

Bottom-up approach based on Internet of Things for order fulfillment in a collaborative warehousing environment



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ABSTRACT

Industrial deployment of the Internet Of Things (IOT) provides development of an ideal platform for decentralized management of warehouses. In this paper, we propose an IOT infrastructure for collaborative warehouse order fulfillment based on RFID, ambient intelligence and multi-agent system. It consists of a physical devices layer, a middleware ambient platform, a multi-agent system and an enterprise resource planning. It integrates a bottom-up approach with decision support mechanisms such as self-organization and negotiation protocols between agents based on “com-peration=competition+cooperation” concept. This approach was selected to improve reaction capabilities of decentralized management of warehouses in a dynamic environment. A collaborative warehouse example was conducted to demonstrate the implementation of the proposed infrastructure.

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1. Introduction

Collaborative warehouse platforms are considered a very promising supply chain solution in response to volatile demand and fluctuating fuel and labor costs. Recent increases in pooling and collaborative warehousing projects for retailers such as Walmart, Carrefour, Tesco and Metro confirm this trend (Bäflan, 2010). This concept can be found in consolidation platforms, like classical cross-docks, urban distribution centers, logistics cities and city hubs. Moving toward more sustainable business (Ageron et al., 2012) requires re-consideration of logistics strategies by combining collaborative warehouse platforms for warehousing, distribution and transport between all supply chain stages (GCI and Capgemini, 2008). Collaborative warehouse platforms like city logistics or city hubs are considered as a dynamic and very complex system. Indeed, fulfillment urban distribution is subject to unexpected incidents that happen during execution of the delivery plans like order cancellation, new customer requests, changes of delivery order and/or destination, mechanical failures, and so on (Zeimpekis, 2011). This seriously impacts warehouse planning and requires re-planning the whole or part of order fulfillment (pick/pack/ship). This also causes performance

inefficiencies (additional handling costs, delay penalty costs, delay in delivery time). There is a significant lack of research related to city logistics warehouse management (Crainic et al., 2009; Morana et al., 2014). Typical warehouse management processes are assured by application software packages such as Enterprise Resource Planning (ERP), Warehouse Management System (WMS), Transport Management System (TMS) and Advanced Planning and Scheduling (APS) software (Helo and Szekely, 2005). These tools are not able to satisfactorily respond to the new challenges and constraints such as flexibility, agility, responsiveness and consolidation of warehousing, imposed by collaborative warehouses and supply chain partners. As a result of this situation, new approaches have to be introduced, but given the current complexity, only adapted and consistent technology seem to provide adequate responses. In this paper, we propose a bottom-up approach for collaborative warehouse order fulfillment based on a multi-agent system and IOT infrastructure. The concept of IOT is defined as a “dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual “things” have identities, physical attributes, and virtual personalities, use intelligent interfaces, and are seamlessly integrated into the information network” (Vermesan et al., 2011). IOT infrastructure is based on many technologies such as Ambient Intelligence, Internet Protocol, Communication technologies (WiFi, Bluetooth, ZigBee), Embedded devices (RFID or wireless sensor networks) and applications. The rest of the paper is organized as follows. In Section 2,

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we detail challenges and trends in future supply chain management in relation with our research. [Section 3](#) reviews the bottom-up approach and shows why and how it can be adopted for collaborative warehouse management systems. This is the theoretical basis upon which we have designed and developed our monitoring system. In [Section 4](#), a city hub platform is presented. [Section 5](#) is devoted to describing system modeling approaches and associated mechanisms. It details negotiation methodology between agents, which is proposed to solve the problem of resource allocation. In [Section 6](#), negotiation protocol based on “comp-eration” scenario is detailed. [Section 7](#) presents an order fulfillment problem example with sample data simulation and managerial implications. Finally, [Section 8](#) is a summary of the paper, and discussion of potential applications by practitioners.

2. Main challenges to future supply chain management

“Economic globalization and growing supply chain interdependence have introduced a heightened level of volatility and vulnerability that is unlikely to subside” (IBM, 2009). Uncertainty has become the norm. This new environment requires responsive and flexible supply chains with greater integration (Gunasekaran and Ngai, 2004), agility (Lee, 2004) and consolidation (Ülkü, 2012). The details of these new environmental factors and challenges are discussed below.

2.1. Integration

When we talk about supply chain interconnection, it does not simply mean interconnection between one's own production, warehouses and shipments (Fig. 1). It means that there is intra/inter firm connection between partners, processes, products and Information Technology (IT) systems along the entire Supply Chain (SC) (Frohlich and Westbrook, 2001). This interconnection enables improved visibility, traceability, interoperability and collaborative decision making between partners. This implies using IOT infrastructure (Atzori et al., 2010) based on supply chain technologies such as deployment of Radio Frequency Identification (RFID) technology, ambient intelligence and sharing real time information. The role of these technologies in supply chain integration is discussed below.

- **SC Technologies.** SC becomes more instrumented using GPS and RFID infrastructure such as tags, readers, sensors and RFID

software. These technologies can improve supply chain performance by increasing visibility of performance, inventory availability, improving coordination, and reducing labor costs and inventory levels (Ngai et al., 2008; Sarac et al., 2010; Shridhar and Deshpande, 2010; Lim et al., 2013).

- **Ambient intelligence.** This technology provides intelligent and personalized application integration systems and services in the surrounding environment to support activities and actor's interactions (Riva, 2005). Ambient intelligence has been applied in trade, logistics, industry, transport and healthcare, as well as in personal identification (Friedewald and Raabe, 2011). Combining RFID technology with an ambient intelligence platform improves supply chain traceability and transparency (Olaru and Gratie, 2011).
- **Sharing real time information.** Ambient platform deployment allows real time information monitoring that improves supply chain visibility. Sharing real time information between partners at this level is essential for greater supply chain responsiveness (Li and Lin, 2006; Gunasekaran et al., 2008). This can be done via joint scorecards and business plans. Indeed, visibility does not simply lead to better planning, it is also fundamental to real time execution (IBM, 2009).

2.2. Agility

SCM must also be agile (Lee, 2004). Integration improves supply chain efficiency and reduces uncertainty, but does not eliminate risk (Prater et al., 2001). To cope with risk and market uncertainty, supply chains need to be flexible, adaptable and reactive, and respond effectively to the question “how can we function” in general terms, not “how will we function” in specific terms. Indeed, the concept of agility has its origin in flexible manufacturing systems that were then extended to supply chain management (Christopher, 2000). This concept has often been implemented in dynamic, re-configurable and self-organized approaches such as the bottom-up principle using autonomous and proactive technology such a multi-agent system (Lüder et al., 2004; Bratukhin and Treytl, 2006; Wurman et al., 2008).

