Conceptualised Visualisation of Extended Agent Oriented Smart Factory (xAOSF) Framework with Associated AOSR-WMS System

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Abstract: The emergence of the fourth industrial revolution (Industry 4.0) has sparked proliferation in the domain of Cyber-Physical Systems (CPS), and extensive research has been conducted in this area since its beginning. However, recent literature claims that Small to Medium Size Enterprises (SMEs) are not getting the benefits of Industry 4.0 (I4.0) in a full potential because of unresolved compatibility-mismatch issues and involvement of high infrastructural cost. In order to help bridge this gap, the Extended Agent-Oriented Smart Factory (xAOSF) framework provides a high-level guideline solution, integrating the whole supply chain (SC), from supplier-end to customer-end with an objective to expose SMEs towards the benefits of I4.0. This paper, as part of a publication series, provides a conceptualised visualisation of the xAOSF framework as a customised CPS, which presents an elegant mediation mechanism between multiple xAOSF agents to uptake negotiation and coordination schemes at different enterprise levels. This paper also includes detail on how the I4.0 based xAOSF framework caters to three-dimensional enterprise integration, in order to provide seamless connectivity and robustness in enterprise-wide operations. Furthermore, for the purpose of validation and to justify the claim, the experimentation is performed by applying a comprehensive test scenario on xAOSF's recommended AOSR WMS strategy in comparison with linear SC-based standard WMS system, which yields a substantial performance improvement in certain key-performance areas.

Key words: Industry 4.0 (I4.0), extended agent-oriented smart factory (xAOSF), agent oriented storage and retrieval system (AOSR), cyber-physical systems (CPS), warehouse management system (wms), small to medium size enterprises (SMEs).

1. Introduction

The gradual industrial revolution has passed through three major technological and conceptual transformations since 18th century, which includes water-steam mechanical systems [1], mass production with auto-mechanical implantation [2] and then Programmable Logic Controllers (PLC) [3]. This continuous change in the technological transmutation has now revamped into a fourth industrial revolution, termed as Industry/Industrie 4.0 (I4.0) [4]. The research trends in I4.0 are progressing in many worthwhile dimensions such as Theories/Perspectives [5], Cyber Physical System (CPS) architecture [6], Interoperability/Integration [7] and Enabling Technologies in an I4.0 environment such as Big Data, Machine Learning, IoT, Multi-Agent Systems (MAS) and their applications [8]. Despite extensive research in this domain, there are still certain areas which require more research, especially from the perspective of integration and interoperability of I4.0 concepts with Small to Medium Size Enterprises (SMEs) [9], supply chain management (SCM) [10], service-oriented architectures (SOA) [11], multi-agent systems (MAS) [8], and enterprise resource planning systems (ERPs) [5].

Industrial automation is becoming more and more incumbent, hence complex procedures may require systems to work autonomously. In integrated industrial environments, different solutions exist with a particular focus on resource scheduling such as solutions based on Genetic Algorithms and Neural Networks [12] and production systems automation e.g., MASINA [13], a multi-agent systems based production planning in automation, SADIA, an architecture for an automated distributed intelligent system based on agents, and SCDIA Model, an intelligent agent-based distributed control system [14]. A similar automation mechanism is discussed in Ruta's KNX System [15] in the context of building automation. Literature also includes manufacturing processes models for providing operational flexibility e.g. PABADIS [16]. PABADIS is a Distributed Control Systems (DCS) similar to the aforementioned SCDIA framework, with a focus on plant automation. Although extensive research is conducted to provide complete autonomous systems, the compatibility issues of the high-tech standards of I4.0 with SMEs are not identified properly, which could be the reason that SMEs may lag behind or may not get the expected benefits to keep up with the current competitive market [17]. The concept of I4.0 is no longer new and is transforming the manufacturing industry thoroughly, but recent literature often claims that I4.0 cannot be purely mapped to SMEs [9] because of several factors including lack of support and guidelines [18].

There are several factors that can help provide SMEs with a suitable framework to cater to the on-going requirement of conventional environments such as the concept of enterprise integration from different dimensions. In order to implement the idea of I4.0, it is necessary to connect three integration levels in an enterprise [5]:

- horizontal integration, connecting all the sub-units of an enterprise together;
- vertical integration, coordinating along the hierarchical chain within the units of an enterprise; and
- end-to-end integration, linking the selective units for customised production chains.

The inclusion of a cloud-based network in I4.0 standard provides a smart architecture to overcome the limits of hierarchical mediation, but it lacks the aforementioned high-level comprehensiveness in SC architecture, especially for SMEs. Literature includes a broader domain of Industrial Automation and Control Systems (IACS) networks, e.g. Cisco's Ethernet-to-the-Factory (EttF) architecture [19] and Rockwell Automation's Integrated Architecture (AIA) [20]. Both EttF and AIA are manufacturing control system architectures based on de-facto Ethernet-based networking standards to provide value within industrial operations. Another more general but comprehensive control system architecture is called the Converged Plantwide Ethernet (CPwE) architecture [21], which connects these two architectures together. There exist several other contributions regarding I4.0 and enterprise setups, including the concepts of supply chain based implementations e.g., [10] and [22], but because of the requirement for large structural change and affordability, the issues for SMEs still exist [17]. This paper does not focus on control system automation though, but it attempts to provide an overarching solution, which includes an I4.0 and Cyber Physical System (CPS) based customised SC architecture incorporating all three enterprise integration dimensions. In order to provide an implementation guideline, this solution includes an associated Agent Oriented Storage and Retrieval (AOSR) warehouse management system (WMS) to reflect how xAOSF framework can help to reduce the baseline problems of SMEs, particularly in warehousing.

