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Intelligent sustainable supplier selection using multi-agent technology: Theory and application for Industry 4.0 supply chains

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ABSTRACT

Advancements in information and communication systems offer immense opportunities for supply chain intelligence and autonomy establishing stepping stones for Industry 4.0 supply chains (SCs). As a crucial SC decision, sustainable supplier evaluation and selection process have been addressed abundantly in the previous literature. However, this process has not yet been realized within Industry 4.0 SCs where interconnection, real-time information transparency, technical assistance and decentralization of members of a physical system (i.e., supply chain members) are regarded as the main design principles. To narrow the identified gap, a Multi-Agent Systems (MASs) approach is proposed for addressing sustainable supplier evaluation and selection process to provide a proper communication channel, structured information exchange and visibility among suppliers and manufacturers. Furthermore, the application of MASs in this process and their natural applicability as one of the enabling technologies in moving towards Industry 4.0 SCs are investigated in detail. It is found that the proposed approach can help decision-makers inside manufacturing firms to make prompt decisions with less human interactions. The merit of the developed MAS is demonstrated through a real-world implementation on a medical device manufacturer. Finally, the limitations and advantages of the proposed approach are presented together with some remarks for future work.

1. Introduction

The application of information and communication technologies (ICTs) started during the 1980s and is ongoing (Giannopoulos, 2004), which has restructured every aspect of our daily life remarkably. Interpersonal communication is changing to human-to-machine interconnection at an unprecedented scale and pace in a cyber-physical system context, and machine-to-machine direct communications without human intervention (Botta, De Donato, Persico, & Pescapé, 2016; Posada et al., 2015). The implementation of this kind of interaction network within the production and operations environment is named Industry 4.0. Industry 4.0 was defined due to the growing trends for the use of ICTs for industrial production (Oesterreich & Teuteberg, 2016). The concept of Industry 4.0 is based on three primary components: internet of things (IoT), cyber-physical systems (CPSs), and smart factories (Hofmann & Rüsch, 2017).

The term "IoT" firstly appeared in 1999, which was proposed by Kevin Ashton in the context of supply chain management at Procter & Gamble (Ashton, 2009). One of the major IoT application areas that have been paid vast attention is IoT-enabled manufacturing. For example, in the automotive industry, IoT is widely used in process control and post-sale management, as well as transport (Kirk, 2015; Zhang, Qu, Ho, & Huang, 2011; Zhong, Dai, Qu, Hu, & Huang, 2013). The term "CPSs" firstly appeared in 2006, which was coined by Helen Gill at the workshop sponsored by US National Science Foundation (Leitão, Colombo, & Karnouskos, 2016). Due to the emergence of Industry 4.0 strategic initiative, a systematical deployment of CPSs in the context of production and manufacturing received lots of attention which is also named as cyber-physical production systems (CPPSs) in some studies (Monostori, 2014; Otto, Vogel-Heuser, & Niggemann, 2018; Vogel-Heuser, Diedrich, Pantförder, & Göhner, 2014). The Industry 4.0 manufacturing has many influences on the entire SC as well.

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Accordingly, collaboration and cooperation among SC members are vital to increase the information visibility in various stages of product life cycle.

Basically, four design principles can be derived for the Industry 4.0 components, i.e., interconnection, real-time information transparency, decentralization, technical assistance (Hermann, Pentek, & Otto, 2016). Due to the dynamic, autonomous and distributed environments embedded in SCs (Ghadimi, Toosi, & Heavey, 2018), the same principles of Industry 4.0 which are primarily envisioned for manufacturing applications can be extended to the entire supply chain. Besides the mentioned enabling technologies in realizing Industry 4.0 in manufacturing and logistics, MASs have been developed to support seamless collaborations for physical systems with distributed behaviors (Ben Othman, Zgaya, Dotoli, & Hammadi, 2017; Tarimoradi, Zarandi, Zaman, & Turksan, 2017; Utomo, Onggo, & Eldridge, 2018). Relying on the modularity, dynamic and distributed characteristics of the MASs and given its applications in manufacturing domain, the multi-agent technology is regarded as another enabling technology in realizing the Industry 4.0 SCs. However, research and industrial applications are still limited and at its early development stage.