2.3. Consolidation

Warehouse consolidation in supply chain is a very attractive solution due to its profitability and positive ecological impact

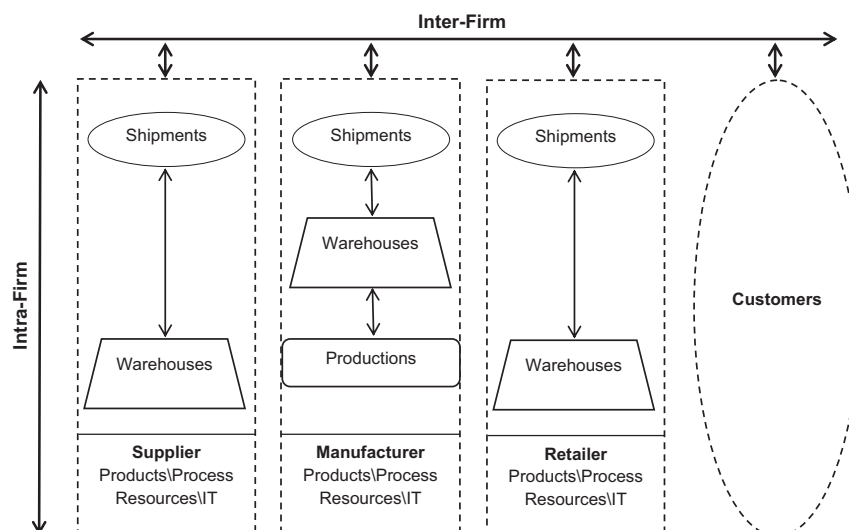


Fig. 1. Integration of warehouse operations in supply chain management.

(Ülkü, 2012). Reduced warehousing, transport, and handling costs are tangible benefits of consolidation, and delivery frequency to customers increases in addition. Reduced traffic congestion, lowered energy consumption and CO₂ emissions are some of the direct ecological advantages resulting from this factor (De Brito et al., 2008; GCI and Capgemini, 2008). To succeed, the warehouse consolidation concept requires high levels of collaboration, trust and commitment between manufacturers, retailers and logistics service providers.

In this paper, we focus on the development of new approaches devoted to monitoring of complex collaborative warehouse concepts that are faced with the challenges we enumerated above. In the next section, we review the bottom-up approach and show how it can be adopted by a collaborative warehouse system.

3. Bottom-up approach based on IOT for warehouse management

Recent advances in ambient intelligence and RFID technology have enabled development of a new approach in the logistics and production domain called “Bottom-up” (Melski et al., 2008). It is based on information recovered from products and resources at the bottom of the chain which is then transmitted to the upper levels and impacts decision making across all supply chain areas. This enhances traceability, visibility and transparency in management of supply chain information (Olaru and Gratie, 2011; Sarac et al., 2010). The bottom-up approach has also been proposed in manufacturing control systems using both holonic (Fletcher et al., 2003) and hierarchical structures (Bratukhin and Treytl, 2006; Reaidy et al., 2006). We present in Fig. 2, below, a comparison between the conventional, static top-down approach (at left) and a dynamic bottom-up approach (at right).

- The conventional approach is based on static functions. It consists of analyzing the complete system to detail its main tasks using the decomposition principle. Its goal is to simplify the process and automate it with the help of computers, and to execute these functions in parallel (if possible) to improve performance. Often, a detailed schedule is generated over a long time horizon. Also, planning, scheduling and execution are

carried out sequentially. Function linking is organized “top-down” (Reaidy et al., 2003).

- The dynamic approach or bottom-up modeling approach is autonomous and considers multi-agent interactions. It is composed of three interrelated elements: agents, interactions and environment (Nan, 2011). Global behaviors and performances satisfactory to this approach are realized through local coordination and control design for multi-agent systems (Karimadini and Lin 2011). This concept provides satisfactory, adaptable and robust solutions in dynamic and complex environments, due to increasing self-organization resulting from interactions between interconnected networks (Adam et al., 2011).

The dynamic bottom-up approach is totally different from the conventional approach and thus requires a different schema. An example of this is the system of auctions and negotiations between agents that indirectly (and organically) generates real-time scheduling, thus rendering the unneeded position of scheduler. (This is in contrast to intelligence generated by a conventional approach that is quite localized at the process level.) This extended, bottom-up intelligence can be distributed at product, environment and process levels or distributed at process and logistic/interaction levels (Reaidy et al., 2003).

The Bottom-up approach uses an IOT infrastructure associating RFID with ambient intelligence and a multi-agent system providing self-organization behavior and interconnection networks between all warehouse entities (i.e. pallets, resources and information technology infrastructure). The Kiva System is a multi-agent warehousing example based on the Bottom-up approach. It is a self-adaptive and self-organized system. Agents communicate with each other, they create a self-organized system to find the optimal local solution to their resource allocation problems, like order fulfillment, replenishment and planning path problems (Wurman et al., 2008). Indeed, multi-agent systems are considered as the most suitable technology for achieving self-organization behavior in dynamic and complex systems (Barbati et al., 2012). Furthermore, RFID technology associated with ambient intelligence provides the main characteristics for network interconnection in a decentralized management approach (Nagy et al., 2009).

Hereafter, we review the concept of collaborative warehouse and we explain how the bottom-up approach can be implemented in Collaborative Warehouse Management (CWM).

3.1. Collaborative warehouse

“Collaborative warehouse” can be considered as a logistic shared platform where several producers and distribution companies share a physical space and logistics information to improve the global performance of the overall distribution processes (GCI and Capgemini, 2008). It lets manufacturers consolidate their warehouse operations and transport from production to the retailer transfer point. This concept can also be found in consolidation platforms, like classical cross-docks, urban distribution centers, logistics cities and city hubs. In logistics, collaboration is a popular practice strategy that remains, however, less explored in the literature (Morana et al., 2014). Tuzkaya and Önüt (2009), develop a top down approach based on linear programs and genetic algorithms to minimize holding inventory and penalty costs for suppliers, warehouse and manufacturers. Yu and Egbelun (2008) propose a top down approach using a priority-rule based heuristic to find the best truck docking or scheduling sequence for both inbound and outbound trucks with a temporary storage buffer in a distribution center. Crainic et al. (2012) propose a framework based on a top-down approach, for integrated urban freight management based on location-allocation formulation for the problem of locating satellite facilities in a multi-echelon system.

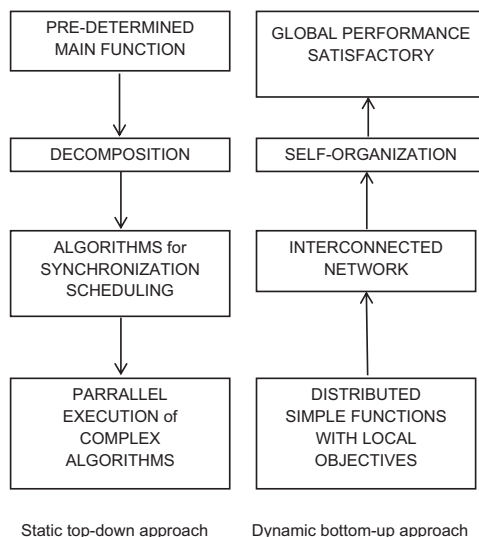


Fig. 2. Basic approaches involved in production system. Derived from Reaidy et al. (2003).

Collaborative warehouse platforms are considered as a dynamic and very complex system. Flexibility, agility, responsiveness and consolidation of warehousing are the new challenges and constraints imposed by collaborative warehouses and supply chain partners. As a result of this situation, new approaches have to be introduced, but given the current complexity, only adapted and consistent technology seem to provide adequate responses.