The xAOSF framework not only includes the CPS like structure, which also caters to the aforementioned enterprise integration mechanisms (as detailed in next sections), but it is also based on Multi-Agent System (MAS), which is considered a suitable technology for developing adaptive, autonomous, robust and complex industrial systems under the umbrella of I4.0 [6], [23], [24]. A possible implementation of such an architecture for large setups is discussed in [25] and [26], which conclude that, in order to provide supply chain flexibility, a sound communication mechanism to support randomness in operations is important, especially in SMEs [27]. The literature claims that the initiative of I4.0 and CPS is an opportunity for utilising the planning features of agent-oriented systems [28]. The design and architecture of MAS are one of the elements that enhance the applicability of agent technologies in industry [28] and, for that, selection of appropriate agent development environments, tools and methodologies are pivotal. This solution has used (JADE) [29] as a tool to develop a dynamic system, which detailed in the later sections.

As warehouses are considered the real backbone of the supply chain for any production/manufacturing organisation [30], the implementation of xAOSF framework includes a particular focus on warehouse management. From many of the problems of the manufacturing industry, managing a warehouse is one of the critical issues [31]. Previous research presents multiple projects, focusing on smart enterprises, particularly from the warehouse perspective, using agent technology to overcome the gap in traditional manufacturing systems e.g. the works presented in [32], [33] and [34]. The work mentioned in [35] is also related to warehouse management and a process control mechanism with an architecture of a specific warehouse of Lareal Company with a predefined number of categories of zones, which is similar to the ones presented in [26] and [36]. However, the management problems of SME-oriented warehouses still persist [37].

The literature presents several contributions made in different dimensions in the domain of warehouse optimisation such as the works presented in [38]-[40]. Most of the problems in SME-oriented warehouses come from mismanagement of design and structure of the warehouses [38]. A warehouse is usually segregated into several sub-areas e.g. Receiving Area (RA), which is a place where products are identified at first for inspection purposes on their arrival and then they are placed in racks; and Expedition Area (EA), which is a place to keep products temporarily before their placement into racks. However, overloading in RA and EA leads to mismanagement in warehouses [31]. Literature also includes automated solutions for warehouse management via AS/RS (robo-machines based Automated Storage and Retrieval System) using predefined trajectory for unmanned vehicles and conveyor belts to pick and place the products [41]. However, such high-cost solutions are not a perfect fit for SMEs. [42]. This paper includes a discussion on how xAOSF's recommended AOSR-WMS system helps to overcome basic warehousing issues (e.g. manual re-slotting planning, stock inaccuracies, unmanaged storage areas [43], [31]).

In order to provide a comprehensive solution, this paper presents the conceptualised visualisation of xAOSF framework as a customised CPS (in Section-2), which provides a high-level view of the whole SC which intelligent agent communication mechanism for smart entities to seamlessly interact together. Section-3 includes details about classification and architecture of xAOSF agents. Section-4 presents the negotiation and coordination mechanism between different constituent agents. Section-5 details how the xAOSF framework provides the perspective of Enterprise Integration (EI). In order to validate the xAOSF architecture, Section-6 includes some results from the implementation of xAOSF recommended Agent-Oriented Storage and Retrieval (AOSR) warehouse management system (WMS), to reflect the efficiency in managing a warehouse for SMEs. Section-7 concludes the contribution and highlights some of the possible future works.

2. Conceptualised Visualisation of xAOSF Framework

In our previous work [44]-[47], we have presented details of xAOSF framework, formal problem and domain definition, and a thorough validation/experimentation of this framework. This paper provides a conceptualised visualisation of xAOSF framework as a CPS architecture to help mapping a guideline in conjunction with general CPS standards [6]. The xAOSF framework basically provides a two-fold solution: firstly to provide an end-to-end integrated Supply Chain (SC) architecture for SMEs in compliance with I4.0 standards; and secondly to provide decentralised decision making via intelligent agents and at the base level (e.g. warehouse management system (WMS)), which is achieved through its associated solution of AOSR-WMS system.

The xAOSF architecture, as depicted in Fig. 1, encapsulates the five-level architecture of CPS into a three generic layers-based model including Smart Connection Layer, Data to Information Exchange Layer, and Cyber Cognition Layer. The integrated and reduced layers based xAOSF framework provides better support for Enterprise Integration (as detailed later in Section - 5). Three tiers of xAOSF framework (Smart Connection Layer, Data to Information Exchange Layer and Cyber-Cognition Layer) provide a seamless mechanism of informational flow and systematic approach with the embedded concepts of MAS to provide an overarching solution.