Almost every decision to be made in the management of supply chains and networks are affected by supplier evaluation and selection activities (Ghadimi, Azadnia, Heavey, Dolgui, & Can, 2016). Besides, sustainability triple bottom line (TBL) dimensions (environmental, economic and social) are being integrated within the supplier management activities and there upon extended to the entire supply chain and manufacturing operations through the whole value chain. Accordingly, many researchers strive to contribute and address the problem of sustainable supplier evaluation and selection by developing various tools and techniques (Ghadimi et al., 2016; Zimmer, Fröhling, & Schultmann, 2016). While great attentions have been drawn by scholars and industry on the importance of sustainability and environmental issues and their incorporation in SCs (Ghadimi et al., 2016; Ghadimi, Wang, & Lim, 2019; Wang, Ghadimi, Lim, & Tseng, 2019), little practical efforts were made in incorporating sustainability issues within the context of Industry 4.0 SCs and more specifically sustainable supplier evaluation and selection within this context. Therefore, more research activities are required to illuminate the research directions in this area. Only recently, Duarte and Cruz-Machado (2017) pointed out this matter and discussed the relationships between green and lean supply chains and Industry 4.0 by proposing a conceptual, theoretical model with the aim of incorporating the industry 4.0 concepts into green and lean SCs. The developments above provide immense opportunities for the realization of digital supply chains with simultaneous consideration of sustainability aspects, specially focusing on sustainable supplier evaluation and selection problem, leading to building theory and practice towards the Industry 4.0 SCs. This domain has also been regarded as an opportunity for research and development in the current paper.

The rest of the paper is presented as follows. The Industry 4.0 SCs related works and the application of MASs in SCs and their natural applicability as one the enabling technologies in moving towards Industry 4.0 SCs are discussed more specifically in Section 2 together with presenting the research design and contributions of this current work. The constituents of developed MAS approach for sustainable supplier evaluation and selection process is presented in Section 3. This is followed by Section 4 where the implementation details of the developed MAS approach are presented together with the case study results and discussions. Finally, theoretical and managerial implications of the conducted research are discussed in Section 5, with some remarks concluded in Section 6.

2. Literature review and research design

Due to the introduction of digitalization and automation of processes, the entire SC structure can be transformed into a network of physical members which are communicating and exchanging information with each other in real-time, intelligent and autonomous manner aligned with the Industry 4.0 principles defined by Hermann et al. (2016). Within this context, Schlüter and Hetterscheid (2017) highlighted that the digitalization scenarios of various SC processes need to be speeding up and, therefore, developed an application oriented framework aiming to extract relevant technologies within the field of Industry 4.0 mapped to various SC processes. Similarly, Oks, Fritzsche, and Möslein (2017) proposed an application map with the aim of distinguishing various opportunity areas for applying industrial cyber physical systems of Industry 4.0 within which integrated supply chain, and e-procurements and logistics were identified as one of the improvements categories. Hofmann and Rüsch (2017) investigated the potential influences of Industry 4.0 on logistics and presented various Industry 4.0 scenarios of the five defined Kanban characteristics.

From a technical and technological point of view, Ivanov, Dolgui, Sokolov, Werner, and Ivanova (2016) developed a short term SC dynamic scheduling algorithm within the context of smart factories of Industry 4.0. Ben-Daya, Hassini, and Bahroun (2017) performed a literature review on the impacts of IoT of Industry 4.0 on SCM and categorized its application on various SC processes. Tu, Lim, and Yang (2018) proposed a practical IoT-based CPS framework for production logistics and SC applications and adopted a case study of electric sports bicycles. Their developed framework showed competencies in moving towards Industry 4.0 SCs. However, it was concluded that integrating these newly developed technologies within the actual ERP and MES of manufacturing firms still faces many important challenges.