3.2. IOT infrastructure for CWM

IOT infrastructure associates RFID technology with ambient intelligence platform and multi-agent systems. RFID technology can play an important role in IOT infrastructure as a means of communication and a data provider to supply chain actors (Lim et al., 2013). Ambient intelligence platforms allow the IOT to connect different physical world objects (pallets, forklifts, trucks) to the IT infrastructure and thus be monitored and potentially controlled. Spontaneous configuration, tolerating partial failures and management of complex systems are the main contributions of multi-agent systems for IOT infrastructure (Katasonov et al., 2008; Nagy et al., 2009). Recently, IOT infrastructure has been proposed in literature to improve the competitiveness and responsiveness of warehouse management. Jiang and Su (2013) propose a comprehensive management platform of modern tobacco logistics based on the Internet of things technology. They show that IOT technologies are able to improve the level of management, reduce operating costs and enhance the quality of service for modern tobacco logistics. Yang (2012) combines the warehouse management system with the Internet of Things technologies, such as RFID, GPS, and sensor technology, to construct an intelligent logistics warehouse management system based on the Internet of Things. Ding (2013) presents a Smart Warehouse Management System based on the IOT. Simplifying the process of inventory of goods and enhancing the level of warehouse automation management are the advantage of this intelligent warehouse management system. In the logistics domain, ambient intelligence has been associated with RFID technology to enhance the warehouse business process, warehouse accident handling and to perform transparent interactions with products handled throughout the supply chain (Kim et al., 2008; Bajic, 2009; Ngai et al., 2012). Kim and Sohn (2009) confirm that logistics processing using RFID systems applicable to ubiquitous-city can improve customer service and reduce logistics processing costs. Furthermore, combining these technologies provides automated monitoring and control of industrial resources and processes. Machines, infrastructure elements, materials, and products can get connected to the information technology infrastructure, and thus be monitored and potentially controlled (Nagy et al., 2009). This provides the basic interconnected network infrastructure for agent warehousing management and control such as physical object auto identification and auto configuration, object-to-object interaction and object-to-environment interaction (Bajic, 2009). Here, physical objects correspond to products, resources, processes and users. This technological advancement opens new horizons to implement agent based decentralized control solutions for industrial applications. In multi-agent warehousing systems, agents may represent order fulfillment, products, pallets, and resources such as forklifts, packing machines and trucks. Agents perform individual tasks via interaction with other agents to fulfill warehousing functions such as receiving, storing, picking, local planning and control, task assignment allocation, or even distribution (Kim et al., 2002; Hiel et al., 2011). Therefore, industrial deployment of RFID infrastructure ultimately reduces investment costs and encourages firms to use the bottom-up approach in warehouse management. In our opinion, collaborative warehouse platforms represent a real application for agent-based management in industry. In fact,

collaborative warehouse platforms like city logistics or city hubs promote implementation of infrastructure (GCI and Capgemini, 2008). This platform is considered as a dynamic and very complex system (Crainic et al., 2009) and represents an ideal context for agent applications (Leitao and Vrba, 2011; Barbati et al., 2012; Ye et al., 2012). Finally, IOT infrastructure provides development of an ideal platform to implement the bottom-up approach for collaborative warehouse management. This perspective allows accelerating adoption of these concepts and technologies in industry, which encourages researchers to refine practical solutions for the industry by developing self-organizational mechanisms to improve robustness of the platform. In the next section, fulfillment, we describe the future supply chain design developed by Capgemini consulting including the city hub model. Then, we will propose a city hub warehouse architecture based on an IOT infrastructure for city hub warehouse management.

4. City hub model

The City hub model corresponds to a collaborative warehouse platform for urban distribution areas (GCI and Capgemini, 2008). It is like a shared gate for cities that ensures the smooth shipment of goods arriving from various provider sources and having various client destinations (Trentini et al., 2010). This implies consolidation of different delivery streams (different products based on different online ordering facilities, all for the same shopper) via city hubs. Thus, shipments can be consolidated in city hubs and be brought into the city with alternative modes of transportation like electric vehicles.

The city hub concept is considered very promising as a forward looking SC solution for reducing traffic congestion in urban areas, energy consumption, CO₂ emissions and the permanent rise in transportation costs (Taniguchi and Thompson, 2002). Moving toward more sustainable business requires that we re-consider logistics strategies by combining collaborative warehouse platforms for warehousing, distribution and transport between all supply chain stages.

- Below are certain SC model characteristics that include the concept of a city hub design for order deliveries in urban and non-urban areas developed by Capgemini consulting (GCI and Capgemini, 2008). It is based on multi-partner information sharing among consumers, suppliers, manufacturers, logistics service providers and retailers.
- After production the products are shipped to collaborative warehouses in which multiple manufacturers store their products.
- Mutualised transport from the collaborative warehouse delivers to city hubs and to regional consolidation centers.
- Non-urban areas will have regional consolidation centers from which products will be shipped for final distribution.
- Final distribution to stores, pick-up points and homes in urban and non-urban areas will take place via consolidated deliveries using the most efficient assets.
- Store orders can be assembled in the collaborative warehouse and consolidated at the city hub. This means that retailer distribution centers can be bypassed.

In Fig. 3, there are eight manufacturers arranged into two groups of four, each running a collaborative warehouse. From these collaborative warehouses, store-picked orders are shipped to either a city hub or a regional consolidation center.

Here, a regional consolidation center is used for non-urban areas. It has a similar function as the city hubs, consolidating the store orders from various collaborative warehouses into dedicated store replenishment routes. At the same time, these consolidation centers are needed to merge the long-distance streams with the

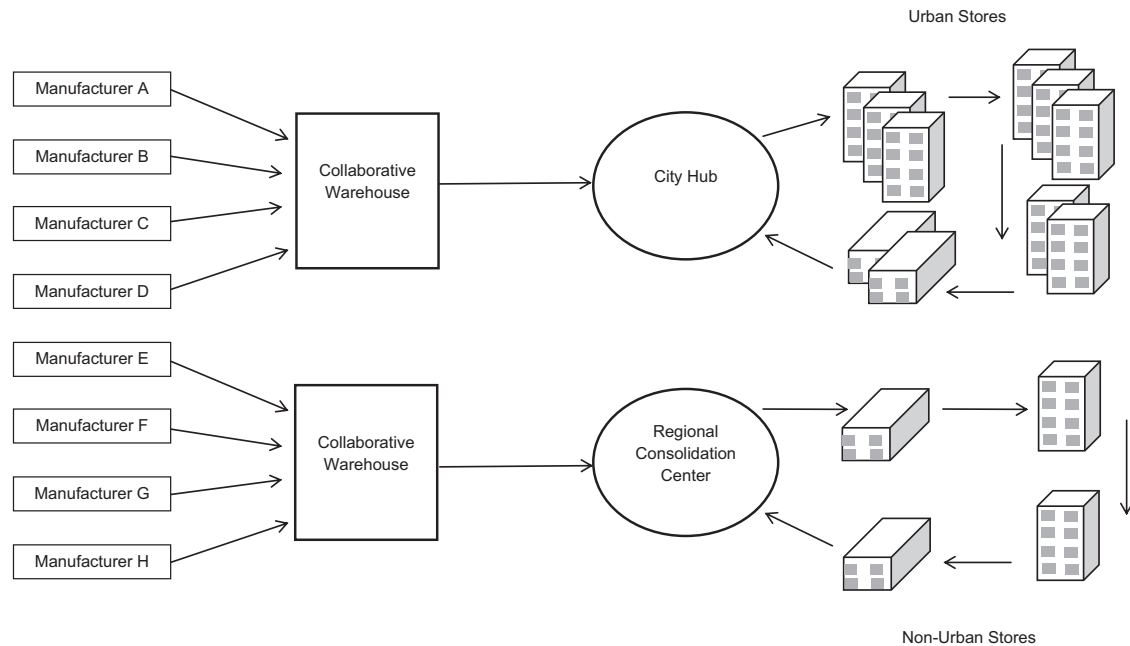


Fig. 3. Future SC design (CCI and Capgemini, 2008).

local product streams to create efficient replenishment for the stores.