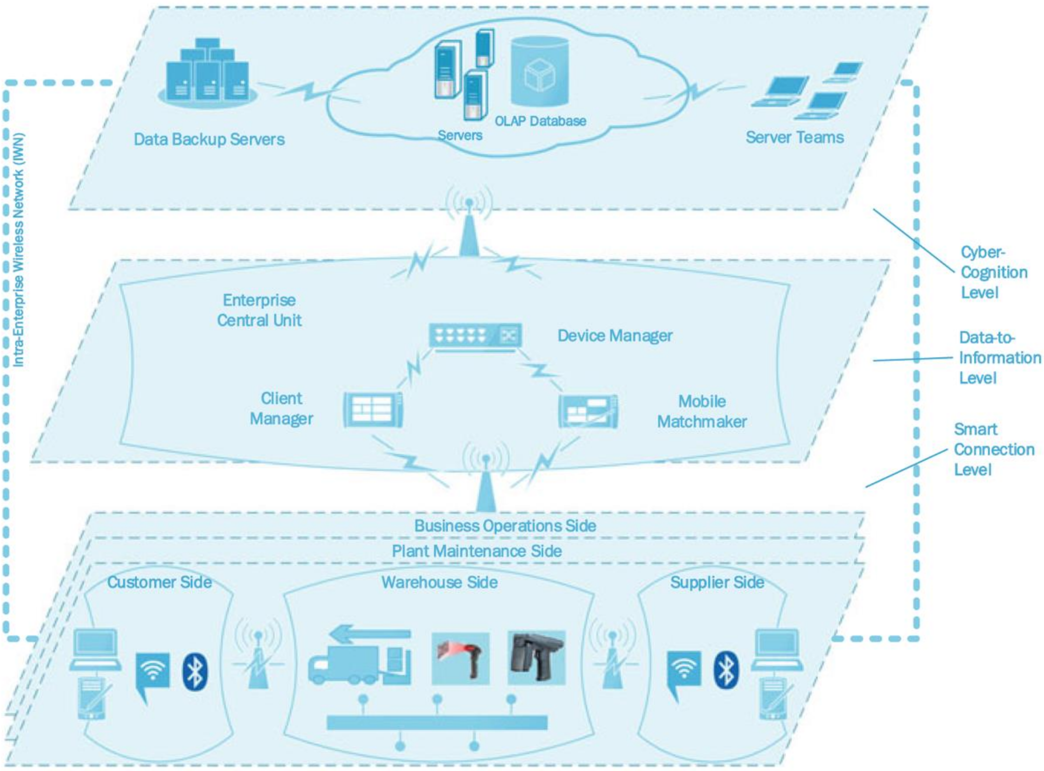

Fig. 1. xAOSF Framework as a customised CPS.

Smart Connection Layer: This is the base layer, which provides the flexibility to include several different subsystems e.g. Plant Side or front-end user side (Customer/Supplier systems). The flexibility at this layer helps in providing an enterprise integration mechanism which can be achieved incrementally in an SME-environment. At this layer, all smart devices are implanted, whether they belong to plant side e.g. bar-code detectors, temperature/pressure sensors, RFID scanners, image analysers and other sensing devices; or from CRM/SCM side e.g. mobile devices/Personal Digital Assistants (PDAs) such as smart-phones, notebooks. All the devices connected to this layer are capable of sending and receiving semantic annotations using the same network (termed as Intra-Enterprise Wide Network (IWN)) to provide a thorough integration (the details on how the device-level components interact is discussed in our previous work [44]). The xAOSF framework provides a solution that incorporates standard SC conventions e.g. for the integration of in-plant components (e.g. Manufacturing Execution System (MES)) and also for

Customer Relationship Management system (CRM), which may be running as part of a central Enterprise Resource Planning (ERP) system. The details on how three-tier based xAOSF framework caters for multi-dimensional enterprise integration is discussed in Section 5.

Data to Information Exchange Layer: xAOSF's Enterprise Central Unit (ECU) is an intermediary layer to control two-way integration (in between cloud server and baseline sub-units of the enterprise) and is responsible for transforming data into decisive information; and hence is generally termed as Data to Information Exchange Layer, concentrating two separate layers (data later, information exchange layer) of general CPS architecture. ECU is a core sub-system that utilises a Device Manager, which coordinates the overall flow of the system with the help of Client Manager and Mobile Matchmaker, and also manages the current status of sensor devices to maintain overall connectivity via a fact table including device details e.g. IP addresses, capacity and other properties. Client Manager manages the clients' requests by ranking them by priority and fulfilling them in coordination with xAOSF agents. Mobile Matchmaker resolves any matching conflicts, that can arise in different resource utilisation requests from either the plant side or CRM/SCM side and processes them in conjunction with Client Manager. The general AOSF framework [44] addresses possible issues related to discovering new devices and coordinating between existing devices and their functionalities by applying its semantic and domotic inferences, prioritising client requests, detecting and resolving inconsistencies in devices' current status, maintaining standardisations and compliance with protocols for bidirectional tunnelling to establish a seamless flow for semantic requests. The details about agent categorisation and their communication mechanism are discussed in the later sections.

Cyber Cognition Layer: The Cyber Cognition Layer is the top-level layer, which maintains the cloud architecture and provides the overall intelligent cognitive abilities of the system. The layer combines the two separate layers (Cyber Layer and Cognition Layer) of the general CPS architecture. The server's management and Online Analytical Processing is performed at this layer. All the data backup and server teams interact with the overall system via this layer, which provides a remote visualisation for top-level management with effective data analysis. The provision of cloud architecture opens up the flexibility for possible inter-enterprise integration in the future, though this paper does not focus on concerns related to security and privacy. However, the implementation of the entire xAOSF framework is discussed in detail in our previous publications [44]-[47]. This paper also includes some results from a test scenario in an SME oriented warehouse environment in Section 6.

3. Architecture of xAOSF Agents

The xAOSF framework defines its own categorisation of rational agents (rather than omniscient agents, as detailed in our previous work [44]). Omniscient agents are based on four basic elements [48]: built-in knowledge, actions, percepts and goals, which are essential to design agents but agents based on only these four basic constructs may not work in a dynamic/non-static environment [49], such as in an SC network, where information keeps on changing over time. The xAOSF rational agents are based on orthogonal baseline dimensions: agent's role, resource, interaction and information [49] on top of the four basic elements of percepts, built-in knowledge, actions and goals. This means that xAOSF agents are not only capable of sensing percepts from the environment in response to some predefined sequence of observations, triggers or actions (if the environment change is visible) but also to update their knowledge base with respect to the information gathered from other subsystems e.g. production system, warehouse or supplier side. The xAOSF framework defines three basic types of model-agents: User Agents (UAs), Mediator Agents (MAs) and Smart Device Agents (SDAs). The architecture of xAOSF agents is depicted in Fig. 2. UAs are utility-based agents focusing on accomplishing user goals as per defined criteria through their coordination and communication mechanism. The utility can be defined as a function to describe user requirements that may have more than one goals, e.g. security, accuracy, availability or safety. MAs are knowledge & goal-based agents and play the role of mediator to resolve conflicts between user requests and available resources. SDAs, which are simple-reflex agents, are modelled on the basis of built-in reflex-actions. All the possible combinations of percept-action incidents are set to be the part of the SDAs' knowledge-base. The knowledge-base of percept-action rules is updated on the basis of trends in the sequence of environmental changes. For example, the same READ action would be initiated in case any bar-code tag is scanned, on the basis of a simple Condition-Action-Rule. UAs run on mobile devices (e.g PDAs) and if needed make requests to utilise any functionality from available resources. SDAs, which are embedded on advanced sensing devices, provide different services (e.g. functional profiles, measurements, scanning or searching). UAs request MAs for any functionality and MAs, after pooling and updating information from SDAs about available resources, allocate services back to UAs. The details of agents' communication are discussed in the next section.

