Blockchains and Internet of Things for the pooling of warehouse resources

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ABSTRACT:

Aims: The purpose of this research paper is the study of the applicability of Blockchain technology and Smart Contracts to manage, control and secure an industrial Internet of Things network (IoT) for pooled warehouses with multiple actors and activities (not only restricted to transport and storage as currently developed in enterprises).

Problem: IoT technology enables things to connect and exchange data, resulting in efficiency improvements, economic benefits, reduced human intervention and enabled interactions (information exchange and analysis) between human/machine to machine. However, the main difficulties lie in the definition of a robust global mechanism to secure the IoT, the awareness of resources diversity (heterogeneity of devices), and physical management of IoT. This article will attempt to answer these questionings.

Results: To respond to these questions, we propose a hybrid architecture based on blockchains and multi-agents system to secure an industrial IoT corresponding to a pooled warehouse system. The proposed hybrid architecture completely represents our system, with all actors and connected objects in the pooled warehouse strategy. It is composed by two parts: a centralized part based on the multi-agents system to represent dynamic evolutions of actors' behaviour, and a decentralized part, which corresponds to our blockchain and smart contracts network to dynamically connect actors' agents to pooled resources. The multi-agent system is coupled with game theory (cooperative game) to have a good systemic representation of our pooled warehouse management problem.

Keywords: pooled warehouses, Internet of Things, Blockchain technology, multi-agents system, game theory with cooperative games.

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1. INTRODUCTION

Supply chain managers face different challenges such as uncertainties (market, concurrencies...), complexities (multiple processes, entities, stakeholders…), and unsustainability (economically, environmentally and socially) [1]. As a reminder, a supply chain is as physical networks of facilities, with transportation links among them, to produce and deliver goods/services to customers. The supply chain aims to improve all interconnected activities that involve the coordination, planning and control of products / services[1] between suppliers, manufactures and customers [2]. Therefore, the definition of smart and digital supply chains becomes very interesting to overcome these problems and generates values by a disruptive transformation effect across industries. In that sense, different methods and technologies could be used: big data analytics and cloud computing[2], virtual/augmented reality (to manage processes and activities such as for example performing maintenance operations made by non-expert maintenance operators), robotics and sensor technologies, computer-aided technologies and of course Internet of Things (IoT) to cite a few. A good survey could be found in [3]. IoTs allow an important number of new potential applications in supply chain management like in humanitarian [4], and customers' links but they are still in their early stages due to various IoT technologies, protocols and supports [5]. Furthermore, the digitization of the supply chain within an Industry 4.0 framework and wireless sensors [6] also allows action to be taken to minimize negative environmental impacts and allows to fulfil the continuously growing energy demand (see [7] and [8] with applications to smart grid industry 4.0 [9]). In our work, we mainly focus on Internet-connected Things networks in supply chain management.

The name IoT was coined by Kevin Ashton, cofounder of the Auto-ID Labs at MIT, in 1999[3] to represent sets of physical and virtual objects which are connected together through a network for the communication, sensing, monitoring and interaction between different entities (firms and customers to facilitate plan, control and coordination of processes in case of supply chains). The use of IoT in supply chains permits to identify products/services automatically, to track flows at each stage (products, information and/or cash), to provide complete information during the entire life cycle of products and to achieve transparency of supply chains to overcome the challenges defined below. However, a vast amount of heterogeneous and noisy data should be mined and analyzed to improve the overall process and results [10]. So, IoTs allow an important number of new potential applications in supply chain management and customers' links but they are still in their early stages due to various IoT technologies. Furthermore, in various applications, IoT is connected and centralized with classical database and cloud computing and the flows are tracked with the help of the RFID/NFC technology, QR code systems and GPS technology or indoor tracking technologies (see [4] for example in food industry). Therefore, different difficulties appear which concern the security/privacy/integrity of data due to the weakness of wireless sensor networks, machine-to-machine and cyber-physical systems, the trust management

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between stakeholders and access control in order to manage availability of services, sinkhole attacks, jamming adversaries and replay attacks [11].

In parallel, the blockchain technology has been defined in 2009 by Satoshi Nakamoto, a pseudonym, for the well-known digital bitcoin money and could constitute a good way to address this problem. If blockchain and bitcoin were built together, today blockchain has encountered many interests far from only digital money. This is true because of its decentralized nature coupled with its very promising security and transparency. The principle is as follows. It chains blocks of data that have been validated by miners and timestamped. Blockchain provides strong data authentication and integrity based on elliptic curve cryptography and SHA-256 (Secure Hash Algorithm) hashing [12]. Therefore, each transaction in the shared public ledger is verified and validated by miners' consensus. Since then, the block data are immutable: data can never be altered or erased. If an error occurs, it would be necessary to add a new transaction. Therefore, the main contribution of blockchains is to generate the confidence and security needful to automate the declarative phases without having recourse to a third party. In addition, in case of a leak or attack that will result in serious loss for users, the distributed database blockchain can address this by providing data security with an asymmetric encryption algorithm to protect users' privacy. Furthermore, permission-less or public network, open to everyone to join in, could be defined (opposed to permissioned/private network which is restricted to a given group of participants). These permission blockchains provide a better access control and more privacy [13]. To improve security and automation, we can consider the smart contract technology too. To simply describe smart contracts, we can compare it to a vending machine. Ordinarily, you would go to a lawyer or a notary, pay them, and wait while you get the document. With smart contracts, you simply drop a bitcoin into the vending machine (i.e. ledger), and your escrow, driver's license, or whatever drops into your account. More so, smart contracts not only define the rules and penalties around an agreement in the same way that a traditional contract does, but also automatically enforce those obligations [14].

In what follows, we will detail our work which concerns the use of blockchains and smart contracts to secure, manage and control a IoT corresponding to an smart warehouse with automated storage areas and several handling/transport materials, an automatic palletizer. This smart warehouse is shared between different firms. The rest of this article is as follows. In a second section, we will present the principle of sharing economy and its application to the pooling of warehouse resources, its interests and limits. The third section will be devoted to the mathematical definition of our pooling, the objective is to define it precisely in order to quantify and size this sharing. For this, a cooperative game will be proposed and detailed. However, the objective of this paper is not to solve the mathematical model but to propose a blockchain strategy coupled with an industrial IoT representing a pooled warehouse to be sure to secure this sharing. Therefore, the fourth section will focus on the concept of Internet of Things (IoT) and chosen technologies associated with it. In a fifth part, the blockchain technology and notion of smart contracts will be developed and associated to our IoT before concluding and giving future perspectives to our work.

