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Physical Internet Enabled Traceability Systems for Sustainable Supply Chain Management

Bakhta Nachet *nachatdal@yahoo.fr*
Faculty of Applied and Exact Sciences
University of Oran1, Oran, Algeria

Mohammed Frendi *mohammedfrendi@yahoo.fr*
Faculty of Applied and Exact Sciences
University of Oran1, Oran, Algeria

Abdelkader Adla *abdelkader.adla@gmail.com*
Faculty of Applied and Exact Sciences
University of Oran1, Oran, Algeria

Abstract

Current supply chain management (SCM) requires the control of physical and information flows in order to satisfy the customer, i.e. deliver the right product to the customer at the right place, at the right time, at the right price and at the lowest cost. SCM is inseparable from traceability which makes reliable the said flows, accelerates the transmission of information on these flows, allows to access a detailed knowledge of the movements, and makes the flows visible. In order to streamline and monitor, if possible, in real time and permanently these logistical processes, we propose the design and implementation of an Ontology-based traceability system based on an architectural model for the physical Internet using computing resources such as Cloud computing, Fog computing and Internet of Things (IoT) to achieve efficiency and sustainability goals. To evaluate our system, we were able to carry out all the queries that the user can express whether he is a customer, a supplier or a manager.

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

1. Introduction

In recent years, logistics has undergone a remarkable evolution at several levels such as production chain, storage policies, and particularly the transportation of goods. Due to industrialization, mass production, the internationalization of trade, the diversification of distribution circuits and the development of ever more numerous and sophisticated products, the sectors have become more complex, adding many intermediate steps between production and the consumer. Supply chains have also become highly interdependent. Intense exchanges of products and information have developed within and between the sectors. The internationalization of trade has taken on a large scale.

The current logistics systems allow exchanging flows of goods on both sides of the globe in a few weeks, while guaranteeing a good quality of service at attractive prices. This progress is related, on the one hand, to technological developments in transport means (truck, container ship, aircraft, etc.) and in packaging and handling (pallets, containers, forklift, container gantries, etc.), and, on the other hand, to organizational progress. But these performances still hide inefficiencies throughout the supply chains and particularly in the transportation of goods [1],[2],[3],[4]. Indeed, this component is more important today due to its delays, the probable increase in the price of oil, taxes and the resulting negative externalities (Carbon dixide (CO2), fine particles, etc.).

Logistics management for flow control is inseparable from traceability, which makes these flows visible. Traceability enables to track or study an entity qualitatively and quantitatively in space and time by means of recorded identifications [5],[6]. The term "entity" can be a process, a product, a person or an organization. In logistics, 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 [7], enabling both suppliers and customers to track the goods throughout the chain and locating them along their route.

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. From the point of view of information management, setting up a traceability system in a logistics chain (supply chain) consists in systematically associating an information flow with a physical flow; the objective is to be able to find, at any time, information, previously determined, relating to batches or groups of products, based on one or more identifiers [8],[9]. 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 [10]. Several solutions are used in automatic identification technologies such as barcode, RFID tag, and matrix codes. RFID tag is currently the most used.

In order to ensure the products traceability, a traceability system is composed of: A hardware platform which consists of a Material Handling System (MHS) with Radio Frequency Identification (RFID), a read/write equipment and barcodes), and a software part which is made up of input/output interfaces associated with tools for controlling, processing and storing data flows in the database [11].

The integration of the Cloud has offered several advantages, particularly in the field of product traceability in supply chains [12]. But, as applications using 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 Fog computing paradigm is used. Fog computing, which represents an extension of cloud computing, is characterized by its calculation and analysis capabilities and its real-time responses [13]. It could improve the performance of different applications such as logistics.

The objective of this research is to design a product traceability system 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 create an ontology that represents the knowledge related to the product traceability in an interconnected supply chain considering the concepts of the Physical Internet (PI-container, PI-hub, and RFID) and a Fog computing architecture associated with a Cloud to collect information and record product events from any point in the supply chain. In this way, the ontology represents the knowledge related to logistics in order to satisfy user demands in terms of the condition, location and traceability of their products. The regular reads of RFID tags by specific readers allows capturing information on the conditions of the product which is then transmitted in the form of an event to the fog.

The remainder of the article is as follows: we first briefly presented the notions of traceability in supply chains as well as the evolution of the latter. Then, we presented the field of the physical Internet and the notions of Internet of Things (ioT), Cloud and Fog computing which represent a new technology applied to logistics in order to meet the challenges of current logistics. Next, we define the research context of setting up a physical internet (PI) to address product traceability and transportation. In section 4, we describe our ontology approach in the domain dedicated to traceability in a current supply chain using the PI paradigm. The system evaluation is presented in section 5. Finally, some clues on future work are given before concluding.