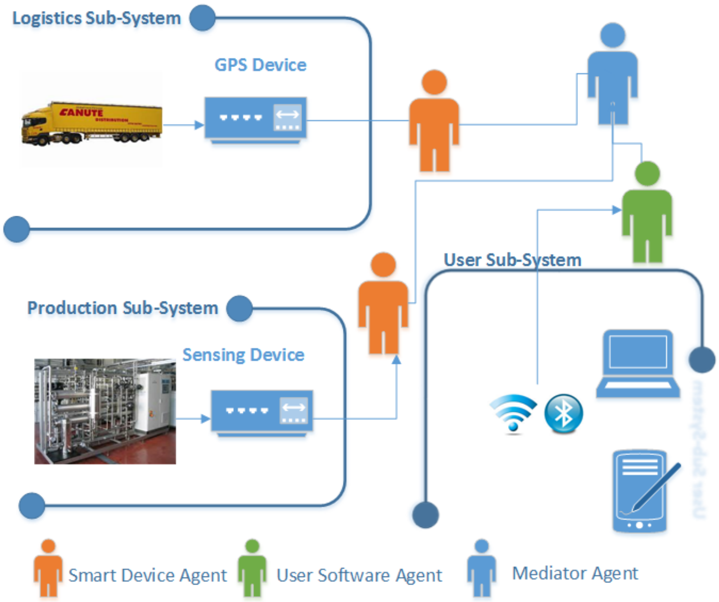

Fig. 2. xAOSF agents' architecture.

In an SC network, any of the resources (e.g. sensors or devices) or agents may add to the network or leave the network as per the requirements of the environment. The xAOSF's agent architecture, with the help of MAs, is flexible enough to handle any new connection or disconnection without any need to update the communication and negotiation protocol. The xAOSF's agent communication mechanism is based on Hierarchical Task Network (HTN) Planning [50]. Our previous work [45] on MAS-based planning strategies based on problem and domain definition provides insight into how the tasks are achieved through breaking down the actions into task and subtasks. The detailed architecture of xAOSF agents is discussed in conjunction with AOSR algorithmic heuristics in our other work [51].

4. Interaction between xAOSF Agents

The xAOSF Agents are modelled on the basis of a typology of dependencies, which includes task-task dependencies, task-resource dependencies and resource-resource dependencies. xAOSF framework provides a coordination workflow that deals with issues of such constraints. The communication involves notions of senders, receivers, messages, and languages.

The pragmatics of xAOSF agents are based on Knowledge Query Manipulation Language (KQML) [52] in compliance with FIPA-ACL (Agent Communication Language) [53]. xAOSF agents and designed and implemented in JADE [29], which provides built-in features to use FIPA-ACL compliant agent communication standards, as depicted in Fig. 3. To represent the interaction between xAOSF agents, a UML base interaction diagram is depicted in Fig. 4.

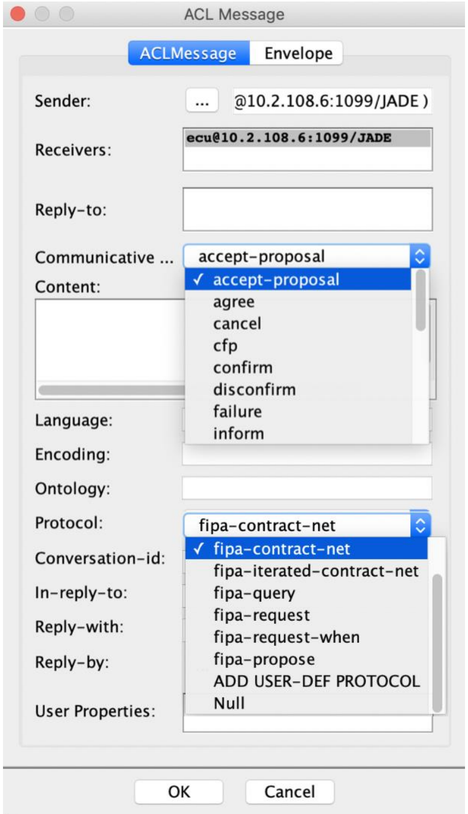

Fig. 3. ACL messaging interface.

MAs are modelled to fulfil the responsibility of providing the semantic conditions for intelligent interaction among agents, against resources, in order to acquire available services. Top-down search [50] is employed for coordinating hierarchical plans, coming from users or devices. MAs are responsible for finding the best deal among the agents in the negotiation phase. For mediation roles, Mas are modelled in a way to follow the sound algorithmic base of Contract Net Protocol (CNP) [54]. Clercq [55] employed the same strategy to find the best option among choices on specific criteria after receiving a service request. Agents in this system are capable to negotiating for available resources and services, to resolve conflicting situations between the agents and provide users with decisive information on the basis of in-built algorithmic intelligence to the agent architecture with respect to a utility. This system's interaction is explicitly mentioned in the sequence/interaction model, as depicted in Figure 4, with an example of resource sharing and plan coordination.

A UA sets up its own plan based on the desired goal and then sends a request to MA with initial status and goals. MA holds the updated status and properties of all SDAs included in the system by a simple pooling sequence of ping requests. On meeting the criteria of plan A sent by UA, MA sends an executable copy to SDA for execution. Otherwise, on unsuccessful criteria with plan A and SDAs' current status, MA sends another executable plan B for approval and, after that, sends an approved, agreed and executable plan to SDA.