2. WHAT IS SHARING ECONOMY?

The concept of collaborative consumption and sharing economy is very ancient since it has allowed the human survival [15]. However, since the industrial revolution and especially since the mass production, the concept of ownership of a good and its use restricted to the owner has been the only economic model to enjoy benefits. Nevertheless, awareness of the challenges of sustainable development has highlighted the limits of this economic model [16] and the advantages of sharing economy. Sharing economy enables the sharing of resources which could be physical goods (a car, a network of computers, etc.), money (like bitcoins), services (assistance to the person), skills (R&D, human resources activities, etc.), spaces (for example a part of a warehouse) [17]. Of course, each of those resource types has some specific characteristics (like immateriality for services, habits for humans or presence for physical goods) which must be taken in account. From this, collaborative consumption websites have been largely developed and have enabled consumers to focus on shared access to products rather than owning them. The main interest is of course an economic profit, but it also allows reducing resources consumption and induced environmental pollution, and maximizing social benefits. The second interest comes from the development of information technology [18] including open source, peer-to-peer exchange and social networks, which provide new platforms for supporting large-scale sharing resources (cloud computing, peer-to-peer memory/files sharing, etc.). However, in parallel to this exponential development of sharing economy platforms, the lack of ethics and appropriate government regulations generated several serious problems like costs and risks externalization and sidestepping regulations designed to protect consumers and externalized actors, good payment and insurance of the activities carried out, successful and real collaborative pooling, etc. [19]. Furthermore, data security and transparency in the sharing are still an opened research.

In this paper, we will focus on the concept of pooled warehouses. A pooled warehouse is defined as a warehouse with a part or all parts of it shared between several actors, which can be manufacturers, logistics providers and distribution companies, in order to share physical spaces, resources and logistics information to improve the overall performances of the supply and/or distribution process [20] Indeed, from one part, there is a lot of enterprises, not only in supply chain domain, which have problems with overcapacity warehouses. Generally, this situation occurs with warehouse from 15 to 20 years' old, which have been design to store a specified lot of goods. However, since their building, environment and context have changed, either the enterprise activity decreased or, the evolutions on storage and supply chain management have led to a decrease in stock need. On the other part, the uncertainties, strong and increasing competition markets but also environmental and social requirements led companies to develop new strategies to ensure very good levels of services, costs control, efficiency and the safety / security. Whatever the reasons, the result is the same: a large part of the warehouse and its associated resources are now underused, unused or misused [21].

One of the solutions is the sharing that allows the enterprise to monetize its empty spaces and optimize the use of its resources. The solution is not new, but in fact, the warehouse is divided into specific zones and each occupant (owner and tenants) stay in its own part, which induces that a free storage place (or handling equipment or workers, etc.) in one zone cannot be used by another tenant. Even if the owner rents also services (administrative, overseeing, guard, etc.) and/or materials (Fenwick, trucks, etc.) there are some billing problems, actually solved by fixed price type contracts. Another solution is derived from well-known methods as Collaborative Planning, Forecasting and Replenishment (CPFR), Vendor-Managed Inventory (VMI), Co-Manage Inventory (CMI), etc. In these cases, dynamic shipments of inventories and transport could be defined with the help of a logistics provider. These dynamics, and then the consequent variable needs of inventories and transport, require to identify and characterize the different elements that can be shared and their availability (an element could be unavailable because it is under maintenance activity for example) and the conditions of pooling (time, quantity, cost, etc.).

In what follows, we will detail our pooling strategy.

3. IOT OF WAREHOUSE RESOURCES

In this paper, we propose to develop a method to obtain a dynamic and secure pooled warehouse, where bills would be established considering the exact used of service/material/worker and the free storage places would be allocated dynamically considering the warehouse as a whole and not a set of separate zones. The main difficulty corresponds to the fact that the actors have different characteristics and needs that requires a good coordination between them and an optimized use of the pooled warehouse and resources. Therefore, it is necessary to define a structure to:

i) manage and secure information in real time (including security and privacy of firms data) and manage the various information systems,

ii) manage the complexity due to the presence of different actors (including competitors) and different physical characteristics (volume, type and number of customers, number of materials, type and number of shared resources, and storage space),

iii) manage the access of all possible services offered in the pooled warehouse such as the allocation and arrangement of storage space, order picking, automatic palletizing, etc.

Generally, pooled warehouses are managed with the help of third party logistics providers (3PLs). In this case, the partners share nothing among themselves and we have a bilateral collaboration. On the other hand, pooled warehouses are managed with the help of fourth party logistics providers (4PLs). In this second case, we could have a total implication of partners in the warehouse management with a multilateral collaboration (which is of course more complex to manage as a simple bilateral collaboration). We will consider this last case which is relatively recent and becomes more important but which is less studied in the literature. Our pooled warehouse is composed by: a 4PL, partners which could be manufacturers, retailers, vendors, 3PLs and customers (which could be the same for different partners), storage spaces with conventional storage areas and automated storage areas, human resources which are essentially operators and warehouse managers, material (handling, packaging, computing, etc.), different methods (work instructions, organizations, management, etc.) and information systems (ERP, WMS, Microsoft Office, EDI, etc.).

We received various kinds of manufactured goods as inputs of our pooled warehouse and as outputs, we have picked and palletized parcels, which are ready to be put in trucks, all these elements, are identified by RFID or NFC tags. Thus, this pooled warehouse will be defined as a network of connected objects, simply speaking an industrial Internet of Things (see Figure 1 which represents an example of connected objects in a warehouse, namely wire-guided or geo-guided trolley, automatic palletizer, conveyor robot, smart container, etc.).