2. Literature Review

Several works have been carried out in the context of logistics traceability. In [26], a traceability system in the meat industry is proposed. 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.

A traceability system in the cold chain of fish is described in [27]. In this system used smart RFID tags to identify products and multiple sensors to capture real-time information about temperature, humidity, and light.

In [28], 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.

An IoT-based system for food monitoring during transportation is presented in [29]. The system ensures a continuous remote monitoring and real-time collection of data which are sent automatically to the Cloud.

In [30] 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.

Traditional platforms 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 are difficult to manage, heterogeneity of the protocols, data inconsistency, response delays, lack of visibility and limited communication with other partners. Current systems are characterized by the use of IoT and RFID. The latter is a promising solution to meet the requirements of real-time traceability systems. However, many issues need to be addressed, such as:

- On a large scale, a large amount of data relating to objects is generated from the various sensors, which makes intricate the processing and analysis of this information.
- The IoT generates a large volume of data that must be processed and analyzed at the cloud level, far from users and connected objects

3. Application 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 context.

3.1. Physical Internet (PI)

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 carrying out these tasks: PI-containers, PI-Protocols and PI-hubs. There are three types of PI-containers [31]: 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 examined in order to optimize their filling rate [32]; 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.

3.2. PI-Hubs

PI-hubs are the routing centers responsible for receiving, storing, and sending PI-containers. 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 allow easy transfer of PI-containers between different transportation modes. 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.

3.3. PI-Protocols

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 [33].

3.4. Identification System

In automatic identification technologies, several solutions are used such as barcodes, RFID tags (Radio Frequency Identification), matrix codes, etc. The RFID 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 two key elements: *1)* An RFID label (or tag): includes a chip for storage and calculation, and an antenna for communication; and 2) An RFID reader, a device that reads RFID tags via radio signals. PI-containers are equipped with smart RFID tags. The latter can have various storage capacities, up to several megabytes. Their contents can be modified endlessly. They are also readable from a distance and several tags can be read at the same time.

3.5. 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.

4. Ontological Approach to Product Traceability

Our approach to develop a traceability system in interconnected supply chains which network structure extends on a global scale is an ontology-based. To do this we have considered the following concepts: PI as it adapts to the requirements of interconnected supply chains; IoT and RFID, a promising solution to meet the requirements of logistics domain; The OWL DL language adopted for data representation, allowing efficient storage, processing and especially sharing and reasoning on the manipulated data; 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 and 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 RFIDs reads 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.

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.

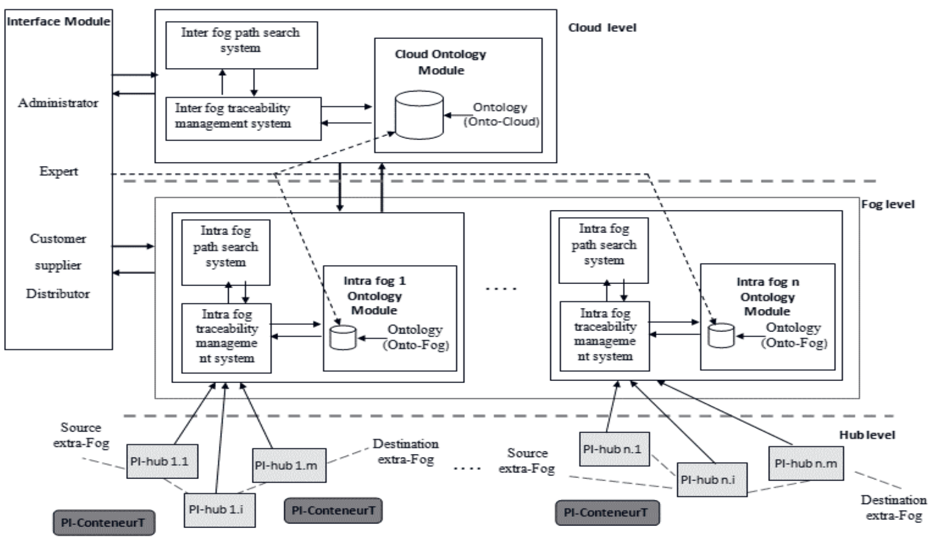

Figure 1. The system architecture.

To construct the two ontologies, we adopted the widely used "METHONTOLOGY" method [11]. The method consists of five phases in order to achieve the operationalization of the ontology.