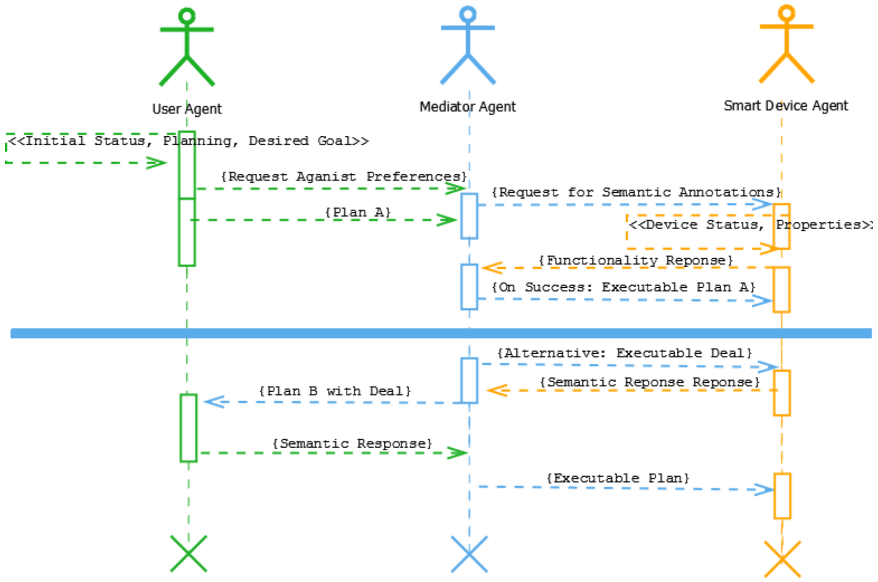

Fig. 4. xAOSF agents' interaction model.

For the logical implementation of the system, UML-based Usecase Model portrays the systematic flow of AOSR WMS Planer system. The heuristics of AOSR-planner agent (PA), which is an MA in nature, are not included as part of this paper as they are detailed in our other work [51]. Use Case Models are the logical schemes to represent different actors and procedures of the working system using multiple relationships like <<uses>>, <<extends >> and generalisation. Fig. 5 represents that a floor supervisor, as a warehouse user agent, initiates the operations. CRM and AOSR algorithm also behave as an agent in the same platform but have different instances in implementation.

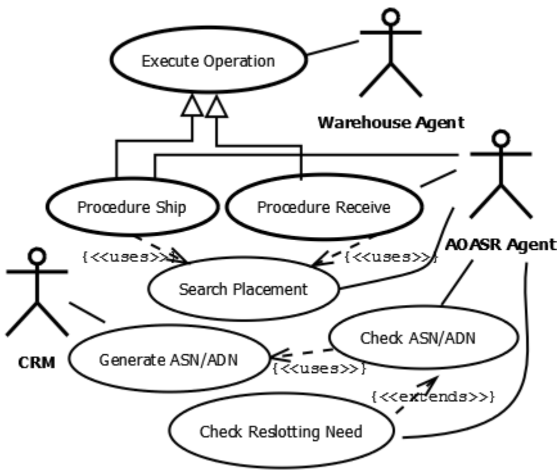

Fig. 5. xAOSF agents' usecase model.

ASN/ADNs represent the input and output of this system and are generated by CRM, which itself behaves as an agent in this environment. AOSR Agent is a Planner Agent that performs as the core agent of the system to initiate the procedures of shipping or receiving. Procedure-Ship and Procedure-Receive use the use-case of Search-Placement in order to find the product in the warehouse whose placement has been generated.

5. Enterprise Integration and xAOSF

In order to cater to the conventional Enterprise Integration (EI) concepts [56], the xAOSF framework includes the concept of Intra-Enterprise Wide Network (IWN), as explained in Section 2. The IWN facilitates the xAOSF architecture by providing a mechanism to maintain an internal supply chain to handle in-plant activities e.g. change in manufacturing capacity, and also an extended SC to coordinate between external entities e.g. suppliers and customers. The xAOSF architecture also supports the concept of the virtual supply chain as all the structural elements (e.g. production and transportation units) and control elements (e.g. demand, supply, process flows and inventory status) have also been incorporated in the architecture.

Enterprises nowadays are more or less distributed, which calls for proper integration measures to be in place, because the loss in dataflow may lead to high impact risks [7]. In order to keep the system running, enterprises sometimes run their contributing subsystems in parallel such as Manufacturing Execution System (MES), which may include CRM/SCM running at different distributed servers. In order to provide coordination and control mechanisms from Physical Layer, xAOSF's Smart Connection Layer provides the utility to connect to top-level component e.g. communication with ERP system, which is maintained at xAOSF's Cyber Cognition Layer. Literature often recommends to keep the Control Layer as a separate middle tier, that is the reason that xAOSF framework has its separate Data to Information Exchange Layer, as depicted in Figure 6, to coordinate with different components. In such a scenario the strategies of Enterprise Application Integration (EAI) become necessary [56].

Integration in enterprises is discussed in two different dimensions: inter-enterprise and intra-enterprise integration [7]. Inter-enterprise integration, which includes the integration of two or more separate enterprises together, yields novel opportunities of cross-enterprise communication services [5]. Interoperability is the next concern while addressing the issue of inter-enterprise integration [24]. On the other hand, integration within the organisation, which is called intra-enterprise integration, is also important to keep the enterprise as one single updated unit. In order to bring an improvement in decision making, there must be a communication mechanism that supports randomness in operations, especially in SMEs e.g. updating the product placement plan during runtime or changing the production requirements [27]. Intra-enterprise integration is further divided into two concentration tracks (i) Vertical Integration; and (ii) Horizontal Integration.