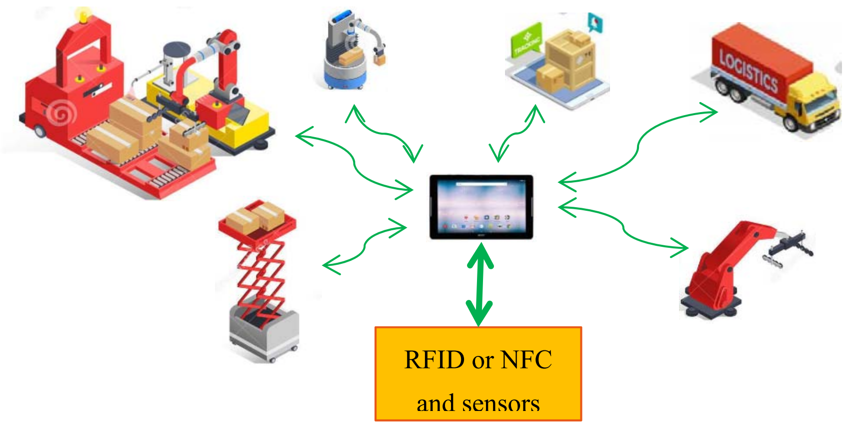

Figure 1. Example of industrial IoT for a pooled warehouse.

Since the last couple of years, thanks to significant evolutions in technologies (RFID technology, WSN, new Ipv6 addresses, OS for IoT, etc.), the growth of developments about Internet of Things (IoT) explodes: in two years, around 80% of consumer services will use IoTs and around 3.5 devices per person will be connected. In 2017, the business segment represents 65% of overall IoT applications, mainly in healthcare and manufacturing / supply chain activities, but smart cities are expected to have the most important increase in IoT applications. IoT is not a single technology but a combination of different ones (communication and information technologies, electronic sensor and actuator technologies, computing and analytics). Currently, there is still no standard architecture for IoTs, but we can found various architectures with three, four or five layers. Anyway, each layer needs to have security and privacy issues to ensure to secure IoT applications. Despite these growing uses, the increasing development of IoTs, and in parallel with them, most of these IoT networks are still easy to hack and compromise due to their limits in compute, network capacity, centralized architecture, energy efficiency and storage [22].

In our proposal, we decide to use a four layers' type IoT architecture, to be able to well model the different stages of a real system. This IoT architecture is given in Figure 2 with: the perception/sensor layer with connected objects (input and output elements but also all warehouse resources represented by RFID/NFC tags, sensors and actuators), a networking layer to support information transfer through a wireless network, a service layer to integrate services and applications through a middleware technology and an interface layer to display information to partners which interact with the system. The overall data of this IoT are then centralized by the 4PL. However, this IoT is subject to many security problems at each layer of the IoT so it necessary to propose a more secure strategy which will be based on an end-to-end security rather than a more classical specific security layer. Furthermore, manufacturers, retailers, vendors, 3PLs and customers need to be sure that the data are private and not identified by the 4PL or hackers.

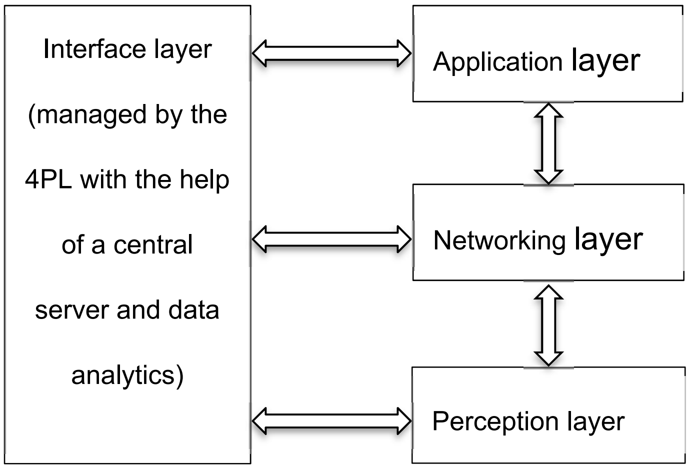

Figure 2. Considered IoT.

In what follows, we discuss how blockchain and smarts contracts could be a key enabler to solve our IoT problems and challenges.

4. BLOCKCHAIN AND SMART CONTRACTS

Such as defined previously, our IoT is composed of each element in the warehouse (storage places, pallet trucks, human resources, goods, etc. Figure 1) which would be equipped with smart identification (RFID/NFC) and sensors (scan, GPS, etc.), as well as the warehouse and its resources and actors. Then, each movement in the building would be noticed and recorded. In fact, no matter what technologies are used at the perception layer, the important things are: i) to be sure that any movements of goods, materials and/or human resources are identified like in any kind of IoT and ii) to know at every time if a resource is available or not and, if not, why? (maintenance, failure, etc.) and for how many time?

Concerning the blockchain part, it is typically a decentralized, distributed, shared and immutable database ledger, which permits to store registry of transactions and assets across a peer-to-peer network. The launched of the Ethereum blockchain in July 2015, which implements smart contracts, offers a potential use space for blockchains [23]. Indeed, a smart contract is a program (also called solidity) written by users which allows to execute the terms of the contract between users based on a computerized transaction protocol. The smart contract system based on blockchain technology has the dual advantages of automatic execution and trustworthiness. Furthermore, Ethereum virtual machines (the miner nodes) are capable of providing cryptographically tamper-proof trustworthy enforcement and execution of these contracts. At each type of resource (people, storage place, truck, etc.) correspond a specific type of smart contract, defined by the 4PL's, taking in account the specificities of each

resources. However, moreover, in our architecture smart contracts are also different in function of the considered coalition to be able to match perfectly the needs of each participant.
Though the birth of the blockchain and IoT took place almost at the same time, the applicability of blockchains to IoTs remains still limited. Nonetheless, the decentralized architecture offered by blockchains directly overturns the old central architecture of IoTs, which not only greatly eases the pressure of central computing, but also releases more possibilities for its organization and provides more space for innovation. The accuracy of records and indiscriminate modification also make privacy security easier to defend and handle in terms of security. Finally, with the development of the blockchain technologies, the subject’s participation in IoT collaboration becomes easier. In addition, the distributed Internet technologies such as peer-to peer networks, network attached storage and content distribution network adopted by the Internet of Things have also natural affinity with the blockchains and smart contracts at the technical level. Therefore, our strategy of conjoint use of blockchains and smart contracts allows defining a more robust global mechanism to manage, control and secure layers of our industrial IoT.
Blockchain and smart contracts will be used on the upper layers of the IoT structure, to ensure recording and security. We give in Figure 3 the transaction process of our proposed work where the smart contacts leaning on the blockchain allow, under the control of the 4PL, to assign (or not) the requests of external companies in logistic activities via the network of connected objects. At the network layer, the identity and address of each object of the IoT would be controlled by blockchain, which has largely enough places to manage up to 1.46 $*$ 1048 IoT devices. The blockchain is maintained by a network of nodes and every node can execute and record the same transactions which permit the decentralization architecture. Smart contracts based on Ethereum virtual machines could manage efficiently the authentication problem (who? when? for what? etc.) and the temporary ownership transfer for material and storage places, following rules defined in the real leasing contract. The smart contract is a piece of code that resides on the blockchain and is identified by a unique address. The Ethereum virtual machine is the runtime environment for smart contracts in Ethereum (open and programmable blockchain platform chosen for its simplicity and since smart contracts are treated as autonomous scripts or state full decentralized applications that are stored in the Ethereum blockchain).