Now we will describe the city hub application architecture used to conduct our validation. It is based on an IOT infrastructure associating RFID with ambient intelligence and MAS.

4.1. City hub application architecture

Platforms associating MAS with RFID and ambient intelligence have been proposed in several research works (Wang et al., 2009; Bade, 2009; Olaru and Gratie, 2011). It consists of many layers such as application layer, network layer and physical devices layer. The city hub application architecture that we propose can be discussed in four different layers, as shown in Fig. 4. The physical devices layer consists of all the physical, embedded devices (i.e. pallets, forklifts, packing machines, trucks) that are equipped with RFID readers and sensors.

These physical objects store information on both RFID tags and on remote databases. The device discovery protocol is selected to implement the UPnP (Universal Plug and Play) middleware layer that then interfaces with the devices. The Multi-Agent System (MAS) layer platform *Jade* comprises pallet agents, resource agents, control agents, and interface agents. Here, the MAS platform is considered as a portal platform because agents are not embedded on the products, but run on “normal” desktop systems or servers (Meyer et al., 2009). The top-most application layer refers to all possible user interface applications and ERP. The MAS layer exchanges information with the ERP and Middleware ambient architecture using an EAI middleware and XML interfaces. This platform is currently under development in the Regional Academic Research Community Project “Innovations, Mobility, Territories and Urban Dynamism” (ARC7, 2012). The main object of this project is to implement a bottom-up approach for warehouse order fulfillment in an ambient and collaborative environment.

4.2. City hub platform

In this section, we consider that the city hub warehouse is composed of pallets, forklifts, an inventory zone and auto packing

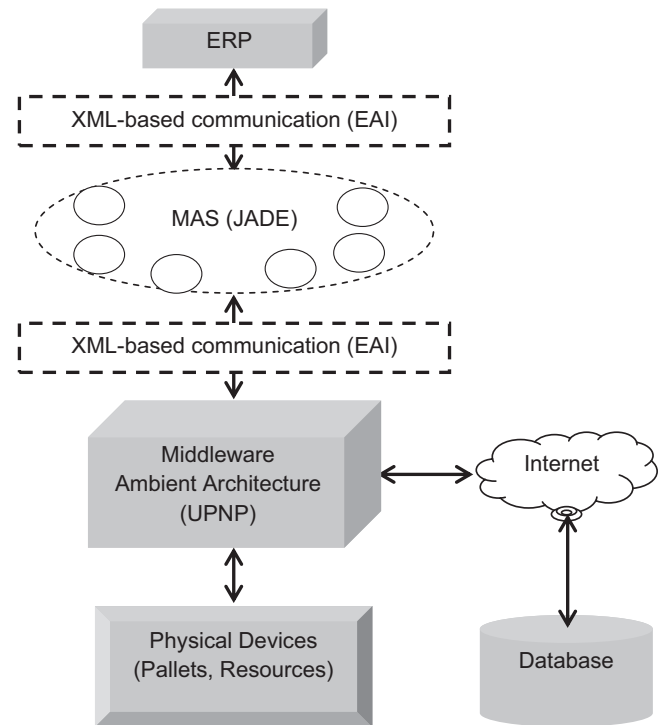


Fig. 4. City hub applications architecture.

machines equipped with RFID technology (Fig. 5). Pallets come directly from collaborative warehouses or from producers. Store orders are assembled in the collaborative warehouse and consolidated at the city hub. Here, order fulfillment concerns only the pick/pack/ship process. It is generated by an ERP system. Warehouse uses an UPnP ambient environment middleware for exchanging information between devices, ERP, and the multi-agent system. Agents will represent order fulfillment, pallets and the different resource devices of the system such as forklifts,

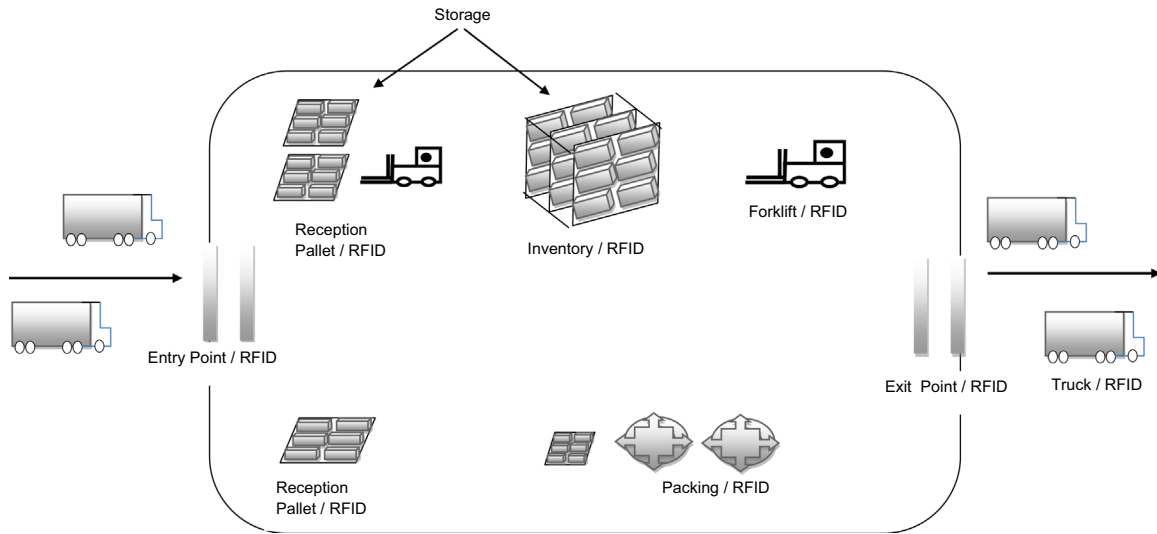


Fig. 5. City hub structure example.

packing machines and trucks. The physical devices interacting with pallets are:

- *Entry/exit point*: these devices equipped with RFID readers located at warehouse entrances and exits provide the possibility to automatically identify pallets arriving at and leaving the hub/warehouse. Pallets use passive RFID tags. The information stored in the tag is transmitted to the ERP via the UPnP middleware.
- *Transport and packing*: forklifts, trucks and packing machines use an ambient intelligent platform to identify pallets and to exchange information with it.
- *Storage*: sensor devices are placed in the storage area allowing automatic identification of the inventory zone of any given pallet.

5. System modeling approaches and mechanisms

In this section, we describe the city hub order fulfillment process using multi-agent system architecture. In our model, the process starts once an Order Fulfillment (OF) is released by the ERP to the city hub (Fig. 6). The OF is analyzed by the Order Fulfillment Agent Supervisor (OFAS). Then it creates an Order Fulfillment Agent (OFA) corresponding to the OF. It then generates a set of Pallet Agents (PA) for each OF. PA is assigned to the real and physical pallet through the UPnP middleware layer. PA follows the physical pallet; it negotiates and schedules for it all its next processing tasks. Each resource is represented by Resource Agent (RA). Tasks provided by resources are for picking, packaging and shipping. The Control Point Agent (CPA) represents UPnP control point architecture. It is used to control and to communicate general information about devices location status and their services in the warehouse. Order Fulfillment Agent Supervisor is responsible for the management of Order Fulfillment Agent life-cycle. It has a connection to the ERP to receive new order fulfillments or changes and to inform about the state of running ones. Information delivered by each OFA will be sent to the ERP.