Vertical Integration is the process to enhance transparency of dataflow and runtime status availability to a top-level application layer [5]. It connects different layers of information processing within a single unit of an enterprise, such as the flow of data from the physical layer to the connection/control layer, passing through the MES layer to update the interfaces of the ERP system. For example, if a customer wants to place an order for a particular product from his hand-held device, the application layer should provide real-time stock availability of the products through its control mechanism. When the order is placed, the MES and ERP sides should also be updated to reflect the integrated change.

Horizontal Integration is essential to provide the coordination mechanism between several entities of the same unit. Distributed organisations often-times need a strategy for coordination or maybe negotiation between several entities in order to properly utilise available resources [56]. Horizontal Integration may be further divided into the integration of physical hardware, a communication layer, a data processing layer and a business logic layer [57].

Another dimension of intra-enterprise integration is inter-departmental integration [58], also known as End-to-End/Unit-to-Unit Integration, which explores the coordination of different subsystems within an enterprise. In order to maintain the consistency of dataflow, all subsystems of an enterprise should receive any update regarding upcoming or undergone changes such as the reflection of actual stock values [59].

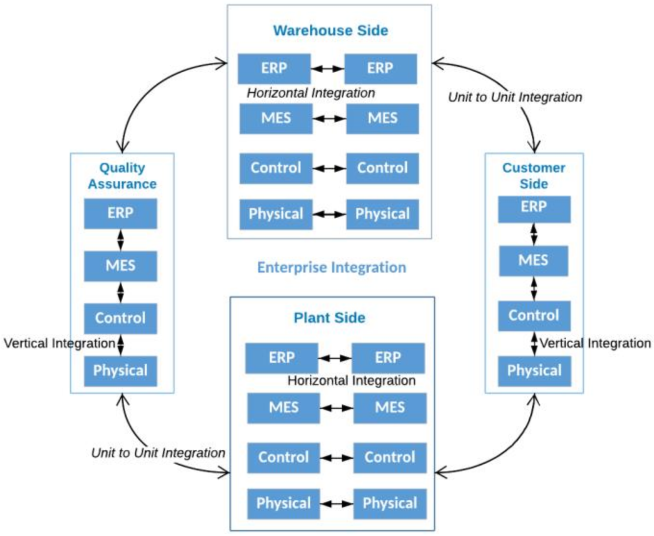

Fig. 6. Enterprise integration and xAOSF.

The comprehensive architecture xAOSF caters for three of the aforementioned types of intra-enterprise integration as shown in Fig. 6. In the xAOSF framework, agents are distributed at different enterprise levels, e.g. SA's and UA's work on both the Data to Information Exchange Layer and Cyber Cognition Layer (conventionally MES and Control layers), whereas SDAs work on Smart Connection Layer (conventionally Physical layer). However, MAs provide a bridge for agents at different layers to communicate for efficient resource utilisation. Input from UAs sets the preferences for the MES layer which passes through to the hardware level via the Control Layer in order to execute some functionality. For example, to pass an instruction related to fewer or more production requirements from the application software layer to the physical hardware layer in a conventional environment, the xAOSF agents perform the following steps:

1) Keeping in view the stock value from warehouse planner agent and the upcoming orders, the CRM component suggests the increased or reduced production requirements to the admin user, by following the procedure from the Cyber Cognition Layer and Data to Information Exchange Layer.
2) Based on user input from the application side, the instructions are transferred to the MES level and then pass through the control mechanism to the sensors, which need to be activated by following the procedure from the Data to Information Exchange Layer to the Smart Connection Layer.
3) In order to accomplish the goal, the embedded smart device agents coordinate to check what tasks should be completed and stop when the goal is achieved, by following the procedure from Smart Connection Layer.

Step 1 follows the concept of End-to-End/Unit-to-Unit Integration as the agents communicate in between different units, e.g. WMS and CRM at different layers i.e. Cyber Cognition Layer and Data to Information Exchange Layer. Step 2 follows the idea of Vertical Integration as it follows the sequence of top-down instructional flow from Application Layer to MES, then Control layer and ultimately to the Physical Hardware Layer, by following xAOSF integrated layer architecture at Data to Information Exchange Layer. Horizontal Integration is performed in Step 3 where SDAs and UAs interact with other same-level agents to complete the goal together at Smart Connection Layer. The xAOSF framework supports intra-enterprise integration with vertical, horizontal integration and end-to-end integration, but for inter-enterprise integration, the concerns of interoperability, trust, security and privacy are still open issues, which are not addressed as part of this paper.

6. Results and Discussion

In order to provide a thorough solution to improve warehouse management in SMEs, the xAOSF framework recommends its associated AOSR-WMS mechanism with its 6-Feature strategy [51], which is prototyped in JADE [29]. Fig. 7 represents the reflection of a Sniffer Agent, which monitors the interaction between xAOSF agents in the JADE interface. In this environment, Agent Monitoring System (ams), Directory Facilitator (df) and Remote Monitoring Agents (rma) are the built-in agents for JADE. The main container includes three different categories of xAOSF agents, (i) Enterprise Central Unit (ecu), (ii) Planner Agent (pa) and (iii) Customer Relationship Management Agent (crm). Two CRM-agents are instantiated in the case presented, named crm and crm1, in order to represent more than one customer location. For every scenario of product delivery to the warehouse ecu sends and advance shipment notice to pa (as shown in interaction 1 and interaction 7) and for every request to order the crm agent sends advance shipment notice to pa (as show in interaction 3,5,9 and 11).