Thus, when a resource demand is formed by an actor, a transaction chain is defined. This transaction chain contains the user information (identified by a key cryptography composed by a public and a private key to ensure privacy of important data) and the transaction information. Therefore, this transaction block contains a digital signature, a timestamp and relevant information including the hash of the previous block. The transaction block is broadcast to all nodes in the distributed network and will be approved or not (authorization phase which allows the introduction or disappearance of actors). Then, if the transaction (resource or service demand) is accepted, the transaction will be executed. Once the transaction is successful, the Ethereum platform will broadcast the contract information to all distributed and decentralized nodes and update the information in the blockchain to complete a new round of consensus. The main difference between our proposed work and a classical IoT managed by a 4PL lies in the fact that in our solution we do not need to have a 4PL central server, which is replaced by the distributed blockchain. The 4PL rule lies in the coalitions creation, maximizing companies (and its own) profit. Finally, the blockchain, as an immutable database, would keep a trace of every transaction, with their characteristics (time, duration, number and type of involved places, materials, workers, etc.) allowing monitoring and dynamic allocation as well as precise billing.

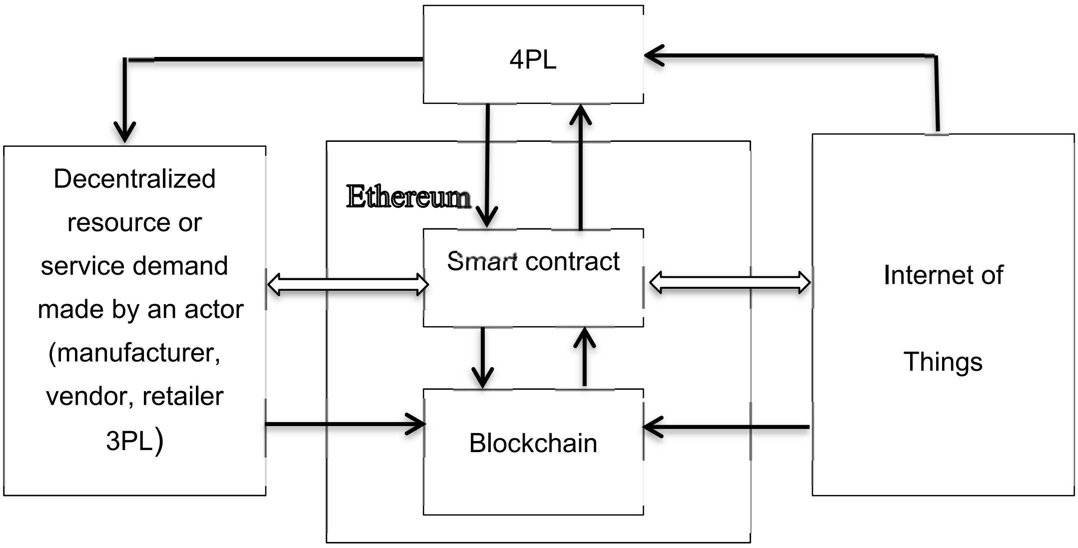

Figure 3. Transaction process of our proposed work.

In addition, as we consider several actors: a 4PL, partners which could be manufacturers, retailers, vendors, 3PLs and customers which could be the same for different partners, we have to define a strategy which allows to identify the fact that these actors will have different activities, actions and needs depending on their behaviour. Indeed, the involvement of these actors in the sharing depends on actor's properties such as autonomy, sociability, distribution, communication, coordination and negotiation…, which could be, characterize by a multi-agents system (MAS). MAS is an environment composed of agents (the considered actors in the pooled warehouse identify as "enterprise" and all connected object identify as "resource") and objects (passive entities can be created, modified and destroyed by agents) which interact to achieve a given goal [24]. Three types of MAS can be defined: cognitive agent systems, reactive agents systems and mixed/hybrid systems. MAS could be open (agents enter and leave freely) or closed (same agents from start to end), homogeneous (same agents) or heterogeneous (with different models). The model used in this paper is an opened MAS (since new actors could enter into the mutualisation) consisting of cognitive and heterogeneous agents with a decentralized control (agents have a certain degree of autonomy. Then, the proposed architecture is given in Figure 4.

So, our proposed Architecture is an hybrid architecture composed by two parts:

1. a centralized part based on the MAS which allows to model: the different behavior of actors, clouded resources exchange and distribution which is composed of two modules:
    - the Artificial intelligence one which is dedicated to market data (analyse, learning and integration),
    - the second module describes agents' decision on use and share of industrial resources.

2. a decentralized blockchain system to dynamically connect "user" agents to "industrial resources" agents and to identify available resources, validate sharing data and operations transactions (and their history).