City hub urban distribution is susceptible to unexpected costs and delays that occur during the execution of the delivery plans due to adverse conditions issuing from clients and from delivery vehicles (Zeimpekis, 2011). We can mention some typical examples such as change of delivery order and/or destination,

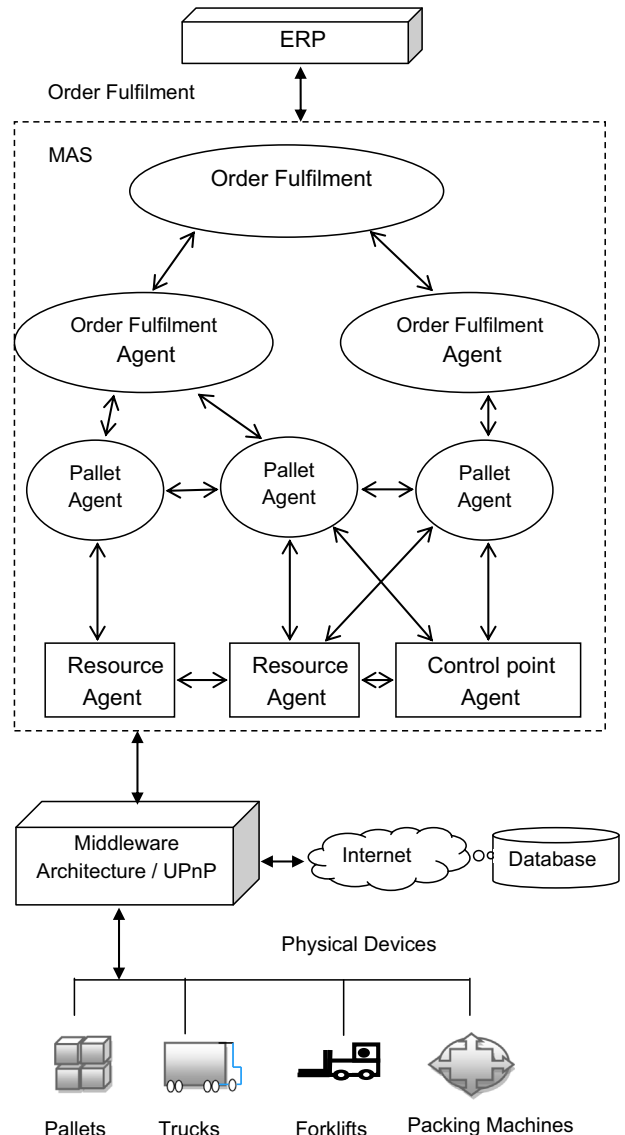


Fig. 6. Multi-agent architecture for order fulfillment process.

mechanical failures and so on. Warehouse scheduling problems in a dynamic environment are considered as NP-hard problem (Zäpfel and Wasner, 2006; De Koster et al., 2007). Traditional warehouse management models are strongly centralized, resulting in large and complex software that is difficult to upgrade and maintain. Often, a detailed schedule is generated over a long time horizon. Also, planning, scheduling and execution are carried out sequentially (Reaidy et al., 2003). Such systems are not able to adapt to changing circumstances over time (such as machine breakdown, changes of delivery order, etc.). In the following subsections, we define and describe some negotiation principles, mechanisms and protocols integrated with the aforementioned city hub platform for the order fulfillment process using a dynamic resource allocation system.

5.1. “Coo-petition” or “comp-eration”?

Market behaviors have evolved as a result of the global economy and have been directly and explicitly influenced by customer requirements. For companies to survive and remain active in this new environment, they have had to modify their strategies, combining the principles of competition and cooperation, leading to two new concepts: “coo-petition” and “comp-eration” These two principles combine strategies that we define as follows (Fig.7):

- “Coo-petition” is a contraction of cooperation and competition. According to this principle, market actors do not initially risk direct competition with other market actors. They start by cooperating with each other (if only partially) with the goal of constructing a global, common good. Later, they become competitors in the division and allocation of the “commonly” created market shares (Brandenburger and Nalebuff, 1996) Agreements between large companies like Intel and Compac for making PCs, between Motorola and AT & T for telecommunications, and between universities and industry for research provide examples based on this principle.
- “Comp-eration” is the contraction of competition and cooperation (Reaidy, 2003, Zouaghi et al., 2010) Reversing the order of these two strategies creates a new, completely different principle from that of “coo-petition”. Providers initially adopt a competitive strategy to ensure their individual interests. These same suppliers progressively adopt more collaborative strategies when price competition increases and production demands become more challenging. The virtual factory configuration system (Liu and Massotte, 1999) is based on this principle.

In the following paragraphs, we will define request session principle and agent architecture.

5.2. Request session principle

Generally, Pallet Agent decision making in a resource allocation system is based on “egoistic” behavior such as “first arrived, first served” or on expected information given by statistical and

heuristic formulas (Krothapalli and Deshmukh, 1999). Because of the constraints required in a dynamic environment, we try, in this paper, to replace the expected or estimated information with accurate, real-time information exchanged between Agents by using the “request session principle”. The main goal of the request session is to provide negotiating agents with real-time information over a given period of time before final decision-making is completed. A Pallet Agent (PA) emitting a request to the Request Session Agent (RSA) for a given task, like Picking (Pi), Shipping (Sh) or Packing (Pa), may find its response from different resources agents and will collaborate and participate with other pallet agents during a given Request Session (RS). In Fig. 8, RSA-Sh organizes shipping assignment tasks of pallets during the RS and the negotiation between agents. Agents in RS will share real time information about their status. The period of time considered during an RS for each PA corresponds to its Processing Task and is limited by the “start time request” and “end time request” or by the requested decision time triggered by pallets agents or resources agents. For example, PA3 finishes its packing processing task and makes a decision about a shipping task, taking into consideration the other PA's status in RS such as PA2 and PA1. Thus, PA decision-making takes into account all PAs processing simultaneously and those arriving just before and after the PA, (for more details see Reaidy et al., 2006).

5.3. Agent architecture

An agent is an autonomous, pro-active and smart object representing the pallets and resources in a city hub. An agent can negotiate (cooperatively or competitively) with other agents and make decisions using protocols and strategies (auctions, game theory) to deal with system constraints and advance toward their own goals (delivery time). In our work, the proposed city hub platform architecture associates ambient intelligence with agent technology. This combination makes the agent more intelligent and cognitive, because of the real time information sharing between agents within the environment. Here, agents are based on the BDI (Belief, Desire, Intention) model (Bratman, 1987). Agent “Belief” and “Desire” characteristics are based on perception and information received from an ubiquitous environment (Tapia et al., 2007) like pallet destination, delivery time and priority. Agent “Intentions” will concern strategies to be used like decision-making rules. In this situation, agents are hybrids (cognitive and reactive) directly responsible for piloting a functional, self-organized system. They co-create the decision and negotiation mechanisms for dynamic resource allocation with other agents. The hybrid nature of an agent is revealed by its interactions with its environment and its strategies that can include cooperation, competition, “coo-petition” and “comp-eration”.