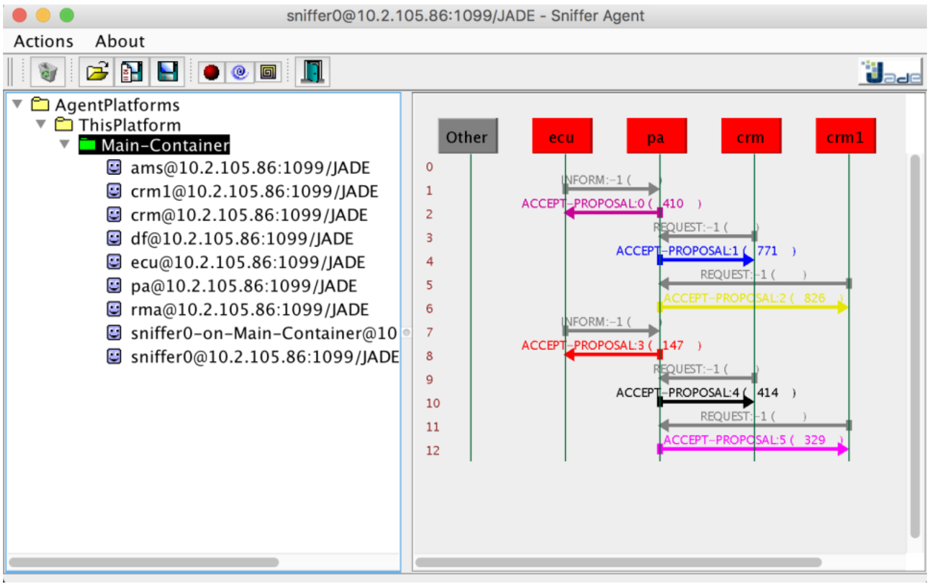

Fig. 7. xAOSF agent interaction in JADE environment.

A test scenario of a distribution warehouse with applied limitations and constraints is applied to the xAOSF recommended AOSR-WMS planner component in comparison with a linear supply chain-based standard WMS system [37], [60]. A comprehensive dataset is applied in this test scenario, including the data used in the products' delivery and shipment processes. The data set is extracted from the online source provided by DGI Global [61] and Eurosped [62] warehousing and logistics companies. Several different variations of data features are included, such as product classes, their characteristics, SKUs and different situations of product delivery and shipment. The applied data set includes maximum variation and can be considered as a representative for large scale applicability (as presented in our previous work [47], which includes the detail of experimental design and experiments with random test data sets). The results presented in this paper are average values for thirty different test cases to reflect the overall system performance. The comprehensive data set, utilised for this project, does not only include one type of product category, but it also consists of the information of several characteristics of products e.g. SKUs, quantity and products classes, from several different industrial sectors e.g. electronics industry, medical industry, textile firms, paint and glass industry.

In contrast to the linear SC-based standard WMS, which works on the basis of centralised management e.g applying a static logic to maintain products locations and rack-level [63], AOSR-Planner Agent (PA) utilises its 6-Feature strategy [51], which is based on a hybrid logic mechanism to be applied as per the products' characteristics to generate the best possible placement plan. The placement plan generated by PA provides the flexibility to be modified during runtime on the basis of new parameters e.g. advance shipment and delivery notices (ASN/ADNs). PA works based on an agent-algorithm (as detailed in our previous work [51]), which reads the data for the warehouse for available capacity and current stock, and from CRM/SCM for upcoming ASNs/ADNs. PA provides a combination of different slotting and re-slotting strategies such as zone logic [63], First In First Out (FIFO) [64], Put/Pick from the fewest [65], which makes it hybrid in nature. After using zone logic, the PA applies the second appropriate logic to store/sort products into the defined zone in accordance with the product specification and categorisation. For example, after selecting Zone logic, FIFO/Fewest logic could be applied based on product characteristics such as for fast-moving consumer goods FIFO would be suitable and for raw material the Fewest logic would be more appropriate. PA is designed to provide the flexibility to reconfigure as per environment/current system state e.g. preliminary, intermediate, bottleneck. For example, preliminary states of the systems are normal initialization states where stocking is initiated assuming the available capacity for each product. Depending upon the arrival of more incoming products the systems states keeps of changing to intermediate (almost half full) and bottleneck (in case of full capacity). The hybrid nature of AOSR provides the ability to reconfigure and adapt as per the environment change, which helps in minimising possible conflicts, and is the reason that, in the preliminary/initialisation states, no conflict arises, because the incoming products normally get a place in the PA-defined zones/racks.

AOSR system utilises the planning constructs of Problem and Domain definitions and Hierarchical Task Networking (HTN), presented in our previous work [45]. HTN-based task resolution helps planner agent to break bigger tasks into smaller manageable primitive tasks which can be achieved based on reflex actions e.g. making up a space for upcoming products can be achieved via base-line tasks recommended by planner agent by applying step by step logic. The hybrid nature of AOSR makes it work pro-actively to sense the upcoming conflict-states of the system. Conflict-states of the system are situations when PA senses the concurrent parameters for a particular product such as receiving an ASN and an ADN for the same product category. In such a case, PA pro-actively updates the placement plan to move the products which need to be re-slotted, based on the prediction for more incoming products. By doing so, the issues of and overcrowded expedition/receiving areas (EA/RA) can be minimised. The concerns of lost/wandering items usually arise by keeping EA/RA overloaded, which leads towards other issues such as stock imbalance [31]. The AOSR algorithm utilises its auto-inspection mechanism including weight sensing and RFID scanning to minimise the wait-time, especially at RA. Thus, the products stay in RA just for a quick identification purpose, while being in their certain packing units (e.g. each/box, box/cases or case/pallets).

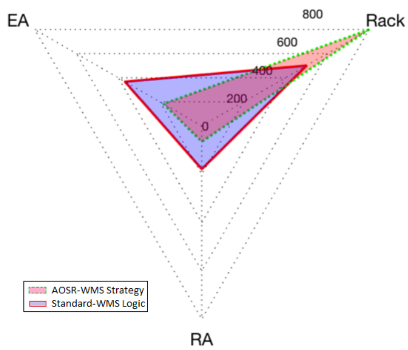

Fig. 8. Performance inclination of xAOSF and AOSR strategy.