Besides other enabling technologies of Industry 4.0 discussed in Section 1, the applicability of agent technology and MASs as the enabling technologies in moving towards Industry 4.0 was discussed by few researchers contributing in SC and manufacturing research domains (Hermann et al., 2016; Leitão et al., 2016; Monostori et al., 2016; Vogel-Heuser et al., 2014; Wang, Wan, Zhang, Li, & Zhang, 2016). This claim can be justified by investigating more into the inherent characteristics of software agents which are autonomy, social ability, reactivity, and pro-activeness. These main features make them suitable for modeling any type of CPSs within manufacturing and SC domains in which local resources are autonomously managed to achieve global objectives within a network of agents. In particular, the four mentioned design characteristics of Industry 4.0 scenario could be mapped entirely onto the main features of software agents and MASs sharing common grounds.

To address the geography distributed, interactive, and dynamic nature of the supply chain, many researchers have applied MAS technologies in the context of SCM across different industries such as e-commerce SC (Li & Wang, 2007), agri-food SCs (Utomo et al., 2018), petroleum gas SC (Gallab et al., 2017) and automotive SC (Avci & Selim, 2016). Within the SC context, the MAS technology has been applied to address problems in the supplier evaluation and selection process. In a research activity performed by Valluri and Croson (2005), a supplier selection problem was addressed using an agent-based game-theoretic model concerning the existence of partial information from both supplier and buyer members. Soroor, Tarokh, Khoshalhan, and Sajjadi (2012) designed a supplier evaluation agent where Fuzzy Analytical Hierarchy Process (FAHP) and Quality Function Deployment (QFD) were utilized for modeling the agent's internal behavior designated to calculate and rank the suppliers in a collaborative environment. Mohebbi and Li (2012) considered the problem of supplier selection in an e-SC network environment and adopted agent-based simulation model to optimize a multi-objective linear model. Hsu, Kao, Li, and Lai (2016) utilized agent-based technology to facilitate the process of information sharing between suppliers and manufacturers using a fuzzy constraint-directed negotiation model tested using a numerical example of SC planning and scheduling problem. Recently, Yu, Wong, and Li (2017) designed a MAS to integrate the products synergy effects with a multi-product supplier selection model. Li et al. (2018) developed a semantic-augmented MAS for the processes of supplier