Generally speaking, an agent can and will switch from a cooperative strategy to a competitive one during its existence to satisfy its interests and achieve its objectives. Fig. 9 shows the different negotiations and decision categories that can be used by an agent in a system. As stated above, different agent negotiation protocols can be summed up as cooperation, competition, “comp-eration” and coo-petition. In the case of cooperation, the agents' decisions take into account other agents' priorities, when, for example, participating in a “Request Session”. Their decisions may be altruistic or consensual. In the second case, that of competition, decisions are selfish and may be based on dispatching rules such as “First-Come First-Served” (FCFS) “Shortest Processing Time” (SPT), or even on heuristic formulas (Krothapalli and Deshmukh, 1999). In the case of “coo-petition”, the agent starts by cooperating, during a Request Session, prepares for allocation of its next task, and then completes the process with competition with specific rules and mechanisms such as game

Step1	Step2	
	Cooperation	Competition
Cooperation	Cooperation	Coo-petition
Competition	Comp-eration	Competition

Fig. 7. Different strategies of interaction between market entities.

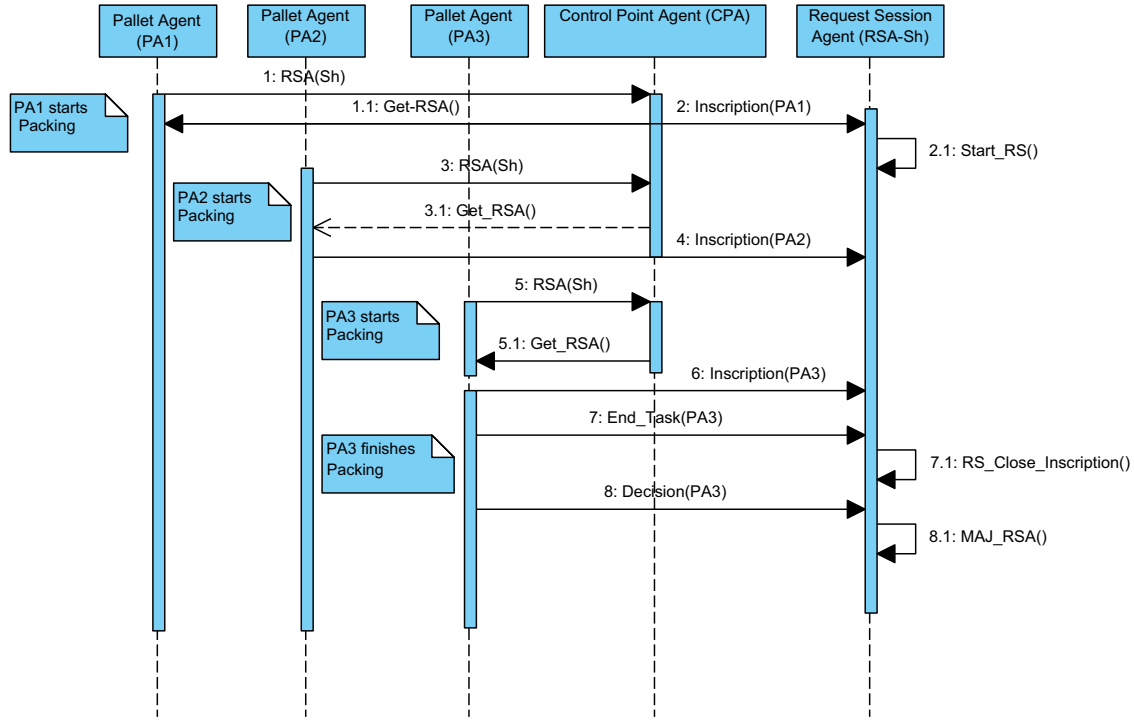


Fig. 8. UML sequence diagram: request session principle.

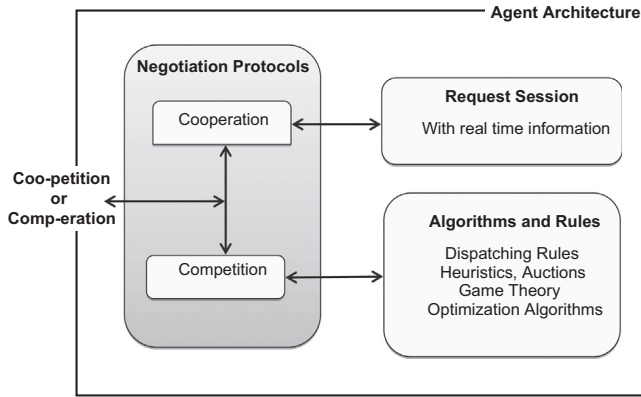


Fig. 9. Categories of negotiations and decisions used by agents.

theory (pareto-optimal Nash equilibrium) and the branch-and-bound algorithm (Reaidy et al., 2006; Khanna et al., 2012) during final decision making. Finally, in “comp-eration” scenario, Agents initially adopt some competitive strategies to ensure their individual interests. These same Agents progressively adopt more collaborative strategies with other agents having some allocation problems. They will participate together on the same request session to solve the declared problem.

5.4. Negotiation methodology for city hub order fulfillment

Here, we consider that the city hub warehouse is composed of pallets, forklifts, trucks and auto packing machines. Tasks provided are Picking (Pi), Packing (Pa) and Shipping (Sh). Picking tasks are executed by forklifts, packing tasks are done by auto packing machines and shipping tasks are done by trucks. Each resource can provide only one type of task. Here, Order Fulfillment (OF) concerns only the pick/pack/ship process. OF is related to one client address with a delivery scheduling time and delay penalty

cost. It is composed of many pallets and needs to sustain a given number of sequentially ranked tasks. OF can be shipped using many trucks. We distinguish two types of order fulfillment inside the warehouse: Type1={Pi, Pa, Sh}, Type2={Pi, Sh}. In this section, negotiation is used for selecting a next task to be assigned to a resource based on time as the ultimate parameter. Agents will represent pallets and resources of the system. When a processing task is started, the assigned Pallet Agent (PA) tries to schedule the next task by participating in a Request Session (RS). For that purpose, PA asks the Control Point Agent (CPA) about the Request Session Agent (RSA) to be used in the next task; then a participation request is sent to the relevant RSA with some information about the Remaining Delivery Schedule Time (RDST), the Remaining Processing Time (RPT) of the current task, the Allowed Processing Time (APT) of the next task and the delay penalty cost. Task Processing Time (TPT) for each pallet agent to the different warehouse zones can be computed using a nominal processing time as an estimate of the processing time taken by the slowest RA or by using some case based reasoning (Poon et al., 2009; Chow et al., 2007; Usher and Wang, 2000; Wang et al., 2008). Hereafter, we will use the terms TPT for picking, packing and shipping tasks. PA is able to compute the value of APT for its next task using the following formula (n being the number of tasks to be done by the PA).

$$APT_{i+1} = RDST - (RPT_i + \sum_{j=i+2}^n TPT_j) \quad i, j \in N \quad (1)$$

When a PA request is received, the RSA adds the PA request to the RS. It opens a new RS if it is not yet done. The RSA may receive several PA requests until the decision time of the RS is reached. After that, PAs ask RAs for their Request Completion Time (RCT). RAs compute their RCTs for PA next task. Pallets waiting in a Packing Machine queue are processed according to their arrival in a first-in-first-out (FIFO) queue. Here, the remaining time for their current Processing Time (RPT), the number of pallets waiting in their queue (Nq) for packing task, and their Packing Processing Time (Pa_PT) for the task needed are taken into consideration.