4.1. 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) (Figure3).

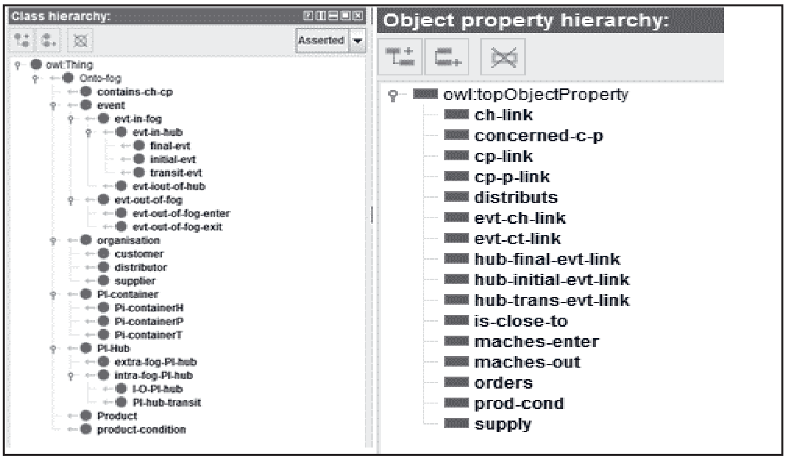

Figure 2. Onto-Fog ontology class hierarchy

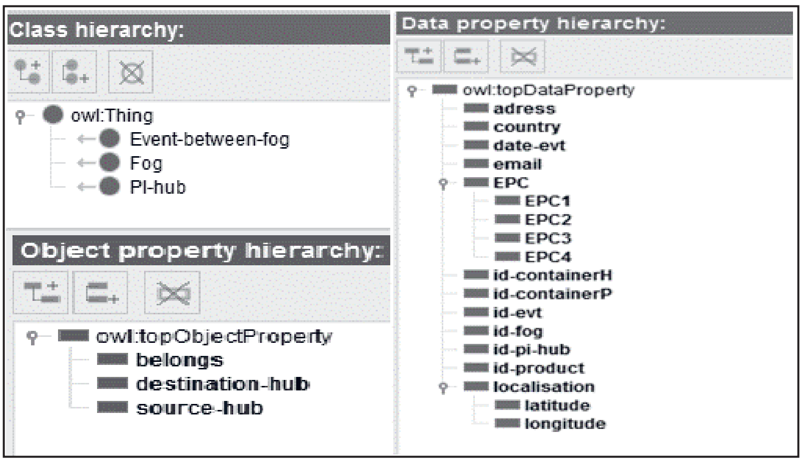

Figure 3. Onto-Cloud ontology class hierarchy.

4.1.1. The Onto-Fog Ontology:

- 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 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.

- *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, since each time an RFID tag is read, an event is generated. Its attributes: an identifier, designation, date and time of the read.
- *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.

4.1.2. 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 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.

4.2. 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 for the creation of ontologies. Figure 4 and Figure 5 depict the two generated corresponding OWL files.

```
</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

```
<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

4.3. 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 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 (Fig. 6a and Fig. 6b). 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.

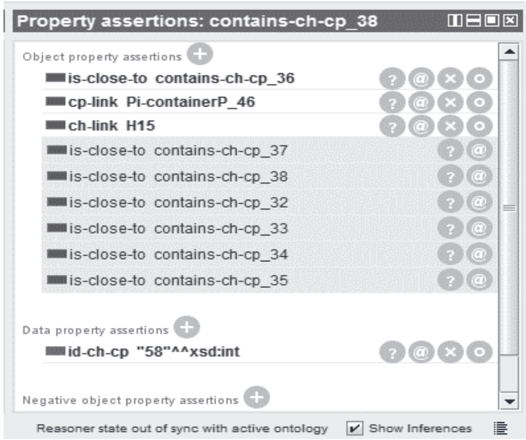

Figure 6a. 1st instance inferred of the class “contains-ch-cp” related to the object property “is-close-to”

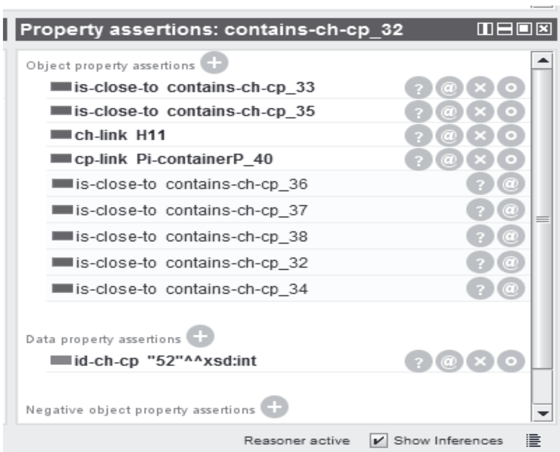

Figure 6b. 2nd instance infered of the class “contains-ch-cp” related to the object property “is-close-to”

The figures 6a and 6b 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 its size and position in the container. In the example, a container sometimes detects 2, 3 or 4 neighbors. After the executing the Pellet reasoner, each instance is linked to all the instances (the seven) which form an H-container by assembly.