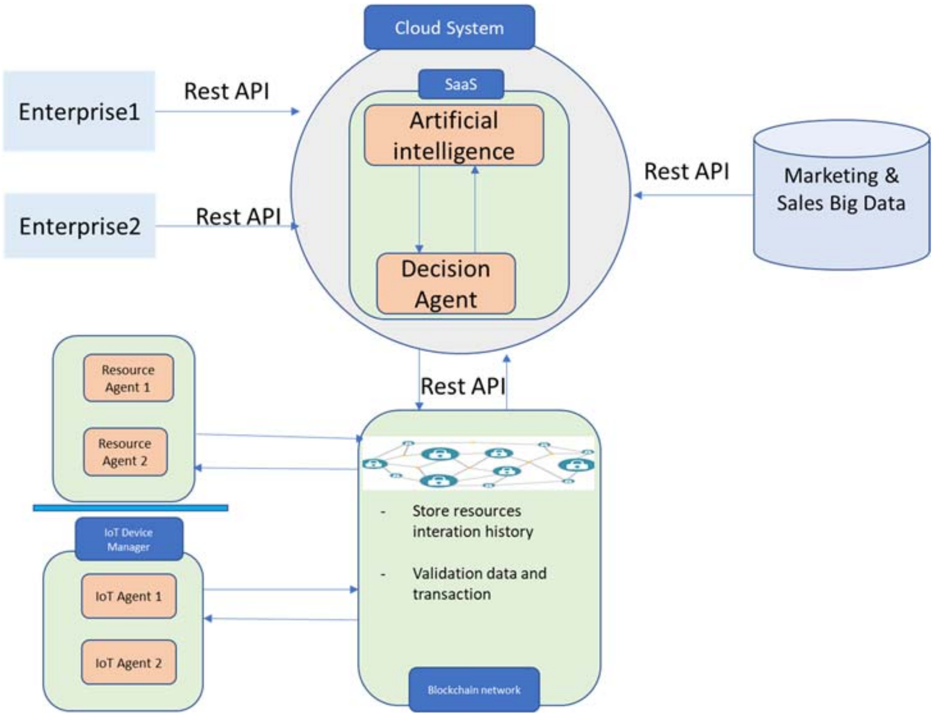

Figure 4. Proposed architecture.

This hybrid architecture allows us to couple the advantages of both approaches (centralized and decentralized) while retaining the best of each. Thus, the management of the pooling is done at the level of the blockchain network, and the general organization considering the interactions between actors and their dynamic evolutions would be done at the MAS level (SaaS).

Actors (even if they are not competitors) are more economic self-interested rather than really in an optimal pooling strategy. So, it would be interesting to clearly identify all possible actors' strategies (how they will act during a pooling period, honestly or not? And if they cheat, how?) and, based on these strategy studies, to size the pooling to obtain the best possible conditions. In that sense, agents are economic and intelligent ones [25]. From the economic aspect, the main idea is to represent the behavior of agents in an economic environment to analyze interactions resulting from these behaviors. Thus, we choose to define a model based on game theory because it is well adapted to our problem, especially because the considered actors can be seen as players, i.e. opponent in the "pooling game". Game theory permits to understand how stakeholders (players) interact in a process of decision-making. These players strive to maximize their own goals despite choosing a common strategy. The games can be cooperative or non-cooperative. For example, Mahjoub and Hennet [26] defined a cooperative game to study a supply chain network design with perfect pooling of production capacity. In that sense, the logistics network can be modeled as a collaboration between players. This model then has practical advantages since it convinces logistics partners to reach an agreement. In another work, the benefit of capacity pooling among independent companies taking into account service level requirements is considered [27]. The authors have also modeled their problem with a cooperative game and found that if service levels are specified in terms of waiting time instead of total delay, and when the companies are heterogeneous, the capacity pooling may not be beneficial. In our work, we choose to use also a cooperative game since we want to analyze the inter-enterprise interactions at a strategic level that induce agreement or alliance possibilities between some players against others ones. Our proposed MAS coupled with game theory will then allow us to have a good systemic representation of our pooled warehouse management problem. In what follows, we will detail our mathematical model.

5. PROBLEM MODELLING

The pooling of warehouse resources will be modeled using game theory with cooperative games. Non-cooperative games are generally used to represent the fact that economic agents are interested only in their own profit. Therefore, they are competitor in the game. On the contrary, cooperative games allow representing coalitions between agents in the game progress and, agents take in account the fact that cooperation could improve the individual profit of each coalition participant. Very good surveys on game theory in supply chain applications could be found in [28]. [29] proposed to strengthen the stability of the coalition by selecting a minimum set of partner companies to achieve the maximum expected profit and ensuring equity for member companies. [30] also develop a cooperative game model to build a coalition and a pricing policy strategy for cooperative inventory management in a retailers' network. Their approach based on a stochastic optimization model with recourse helps sellers to decide if they should exchange their products with each other (satisfaction of local demands), or if they should solely rely on their seasonal delivery from a supplier. In another work, authors propose a model based on non-cooperative game to model a production resource pooled between two companies [31]. The proposed model allows describing possible cheatings and deviations from the initial contract and their impact on the initial collaboration.

In this paper, we will consider cooperative games that will allow us to represent the pooling as a set of coalitions between several players. Indeed, let's take for example two competing companies sharing the same market (see Table 1). Their tactics could be:

- choice 1 to participate in a pooling strategy when distributing their finished products with a more important risk (*Riskmax*) of seeing crucial information (characteristics / customer needs, lead time, etc.) but lower distribution costs (*Cdmin*),
- choice 2 not to participate in a pooling strategy when distributing their finished products with less risk (*Riskmin*) of losing crucial data but higher distribution costs (*Cdmax*).

This corresponds to the prisoner's dilemma. The prisoner's dilemma embodies the idea that the aggregation of individual preferences does not necessarily lead to a collective optimum.

Table 1. Example of two competitive companies.

		Company B	
		Do not participate to the pooling	Participate to the pooling
Company A	Do not participate to the pooling	Cd_{Amax} / Cd_{Bmax} $Risk_{Amin}$ / $Risk_{Bmin}$	Cd_{Amax} / Cd_{Bmin} $Risk_{Amin}$ / $Risk_{Bmax}$
	Participate to the pooling	Cd_{Amin} / Cd_{Bmax} $Risk_{Amax}$ / $Risk_{Bmin}$	Cd_{Amin} / Cd_{Bmin} $Risk_{Amax}$ / $Risk_{Bmax}$

In this paper, we consider a total number *N* of companies (including the 4PL). These companies could participate (be active) or not (be passive) to the pooling. More precisely, at a period of time *k*, with *k = 1* to *K* (finite time horizon), a given number of companies *N+(k)* want to participate to a warehouse pooling which will be described as coalitions, generated in function of companies' needs, denoted $S(k)$, with *N+(k)* a subset of *N*. In this case, the *N+(k)* companies (including the 4PL) will share the global payoff, denoted by $v(S(k))$, corresponding to the economic gains resulting from the pooling of warehouse resources. So, as a result of this cooperative game, at each period of time *k*, each company *i*, with *i* in *N+(k)*, would obtain an economic share $v_i(S(k))$ which is greater than if *i* does not participate in the pooling, with $\sum_i v_i(S(k)) = v(S(k))$.