RA computes the value of its RCT for packing using

$$Pa_RCT_{i+1} = RPT_i + (Nq + 1)Pa_PT \quad i \in N \quad (2)$$

RCT for picking tasks consider RPT and Picking Processing Time (Pi_PT) see formula (3). PT can be computed using a case-based reasoning engine, an effective triangular localization scheme and a material handling problem solver. For more details see [Poon et al. \(2009\)](#).

$$Pi_RCT_{i+1} = RPT_i + Pi_PT \quad i \in N \quad (3)$$

RCT for shipping tasks take into consideration Shipping Travel Time (Sh_TT) and Depart Time (DT) to order fulfillment address.

$$Sh_RCT_i = Sh_TT_i + DT \quad i \in N \quad (4)$$

PA uses some basic algorithms and negotiation protocols to choose the best RA answer related to its criteria. As soon as the PA has setup a decision, it allocates a given processing time in the RA and provides that fact to the RSA to delete it from the session. In the next section we will detail negotiation protocols used by agents to solve dynamic resource allocation problems.

6. Negotiation protocols

Negotiation Protocol (NP) is a set of rules used to organize negotiation, communication, conversation sequence and decision-making between agents ([Krothapalli and Deshmukh, 1999](#); [Kraus, 2001](#)). Negotiation protocol between agents for dynamic resource allocation is based on a “contract net protocol” ([Smith, 1980](#)). It consists of five steps: a requested task is announced by a manager (from a given set of manager), potential contractors evaluate task announcements coming from several managers, potential contractors bid upon the selected task, the task manager awards the contract to one of the bidding contractors, finally the manager and a contractor communicate to execute the contracted task. This protocol can be applied to the warehouse system context in several ways: Manager and contract are both resources, they can use subcontracting to distribute and dispatch the workload. Managers are “product offering work”, and contractors are “resources bidding” to get the work assigned. Managers are “resources offering capacity” and contractors can be “product bidding to use this capacity”. In warehouse

context, resources correspond to forklifts, packing machines and trucks while products correspond to pallets. The negotiation mechanism for generating and maintaining order fulfillment schedules in the contract-net protocol is developed as a bidding process within a warehousing system. Agents can negotiate (cooperatively and/or competitively) with other agents and make decisions using protocols and strategies to deal with system constraints and advance toward their own goals. In this section, we propose a new negotiation protocol for agent decision-making based on “comp-eration” scenario.

6.1. “Comp-eration” protocol

Here, we present a new negotiation protocol based on the “Comp-eration” approach developed in [Section 5.1](#). It concerns resource agent decision-making in the system. Resource Agents (RA) initially adopt some competitive strategies to ensure their individual interests (full trucks) by using a “contract net protocol”. RAs try to win each bidding process by providing their best offers. These same RAs progressively adopt more collaborative strategies with resources having some order fulfillment problems such as truck failures, difficulties in loading pallets and delivery scheduling time.

RAs will participate together in the same Request Session (RS) to reallocate pallet tasks between themselves. Request Session Agent (RSA) will use a branch-and-bound algorithm to solve declared resource allocation problems at local level. The object function to minimize corresponds to the total delay time or the total shipping cost of order fulfillment. In [Fig. 10](#), RAs cooperate between themselves by using a common RS and accept a new allocation task proposed by RSA to solve the declared order fulfillment problem. In the following section, we will present an order fulfillment problem example with sample data simulation using “comp-eration” negotiation protocol.

7. Order fulfillment problem example and implications

Delay in delivery time is considered as one of the main critical success factors for the Urban Distribution Center ([Marcucci and Danielis, 2008](#)). City hub urban distribution is subject to unexpected costs and delays that happen during the execution of the delivery plans due to changes of delivery order and/or destination and

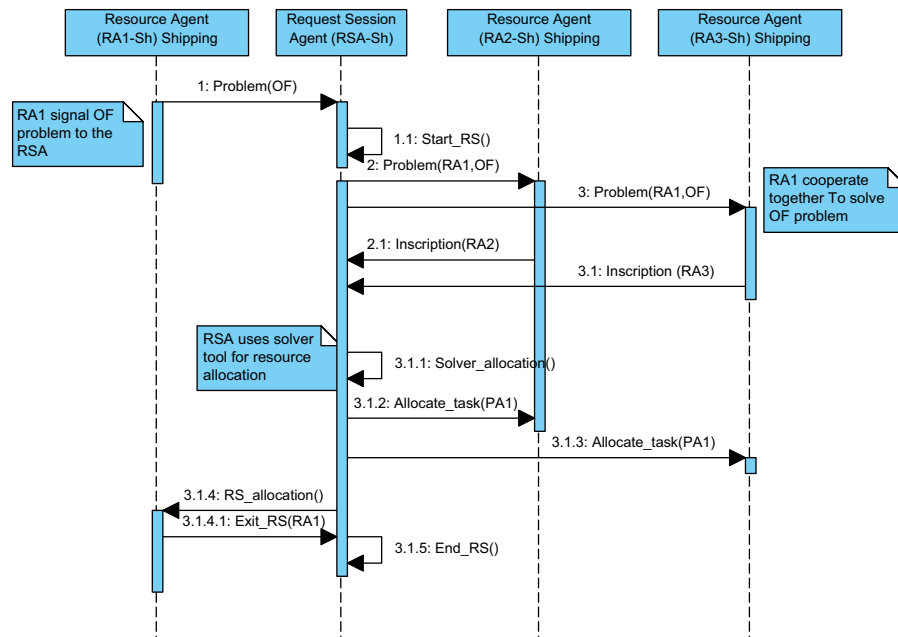


Fig. 10. UML sequence diagram: “comp-eration” scenario.

mechanical failures. Here, we propose a sample data simulation of “comper-ation” negotiation protocol between agents to show the reaction capabilities of this approach in a dynamic environment like a truck breakdown. Let us assume that there are 5 pallets (P1, P2, P3, P4, and P5) having a delay in delivery time due to a breakdown on Truck1. These pallets have the same size loads and must be delivered to five different destinations. In our model, pallets (P1, P2, P3, P4, and P5) are represented respectively by Pallet Agents (PA1, PA2, PA3, PA4, and PA5) and Truck1 is represented by Resource Agent1 (RA1). RA1 signals the declared problem to the Request Session Agent (RSA). RSA starts a new request session to solve this problem and sends requests to all Resource Agents (RAs) available and susceptible to ship these pallets to their destinations. The RSA request contains information about pallet sizes and destinations. RAs will answer these requests and participate together on the same request session to reallocate pallet shipments between them. Then, RSA selects only RAs respecting the delivery schedule for each concerned pallet. RA answers contain delivery schedule and shipping cost for each pallet and the allowed pallet quantities to be loaded. In this example, we consider that only three resource agents have participated in the request session (RA2, RA3, and RA4). Table 1 represents resource agent shipping costs per pallet.