5. System Evaluation

Evaluation requires populating the ontology with real data then applying SPARQL queries. Therefore, to evaluate the ontology, we considered a fairly representative population of individuals upon which we proceeded to the execution of some SPARQL queries related to product traceability, condition and location in order to test the use cases we specified. The results returned by these queries are used to evaluate the ontology.

5.1. 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:

5.1.1. Product Trace Related Queries

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

In response to this query, the product P with id = 2 is deposited and delivered at the same fog. His path is completely local as depicted in Figure 7.

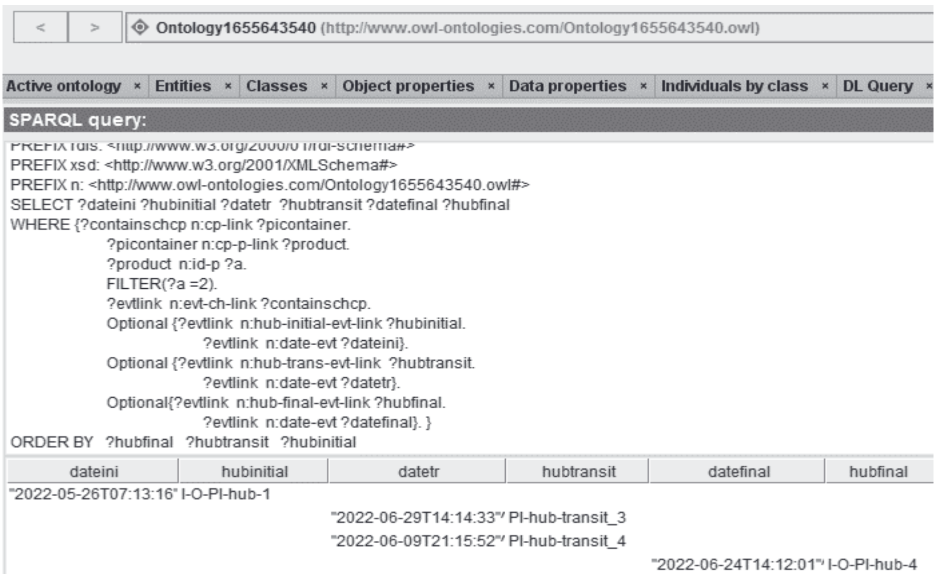

Figure 7. The path taken by the product P with id = 2

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 8.

SPARQL query:

```
SELECT ?dateini ?hubinitial ?datetr ?hubtransit ?date_evt_tr ?latitude ?longitude ?datefinal ?hubfinal
WHERE {
            ?pc n:cp-p-link ?p.
            ?p n:id-p ?a.
              FILTER(?a =6).
            ?y rdf:type n:contains-ch-cp.
            ?y n:cp-link ?pc.
            ?x n:evt-ch-link ?y.
            ?x n:id-evt ?u.
            ?z n:evt-ch-link ?y.
            Optional {?x n:hub-initial-evt-link ?hubinitial. ?x n:date-evt ?dateini}.
            Optional {?x n:hub-trans-evt-link ?hubtransit. ?x n:date-evt ?datetr}.
            Optional{?x n:hub-final-evt-link ?hubfinal. ?x n:date-evt ?datefinal}.
            Optional{?z n:lat ?latitude. ?z n:lng ?longitude. ?z n:date-evt ?date_evt_tr}.    }
            ORDER BY ?datefinal ?date_evt_tr ?datetr ?dateini
```

dateini	hubinitial	datetr	hubtransit	date_evt_tr	latitude	longitude	datefinal	hubfinal
"2022-05-25T12:12:40"	I-O-PI-hub-2							
		"2022-06-19T12:22:20'	PI-hub-transit_3					
		"2022-06-22T12:23:11'	PI-hub-transit_4					
				"2022-06-20T09:10:55"	"-0.6381958"'	"35.711227"^		
				"2022-06-21T09:11:08"	"38.931236"^^	"-0.6915123"		
							"2022-06-24T12:24:37"	I-O-PI-hub-4

Figure 8. The trace of the product P with id = 6

5.1.2. Product Condition Related Queries

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

As depicted in Figure 9, 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.