Then, our problem is described by two steps:

- Step 1. Tactical level: at this level, knowing the number of companies $N^+(k)$ at each period of time *k* and their needs (in terms of resources and logistical services), the 4PL will define for all periods of time (finite horizon) optimal allocations of resources and logistical services and therefore an access to the IoT. At this level, depending on the optimal allocation for each period of time *k*, the maximal payoff is obtained. It is given by $v^*(k) = max_{S^j(k)} \ \sum_j v_j(S^j(k))$. So, at each period of time *k*, depending on capacity constraints and needs, the 4PL could define different kind of allocations of resources / services corresponding to different kind of sharing (coalitions) denoted $S^j(k)$ with $0 \leq j \leq N$. The objective of the 4PL is then to maximize the use of its resources / services, i.e. maximize the productivity / the total use of resources (or minimize makespan for each resource and offered service) at each period of time *k,* and also to maximize the economic profit (or minimize the costs considering that when a company participate to a coalition the price of use would be lesser than when it does not participate to a coalition). We suppose that when a company *i* does not participate to a pooled warehouse strategy, it should pay a more important cost denoted $C_{max}^i(k)$. So, its utility function will represent a payoff resulting from the difference between this maximum cost $C_{max}^i(k)$, paid in case of no coalition, minus the costs paid in case of coalition (pooling). This biobjective problem is subject to capacity constraints: storage capacities and time capacities for logistic services. However, when the 4PL have specific contracts with companies corresponding to a sharing, it allows the 4PL to earn more money and satisfy better these particular customers.

- Step 2. Operational level: the current use of resources and logistical services during a period *k* will be managed by our proposal of IoT coupled with different blockchains and smart contracts (the blockchain network part see Figure 4). Indeed, we will define for each coalition a specific smart contract that allows allocating resources to companies during a considered period *k*. This smart contract of a specific coalition $S^j(k)$ during *k* will also take into account the fact that a resource/service could be available or not, and that companies could decide not to use a resource/service and that other companies (new companies not included in the coalition) could use it. Simply speaking, the role of the smart contracts would be to allocate in real time resources/services to companies, which could be in a pooled warehouse strategy, or not. The smart contract associated with the blockchain will allow us to run automatic actions with Turing-complete abilities based on collected information. The blockchain control architecture is given in Figure 5 with different kind of actors throughout the supply chain coming from the suppliers who exchange raw material and components information with producers, these producers exchange their products information with wholesalers, these wholesalers are in charge of transport booking, and transporters will communicate their shipping information to customers. All necessary exchange data are also collected by the 4PL to allow the control of the pooled warehouse strategy by the blockchain.

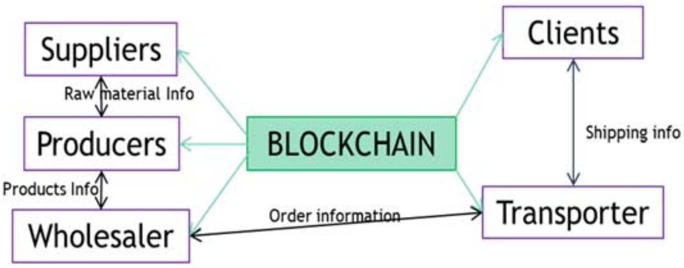

Figure 5. Supply Chain Blockchain control architecture.

Therefore, to represent mathematically our problem, it is necessary to clearly define the specificities in terms of storage and logistics services for all considered companies and each period of time, and to size resulting costs. Of course, these needs are provisional and could vary a little bit during the total sharing horizon. The needs in terms of equipment levels and their characteristics are of course variable depending on the needs of the companies. Therefore, it is necessary to characterize them at each beginning period of time *k*:

- Storage areas are composed of shelves, racks, a mass area and a cross-docking area. The companies will express to the 4PL their specific need for each period of time *k* at the beginning of the study, this need could be of course null for a given period of time *k*.
- The total storage area (except the cross-docking area which is proposed as a logistics service and the mass area described below), determined by the nature and quantity of elements to be stocked, will be noted *Sup(k)* for a period of time *k*. To simplify, *Sup(k)* corresponds to a maximum number of EPAL pallet spaces (120 × 80 × 200 cm). It has to be noticed that the 4PL

has other customers than only companies, which want to participate to a pooling strategy. So, for each period of time *Sup(k)* corresponds to the remaining storage space (without the needs of classical customers have been), with $0 \le Sup(k) \le Sup_{max}$. For each company *i*, the maximum required of storage area also defined in pallet spaces is noted:

$S^{i}_{up}(k)$ with $\sum_{i=1}^{n} S^{i}_{up}(k) \le S_{up}(k)$. (1)

- For the mass area (large and unconventional products / pallets), the total storage area is given by *SCDup(k)*, with with $0 \le SCDup(k) \le SCDup_{max}$, and the total storage area required for each company *i* is given by:

  $SCD^{i}_{up}(k)$ with $\sum_{i=1}^{n} SCD^{i}_{up}(k) \le SCD_{up}(k)$. (2)

- These required areas correspond to a total storage number of goods represented by a quantity which will be identify for each company *i* at time period *k* by $Q^{i}(k)$. $Q^{i}(k)$ is given by:

  $Q^{i}(k) = \alpha^{i}_{mass}(k).SCD^{i}_{up}(k) + \alpha^{i}_{classical}(k).S^{i}_{up}(k),$). (3)

  where $\alpha^{i}_{mass}(k)$ and $\alpha^{i}_{classical}(k)$ are known values in [0, 1]. These values depend on the volume and mass of goods and / or pallets.