Allowed pallet quantities for resource agents (RA2, RA3, and RA4) are respectively (2, 1, and 2). Request Session Agent (RSA) will use Microsoft Excel Solver tools, based on branch-and-bound algorithm, to solve the declared resource allocation problem. Here, the resource allocation problem to solve is a linear programming problem. The object function to minimize corresponds to the total shipping cost of pallet agents. Hereafter, we detail Solver Parameters such as *objective function value*, decision variables and *constraints*. The pallet shipping cost details are referenced in cells C7:C21 (Fig. 11). The allowed pallet quantities for resource agents are represented in cells B24:B26. The *objective function value to minimize* is calculated by the formula $\text{Sumproduct}(C7:C21;D7:D21)$ in cell B28. The decision variables are referenced in cells D7:D21. *Solver Constraints are*: D7:D21=binary; $\text{Sum}(D7:D9)=1$; $\text{Sum}(D10:D12)=1$; $\text{Sum}(D13:D15)=1$; $\text{Sum}(D16:D18)=1$; $\text{Sum}(D19:D21)=1$; $\text{Sum}(D7, D10, D13, D16, D19) \leq B24$; $\text{Sum}(D8, D11, D14, D17, D20) \leq B25$; $\text{Sum}(D9, D12, D15, D18, D21) \leq B26$.

The best overall total shipping cost is 195\$ (cell B28) and the resource allocation solution can be constructed by the decision variables values (D7:D21). Finally, RSA proposes the new allocation tasks for each RA based on decision variable solution values, i.e. pallets (PA1, PA2, PA3, PA4, and PA5) will be shipped respectively by trucks or Resources (RA4, RA3, RA2, RA4, and RA2).

As a result, the negotiation protocol proposed based on a “comp-eration” approach provides local scheduling solutions for the shipping problem in a dynamic environment. It is based on the “request session” principle for locally sharing real time information between agents and on global optimization algorithms (such as solver, game theory, optimization program algorithms) for agent decision-making. This solution can be implemented and executed simultaneously for other tasks within warehouses (i.e. picking, packing, etc.) to solve dynamic resource allocation problems that considerably improve responsiveness and agility of warehouse management in dynamic environments.

Table 1
Pallet shipping costs per trucks

Trucks	Pallets				
	PA1	PA2	PA3	PA4	PA5
RA2	40\$	40\$	40\$	55\$	50\$
RA3	30\$	30\$	50\$	55\$	60\$
RA4	25\$	50\$	40\$	50\$	55\$

7.1. Managerial implications

We believe that using IOT infrastructure for collaborative warehouse management improves warehouse visibility, traceability, transparency (Olaru and Gratie, 2011) and supports the development of a bottom-up approach for warehouse management (Nagy et al., 2009). This approach enables improved reactivity and competitiveness of warehouse management in a dynamic and complex environment like classical cross-docks, urban distribution centers, logistics cities and city hubs. In spite of that, there are still a number of challenges in such areas as standards, return on investment (Vermesan et al., 2011), and manager trust and guaranteed performances (Trentesaux, 2009; Leitao and Vrba, 2011). These challenges have managerial implications for further implementation in a collaborative warehouse platform.

In fact, the issue of IOT standards, especially in complex systems like collaborative warehouse management, is a crucial concern. The lack of standard interoperability between different IOT technologies, like RFID, ambient architecture and ERP discourages managers from making large investments in IOT infrastructures (Vermesan et al., 2011). The promising technologies for tackling interoperability problems are the Semantic technologies (Katsanov et al., 2008).

The next challenge is Return on Investment (ROI). In the IOT the range of connectivity options like communication with actuators, sensors and distributed storage units will increase exponentially while the return on investment for network operators will remain stable (Vermesan et al., 2011). In addition, the cost of IOT technologies such as RFID, ambient intelligence platform and agent technology is quite large, and this is a further obstacle to the implementation of this infrastructure (Moon and Ngai, 2008; Kim and Sohn, 2009; Leitao and Vrba, 2011).

The last challenge concerns the issue of performance guarantees and manager trust in decentralized warehouse management. Indeed, the bottom-up approach provides adaptable and robust solutions in dynamic and complex environments (Adam et al., 2011). Global behaviors and performances satisfactory to this approach are realized through local coordination and control design for multi-agent systems. The dynamic behavior of interconnected autonomous decisional entities, like multi-agent systems, does not provide guarantees of overall performance. This difficulty is mainly due to the local scheduling or “myopic behavior” of decentralized systems (Trentesaux, 2009). In fact, this myopic behavior is one of the major obstacles to using such systems.

Leitao and Vrba (2011) consider that distributed thinking (centralized and hierarchical oriented) and industrial maturity of Agent technology are the principle reasons for the weak acceptance of the bottom-up approach in industry. In centralized or hierarchical management systems, trust in the system is evident. This is not the case for a bottom-up approach in which the complexity of the interactions is hard to understand, support and manage (Trentesaux, 2009). While these issues remain, no industrial manager will trust and deploy decentralized management systems. However, the main challenge for the near future in the multi-agent warehouse applications is to convince managers of the benefits of warehouse decentralized management by providing more demonstrators running in warehouses. Finally, we have to mention that fundamental changes have to be introduced into our culture and way of working to integrate these approaches and paradigms into our management and decision making processes (Reaidy et al., 2003).

8. Conclusions

In our work, we have shown that IOT infrastructure based on RFID technology associated with ambient intelligence and multi-

Optimal Shipping Scheduling			
PA1, PA2, PA3, PA4, PA5 : Pallet Agents			
RA2, RA3, RA4 : Resource Agents			
Pallets	Trucks	Shipping Cost	Decision Variables
PA1	RA2	40\$	0
	RA3	30\$	0
	RA4	25\$	1
PA2	RA2	40\$	0
	RA3	30\$	1
	RA4	50\$	0
PA3	RA2	40\$	1
	RA3	50\$	0
	RA4	40\$	0
PA4	RA2	55\$	0
	RA3	55\$	0
	RA4	50\$	1
PA5	RA2	50\$	1
	RA3	60\$	0
	RA4	55\$	0
Allowed Pallet Quantity			
RA1	2		
RA2	1		
RA3	2		
Total Shipping Cost	195\$		

Fig. 11. Spreadsheet with the solver optimization allocation solution values.

agent systems enhance development of an ideal platform for decentralized warehouse management. This improves the competitiveness of warehouses in a dynamic environment and allows accelerating the adoption of these concepts and technologies in warehouses. This also encourages researchers to refine practical solutions for the industry by developing self-organizational mechanisms to improve platform robustness. We propose a city hub architecture based on dynamic bottom-up approach for warehouse order fulfillment processes. It develops and combines existing architecture layers with a middleware layer represented by a multi-agent system. A collaborative warehouse example was conducted to demonstrate the implementation of the proposed architecture. Negotiation protocols between agents were developed with different scenarios for resource allocation problems. A sample data simulation of a “comper-ation” protocol was proposed to show the reaction capabilities of this approach in a dynamic environment. The limitations of this study concern the city hub warehouse example used in this paper. Indeed, the proposed approach was not tested on real collaborative warehouse platforms. Future research will be limited to eliminating these assumptions. The warehouse application architecture proposed in our research is currently under development within the ARC7 Rhône-Alpes-funded project. Reactivity, adaptability and robustness of the city hub model will be evaluated and validated through simulation. It will take into consideration several criteria such as cost, delay and priority. Experimental tests will concern the pick/pack/ship process to minimize warehousing delay and cost, and to improve service in various dynamic environments. The city hub application architecture proposed in this work can also be successfully extended to other consolidation platforms such as classical cross-docks and urban distribution centers to improve their capacity to respond to complex and dynamic supply chain realities.

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