SPARQL query:

```
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX n: <http://www.owl-ontologies.com/Ontology1655643540.owl#>
SELECT ?num_event ?date_event ?t_min ?t_max ?t ?h_min ?h_max ?h
WHERE {   ?pc n:cp-p-link ?p.
          ?p n:id-p ?a.
            FILTER(?a =6).
          ?p n:temp-min?t_min.
          ?p n:temp-max ?t_max.
          ?p n:hum-max ?h_max.
          ?p n:hum-min ?h_min.
          ?y rdf:type n:contains-ch-cp. ?y n:cp-link ?pc.
          ?y n:prod-cond ?x.           ?x n:concerned-c-p ?p.
          ?x n:hum ?h. ?x n:temp ?t.    ?z n:evt-ch-link ?y.
          ?z n:id-evt ?num_event. ?z n:date-evt ?date_event.}
          ORDER BY ?date_event
```

nu...	date_event	t_min	t_max	t	h_min	h_max	h
"2"^^·	"2022-05-25T12:12:40"	"6.0"^^<	"18.0"^^	"10.0"^^	"80"^^<ht	"85"^^<http://v	"82.0"^^<http://www.w3.org/2001/XMLSchema#float>
"4"^^·	"2022-06-19T12:22:20"	"6.0"^^<	"18.0"^^	"20.0"^^	"80"^^<ht	"85"^^<http://v	"81.0"^^<http://www.w3.org/2001/XMLSchema#float>
"31"^	"2022-06-20T09:10:55"	"6.0"^^<	"18.0"^^	"9.0"^^<	"80"^^<ht	"85"^^<http://v	"81.0"^^<http://www.w3.org/2001/XMLSchema#float>
"35"^	"2022-06-21T09:11:08"	"6.0"^^<	"18.0"^^	"15.0"^^	"80"^^<ht	"85"^^<http://v	"90.0"^^<http://www.w3.org/2001/XMLSchema#float>
"38"^	"2022-06-22T12:23:11"	"6.0"^^<	"18.0"^^	"15.0"^^	"80"^^<ht	"85"^^<http://v	"90.0"^^<http://www.w3.org/2001/XMLSchema#float>
"40"^	"2022-06-24T12:24:37"	"6.0"^^<	"18.0"^^	"13.0"^^	"80"^^<ht	"85"^^<http://v	"84.0"^^<http://www.w3.org/2001/XMLSchema#float>

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

Q4: Search for all expired products in the chain?

The list of all expired product is given in Figure 10.

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 ?perdate
WHERE {
                ?P  rdf:type n:Product.
               ?P   n:id-p    ?idprod.
              ?P   n:per-date ?perdate.
          FILTER (?perdate < "2022-06-25"^^xsd:date) }
```

idp...	perdate
"3"^^<	"2022-06-15"^^<http://www.w3.org/2001/XMLSchema#date>
"4"^^<	"2022-05-11"^^<http://www.w3.org/2001/XMLSchema#date>
"5"^^<	"2022-06-22"^^<http://www.w3.org/2001/XMLSchema#date>
"19"^	"2022-06-06"^^<http://www.w3.org/2001/XMLSchema#date>

Figure 10. List of expired products

5.1.3. 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 11 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).

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 11. The location of the product P with id = 3.

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 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 12).

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 12. List of products that have left the fog_1

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 13).

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 13. 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.

5.2. Discussion

The developed ontology completely satisfies the assigned objectives. In fact, we were able to carry out all the queries that the user can express whether he is a customer, a supplier or a hub manager. 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.

6. Conclusion

SCM is inseparable from traceability which makes reliable the physical and information flows, accelerates the transmission of information on these flows, allows accessing a detailed knowledge of the movements, and makes the flows visible. In fact, the traceability of logistical objects allows identifying all the objects in the same flow of goods to know for each object its origin and its destination, its state as well as the different stages of its journey throughout the chain, from the manufacturer to the final consumer. However, despite technological advances in logistics 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 a storage problem 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 logistics 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 physical Internet logistics traceability system based on the Internet of Things, Cloud and Fog computing to improve the visibility of the supply chain and meet 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.

We adopted an ontology approach to ensure the traceability of the products by representing their traces in terms of paths formed by the different PI-hubs, and all the T-containers and H-containers having contained the product at one time or another.

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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