- The resulting inventory costs which could be separate into a fixed part and a variable part are given for each time period *k* and each company *i* for a coalition $S^{j}(k)$ by:

  $$C^{i}_{storageS^j}\left(S^{j}(k), Q^{i}(k)\right) = a^{i}_{S^j}\left(k, S^{j}(k)\right) + b^{i}_{S^j}\left(k, S^{j}(k)\right).Q^{i}(k) \text{).} \quad (4)$$

- with $a^{i}_{S^j}(k)$ the fixed part related to the implementation of the required inventory, $b^{i}_{S^j}(k)$ the variable part, and $Q^{i}(k)$ the quantity of goods for *i* during *k*. We suppose that at the end of a period *k*, the total number of storage goods will be sailed or transferred in another warehouse and would not generate supplementary inventory costs for the next period of time *k+1*.
- The needs in logistics services for each company *I* could be: a customs clearance service, special packaging, cross-docking activities, inventory management, etc. These needs will be noted as a vector $L^{i}_{services}(k)$, which depends on the kind of needed logistics services during *k*. If a logistics service is required, the corresponding value will be equal to 1 and if not it will be equal to 0 for all possible logistics services.
- The capacity constraint for each service is given by the time spent for doing this service for a company *i* during *k*, this time depends on the number of goods for *i* during *k*. The time spent for all services during *k* for a company *i* is given by a vector $T^{i}_{services}(k)$. The time capacity constraint during *k* for all services is given by $T_{services-sup}(k)$ with $0 < T_{services-sup}(k) < T_{services-supmax}(k)$. So, we have to check that:

  $T^{i}_{services}(k) \le T$[redacted]$_{services-sup}(k)$.). (5)

- The logistics services costs which could be separate into a fixed part and a variable part are given for each period of time *k* and each company *i* for a coalition $S^{j}(k)$ by:

  $$C^{i}_{logS^j}\left(S^{j}(k), Q^{i}(k)\right) = [a^{i}_{logS^j}(k) + b^{i}_{logS^j}(k).Q^{i}(k)].L^{i}_{services}(k) \text{).} \quad (6)$$

with $a^{i}_{logS^j}(k)$ a fixed part related to the implementation of the required logistics service(s) paid by the company *i*, $b^{i}_{logS^j}(k)$ the variable part, and $Q^{i}(k)$ the volume of goods for *i* during *k*.

A transportation cost to transport goods to the warehouse could also be defined for each company. However, in this paper, for sake of simplicity, we suppose the warehouse is ideally located for all companies and then we do not consider the transport. Likewise, we do not consider losses from breakage / theft / etc.

So, the total profit (regardless of sales, which are company-specific profits, the companies could be concurrent or not) for the company *Ei*, in case of participation to a warehouse pooling, is given by:

$$\text{Max} \quad \pi^i_{S^j}\left(S^j(k), Q^i(k)\right) = C^i_{max}(k) - [C^i_{S^j}\left(S^j(k), Q^i(k)\right) + C^i_{logS^j}\left(S^j(k), Q^i(k)\right)] \qquad (7)$$

And, the bi-objective problem for all companies in *N+(k)* at each time period *k*, solved in step 1 by the 4PL, is given by:

$$max_{S^j(k)} \ \sum_j v_{storage-j}(S^j(k)) \ + \ max_{S^j(k)} \ \sum_j v_{log-j}(S^j(k)) \qquad (8)$$

$$min_{S^j(k)} \ \sum_r Makespan(r, S^j(k)) \qquad (9)$$

Subject to the following constraints (corresponding to equation (10)):

$$\sum_{i=1}^{n} S^i_{up}(k) \leq \mathrm{S}_{up}(k),$$

$$SCD^i_{up}(k) \text{ with } \sum_{i=1}^{n} SCD^i_{up}(k) \leq \mathrm{SCD}_{up}(k), \ ). \qquad (10)$$

$$T^i_{services}(k) \leq T^{\blacksquare}_{services-sup}(k).$$

With $v_{storage}$ the utility function corresponding to the storage resources and v_{log} the utility function corresponding to the logistic services, *r* a resource, *r = 1* to R (the total number of resources). It has to be noticed that these utility functions for the 4PL depend on the costs paid by companies that participate to a pooling strategy (i.e. prices defined and given by the 4PL) minus real costs paid by the 4PL. These utility functions could be lesser than in case of no pooling strategy for the 4PL but the interest for the 4PL is to define more reliable links with these particular customers and thus to obtain a gain probably more important for several periods of time because of this loyalty.

At the operational state, we have to control, schedule and monitor the current use of each kind of resources. In that sense, the blockchain technology, coupled with smart contracts would be very useful.

6. DISCUSSION

This work is developed with the help of a French 4PL enterprise implemented all over the world. This 4PL enterprise has given us its needs and based on these needs we pursued the following methodology (see also Figure 6 which represents the methodology pursued).

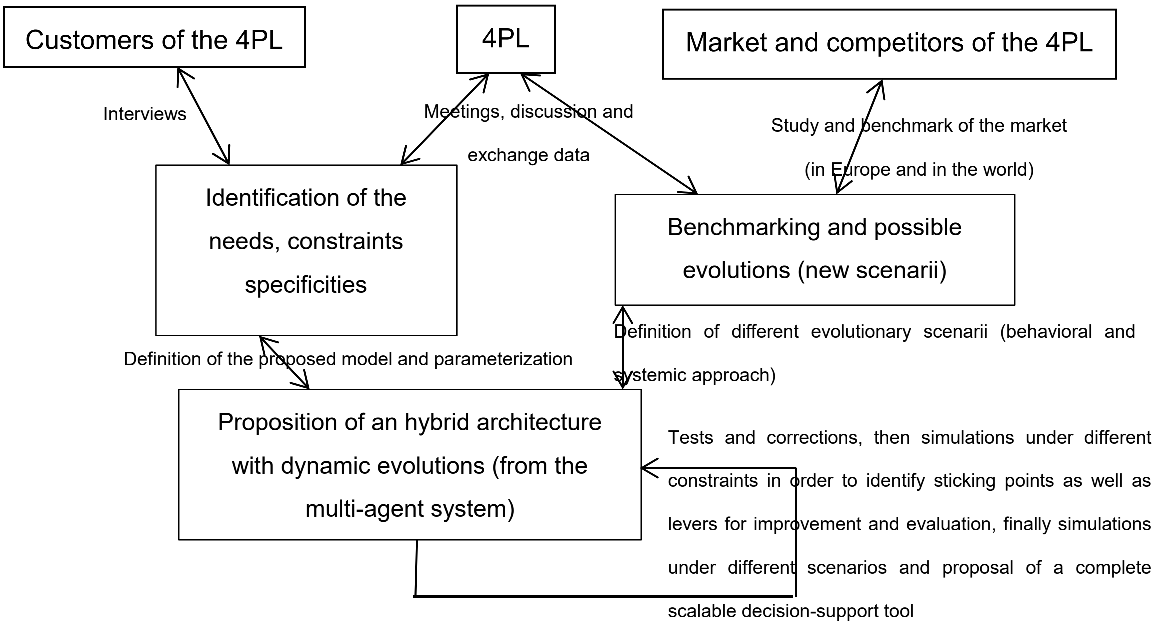

Figure 6. Methodology.

