed.

Discussion

Due to globalization of the product supply chain, the interests for product related safety issues have been heighten and the demand for more information and transparency about product traceability has been intensified which resulted in an important issue of 'traceability' in global supply chain.

Product traceability system is essential for quality management. It is aimed to keep the data tracking of product routes and provide information visibility through the distribution, transportation, and sales chains, but this is only effective when the product flows with associated information are provided in real time, hence the essential use of efficient artificial intelligence tools. All stakeholders involved in product traceability must be able to identify the origins of all raw materials and products, their locations, conditions and destinations. Identification systems and data handling procedures are applied and integrated into the quality management system of the organization. The traceability system aimed to provide services for the stakeholders on cooperative basis of the mutual interests.

Ontologies-based approaches have generated increased interests in the logistics. Various systems in the organizations are currently developing ontologies as a means to support traceability and supply chain management. This allows planning and deploying hardware and software technologies across the organization, representing traceability complexity, and accessing paramount effective and efficient data. Moreover the ontology along with the system serves as a communication medium between all actors involved in the supply chain.

In this research, a fog computing-based ontology approach is used to develop a traceability system that tracks and traces product flows in the context of physical internet. The ontology will provide a standard for product traceability, enabling a common language and understanding among different actors involved in supply chain. To test the ontology, we carried out all the queries that the user can express whether he is a customer, a supplier or a hub manager related to different traceability scenarios. The validation results indicate that the developed ontology has the expressivity necessary to represent all the knowledge related to the product traceability domain.

In order to simplify the understanding of the different queries, we have searched and displayed the products by the ”id-p” attribute, but really the products are identified by the EPC which is one of the properties of the physical internet. Concerning the PI-hubs where the products are located, we visualized their URIs in place of displaying their identifiers, names as well as their addresses.

In addition, we considered representing the transit events as the events are generated in real time. Also, sometimes, RFID tags are read during product transportation, for example on a boat which is not a PI-hub and moves (its position is variable). So in this case, our ontology represents the event as a transit event (between two PI-hubs). The latter is characterized by a position (latitude, longitude) and not by a PI-hub.

The advent of the concept of the physical internet has raised some logistical challenges. Its combination with SCM has given a new vision for companies while keeping product traceability with a gain in transport costs.

We carried out a traceability simulation and sample queries to validate our approach and evaluate the system performance. Applications of this traceability system show that the complicated manual traceability data recording are improved and significantly reduced for the stockholders.

The proposed frameworks should be improved to ensure architectural design of modular ontology development which will strengthen the reuse and maintainability of fog and cloud-based ontologies. Furthermore, the ontologies proposed in this research will be of interest to ontological practitioners in other domains

8. CONCLUSION

Traceability of logistical objects is inseparable from SCM. It allows identifying all the objects in the same flow of goods to know for each object its origin, destination, state as well as its different stages throughout the chain from the manufacturer to the final consumer. However, despite technological advances in SCM support, the need for identification and traceability of logistics objects remains a challenge. Indeed, there are more and more objects to identify, and with the advent of connected objects, there is more and more data collected on these objects. These data pose various problems because of the large volume of data generated, exchange and storage formats, and communication protocols. It is essential to identify innovative approaches and solutions in SCM and transport of goods, storage platforms, traceability technologies, and communication protocols for identification, traceability and monitoring of logistics objects in different industrial fields.

The challenge therefore is to design a system that will be able to ensure and support all logistics operations related to physical objects worldwide in an efficient and sustainable manner. We believe that the physical Internet is one such innovative solution. In this article, we proposed a novel ontology model for traceability in product supply chains. More specifically, the ontology represents a physical Internet logistics traceability tool with emerging computing resources such as IoT, Cloud, and Fog computing which are crucial for effective system management, data integration, end-to-end traceability, decision-making, and compliance.

The developed ontology provides a unified and contextual understanding of traceability information, enabling stakeholders to leverage the benefits of these computing resources while ensuring system reliability, security, and accountability. It also improves the visibility of the supply chain and meets the needs of supply chain actors in terms of the condition, quality and location of their goods throughout the supply chain. The proposed system takes advantage of the supply networks interconnected on a global scale through a standardized set of collaboration protocols, modular containers and intelligent interfaces for greater efficiency and sustainability.

To the best of our knowledge, our approach is the first ontology in this domain that captures all the relevant aspects of the product supply chain traceability in the context of physical internet. We believe that the findings of this study make an important contribution to practitioners and stakeholders as they provide useful shared language enabling interoperability among supply chain actors. In future, we plan to extend our work with a third ontology at the PI-hub level (onto-Hub). This ontology will have the role of representing the trace of the products in terms of used transportation means as well as the drivers (in the case of trucks or vehicles).

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