The results extracted from the test scenario applied to xAOSF's recommended ASOR-WMS strategy, as represented in Figure 8, reflect the inclination of both strategies: AOSR's hybrid-logic strategy and standard WMS's static-logic strategy. In order to bring clarity in results and to provide better recommendations, this research is constrained to three very important key performance indicators (KPIs):

1) number of products stored in racks;
2) number of products kept at receiving area (RA); and
3) the number of products placed in expedition areas (EA).

Low performance in managing these three parameters results in basic WMS issues such as receiving area overloading, demarcation lines vanishing, manual re-slotting and wandering/lost items [43]. Literature has often mentioned persisting SC and WMS issues, and the main reasons behind such problems are mostly the unmanaged receiving and expedition areas [31] and unmanaged storage capacity [37]. A higher number of products within the racks is usually considered as a performance metric for efficiency in warehousing [66].

The data represented in Figure 8 reflects the average results acquired by applying thirty different test cases of the aforementioned data set to the AOSR-planner and demonstrates how the focus of the xAOSF recommended AOSR strategy is different from a standard WMS in a linear SC model. In the graph, all three preference points (corners) reflects the aforementioned KPIs, which reflect the number of products in the three main areas of the warehouse, RA, EA and Racks. As per the concentration of data points, the graph shows more tendency towards a certain corner. The deflection in the shaded areas reflects the condensation of data points, which shows the preference of the strategy. For example, the placement of upcoming products within the defined racks is the main priority of xAOSF-AOSR strategy (represented in the orange shaded region for colour print and light grey in black&white print) so the deflection of data is towards the point `Rack', while the standard approach uses a balancing approach (represented by the purple shaded region for colour print and dark grey in black&white print) and reflects a balanced data deflection for all the three points. In the case of AOSR, the graph explains the deviation of data towards the higher number of products at `Rack' point with almost 800 out of 1080 total products placed in the racks. The manual method of sorting and identifying the proper location of received products takes almost 41% of the time and effort in a standard SC warehouse [66]. Conversely, xAOSF framework and the 6-Feature Strategy of AOSR [51] recommends the BPR-based proactive and automated approach of sensing the ASNs and ADNs (advance shipment and delivery notices) by utilising its cognition features and fully integrated environment, thus takes less time and maintains a very low number of products in EA and RA (almost 100 on average in this scenario as compared to 300 using the standard approach).

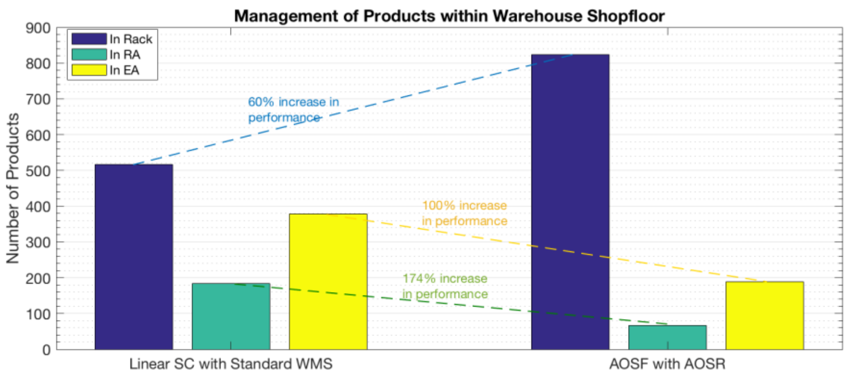

Fig. 9. Linear SC network/standard WMS vs xAOSF-AOSR strategy.

Based on the results shown in Figure 8, which highlight the preference of AOSR strategy in comparison with a standard WMS, the results shown in Figure 9 represent the performance increase while utilising AOSR strategy. A constrained test case of around 1,000 products in the rotation was applied to both approaches. Following the xAOSF architecture and recommendations of the AOSR strategy [51], results are better in all three of the aforementioned performance metrics. There is a significant increase of almost 60% in the products stored in racks by using AOSR recommendations. In order to adjust the upcoming products, AOSR-WMS strategy provides a comprehensive zoning plan within the shopfloor to cater to a wide range of products with several different characteristics. This provision of volatility in different zones provides flexibility and stability to cater to any future change in business operations. The proactive and predictive nature of xAOSF-AOSR strategy, as discussed in this case, reduces the number of products in EA and RA to half and less than half respectively, leading to improvements of 100% and 174% in these areas, which is a significant increase in performance with a focus of aforementioned KPIs.

7. Conclusion

The xAOSF framework includes an end-to-end integration of the whole enterprise, covering both the upstream and downstream operations of both supplier and customer sides. The conceptualised visualisation of the xAOSF framework provides a guideline in terms of mapping it with CPS and I4.0 in terms of compatibility. It presents the design constructs for the implementation of an AOSR system, which focuses explicitly on the warehouse side of SMEs. It tends to provide a flexible placement plan with moderate level storage and retrieval system excluding automated conveyor belts and robo-machines, which makes it affordable for SMEs. A comprehensive SC architecture and associated low-cost AOSR-WMS system make this solution favourable for SMEs.

In future, utilising features of Big Data may provide this system with more cognitive abilities in order to provide more intelligence, based on past data trends. Although most SMEs do not currently consider data as a source of added value [67], it could be a valuable addition in the future. Furthermore, other than focusing the issues of EA/RA and warehouse management, there could be more dimensions to work upon in the future such as movement within the warehouse shopfloor using forklift trucks, utilising collapsible racks or small-scale drones. These solutions provide nice cutting-edge features but come with an additional infrastructure cost. The solution presented in this article can also be used for incremental improvements since, by employing this system, basic SC and warehouse management issues can be reduced; and later on, if needed, automated features such as conveyor belts and picking machines can be added into the system. xAOSF framework provides a generic and dynamic solution, which can be customised in future as required.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Fareed Ud Din: Conducted the primary research and drafted the article.

David Paul: Provided active feedback on the drafts for revision.

Frans Henskens: Supported and overlooked the research idea overall.

Mark Wallis: Analysed the data and initial experiments.

All authors had approved the final version.

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