Thus, as a first step, we had a lot of exchanges and interviews with the managers but also with the warehouse operators of this enterprise to clearly identify their needs, constraints and specificities. We also had meetings with their sales department as well as with some of their clients. In parallel, with the help of their sales department and data from Internet, we conducted a benchmark in order to identify the strategies currently being developed but also to identify the innovations under development. This allowed us to identify more precisely on the one hand the behavior of the market but also possible developments Then, we developed our work, presented in part in this article, based on these needs, specificities and constraints. The possible dynamic evolutions are integrated in the multi-agent system not detailed in this work (indeed, the systemic and behavioral approach allowing integrating different evolutions). The finalization of this work and the tests and corrections are still in progress. When this step will be finalized, we will then be able to simulate our hybrid architecture under different possible scenarii in order to evaluate its robustness against, for example, cyber-attacks or important requests arriving at the same time. Once these evaluations have been carried out and the resulting corrections made, we will be able to propose a complete decision support tool for our industrial partner.

The idea is for this partner to have a tool that will allow it on the one hand to optimize its own resources while offering new logistics services. In the other hand, it will also allow to have a strong impact in terms of economic and sustainable development in order to face the spectacular increase in the variety of products and services and the mass customization generating the need to define new logistics strategies. The competitive advantage, in these circumstances, lies in improved integration and coordination between associated partners and in the modelling of decision support systems that can increase awareness of decision makers and their associated partners in the supply chain. However, the main bottlenecks in the deployment of such strategies lie in the security, reliability and confidentiality of data with differentiation between public and private data. New technologies and approaches, such as those used in our work, may allow us to rethink cooperation and coordination within supply chains.

Indeed, the decision support tool that we wish to develop will facilitate the sharing of resources and possible pooling within supply chains. As a result, the results obtained will make it possible to act on the one hand on the emissions of greenhouse gases, fine particles and other pollutants and on the other hand on energy consumption. We are aware, however, that the digital tool developed will also lead to energy consumption that may be significant following the use of blockchains. An effort will therefore be made to integrate this over-consumption.

7. CONCLUSION

The essence of sharing economy is to change the transaction from ownership to right-of-use, and it is hoped that people who have idle resources and those who need to use these resources can carry out point-to-point transactions in a low cost. Currently, sharing economy is still at an embryonic stage, and we think that the emergence of blockchains and other decentralized method will make sharing more efficient, reliable, secure and inexpensive. The sharing economy is indeed taking off but with more trust and efficiency.

In this work, we are interested in the pooling of different resources of a warehouse using an Internet of Things network (IoT). We propose a four layers' type IoT architecture that models the different stages of our pooled warehouse. In fact, the perception/sensor layer corresponds to the connected objects (i.e. all pooled-resources warehouse represented by RFID/NFC tags, sensors and actuators). The networking layer allows supporting information transfer through a wireless network. The service layer will then integrate services and applications through a middleware technology and an interface layer to display information to partners, which interact with the system. The advantages of IoTs are multiple with many simple and inexpensive uses (with phones) of the connected objects, less monitoring/control activities (since resources are online) and possible optimization in (near) real time. However, significant risks of cyber-attacks and data security problems (often centralized in the cloud) coupled with failures whose propagation is important because of the centralized management do not facilitate their use.

So, we proposed to secure, manage and control of IoT representing all possible pooled resources of a warehouse by a blockchain and smarts contract associated with it. Blockchains allow decentralizing the network of connected objects and permit to secure this network as the transactions recorded on the blockchain after a consensus cannot be altered or deleted and new peers can join the network. Furthermore, blockchain is resilient to failures (since it is a decentralized peer-to-peer network with no single point of failure). In our system, smart contracts will model the specificities of each resource into each coalition, which allows us to have tailor made secured and monitored transactions between participants and to make the best operational use of these resources. Based on this, we propose a hybrid architecture to completely represent our system (actors and connected objects in the pooled warehouse strategy). This hybrid architecture is composed by two parts: a centralized part based on a multi-agents system with to represent dynamic evolutions of actors' behaviour, and a decentralized part, which corresponds to our blockchain and smart contracts network to dynamically connect actors' agents to pooled resources (all of these elements are represented by agent in our MAS). Our proposed MAS is coupled with game theory to have a good systemic representation of our pooled warehouse management problem.

Thus, we proposed, at tactical level, to divide the pool of participants into different coalitions based on their specific needs on a period k, this division will be made thanks to the use of a cooperative game theory model (not solved here). Indeed, we want to maximise the profit of each (including 4PL) companies by a perfect resource type allocation considering their planned uses on k.
At the operational level, we plan to use jointly the Internet of Things and blockchain technologies with the support of smart contracts to manage efficiently the considered pooled warehouse. The IoT technology, for its part, allows us a simple identification of resources and services, and communication about their availability, their use or their state. For that, they must be instrumented with sensors, identifications, and communication abilities to share data.

We conclude this paper by pointing out the next venues for our researches. Thus, the specification of all used technologies for all layers of the IoT should be clearly identified and justified. In a same way, the choice of the best economic and ecological value of elements of the IoT should be determined. Indeed, for example, environmental and social requirements, which become more and more important for firms are not taking into account. Furthermore, a warehouse control system will be used in the software level of the structure to control warehouse, materials and human resources. Our aim is to improve the warehouse efficiency, reduce the unused free places, better use resources and provide way to establish precise bills to forget fixed price type contract. Furthermore, the main challenge is to optimize flow in the virtual supply network depending on the physical state of the supply chain system (and not only the warehouse system) and the dynamical changes. Future work will also focus on implementation and demonstration of our proposed work with realistic solutions such as device self-service and integration of maintenance activities.

The finalization of this work and the tests and corrections are still in progress, but we already know that we will have to take in account some aspects, ignored until now, such as sustainable development, storage and resources use optimization, automatic and precise billing, etc. More than that, we will need to focus not only on the warehouse itself, but also on the entire supply chain.

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