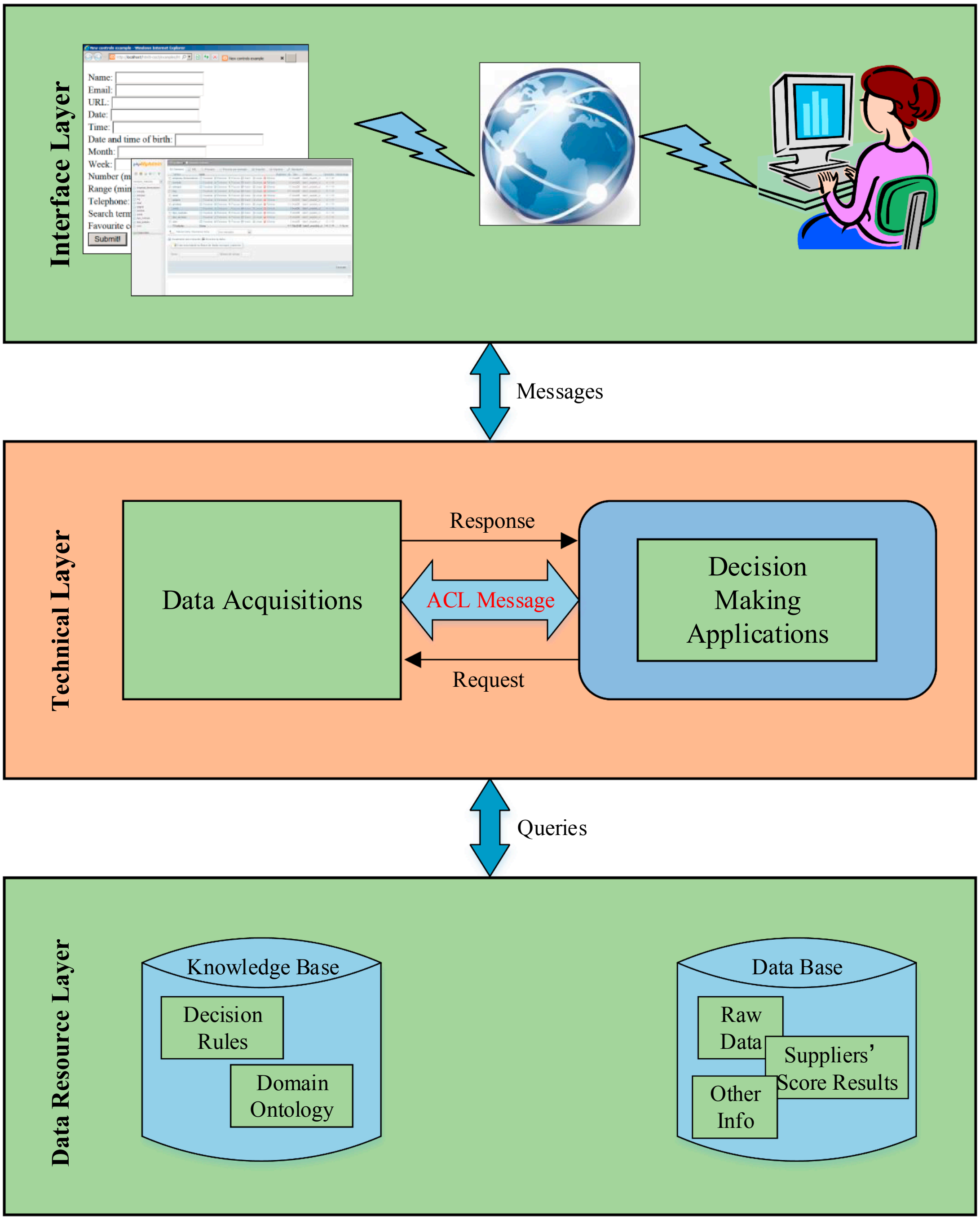

Fig. 1. Three layers system architecture.

selection and research connection in a distributed SC.

Besides, there are few studies that examined the effect of considering environmental and economic dimensions of sustainability into the supplier evaluation and selection problem combined with MASs (Ghadimi et al., 2018; Mishra, Kumar, & Chan, 2012). Hence, research into incorporating sustainability aspects in agent-based supplier evaluation and selection to realize the Industry 4.0 SC environment needs more scholarly attentions and practical demonstrations. Moreover, the reviewed studies that addressed the process of supplier selection using agent-based approach, considered the process as a "once-off" process resulting in adopting a developed evaluation approach to select the most potential suppliers from a pool of candidates (Soroor et al., 2012; Valluri & Croson, 2005; Yu et al., 2017). Using this once-off approach, the selection and evaluation process was often performed at the beginning of a planning period with no further evaluations on suppliers' performance for another period.

Building on the above reviewed works and the identified gaps, the theoretical underpinnings of the current work distinguishes itself from previous literature related to the Industry 4.0 SCs and sustainable supply chain management by proposing a distributed MAS approach for addressing the sustainable supplier evaluation and selection problem where proper information exchange in a prompt and real-time manner can be of great importance. The literature provides little attention on the application of MASs for addressing Industry 4.0 SC scenario with a focus on sustainable supplier evaluation and selection process. In this paper, the adoption of MASs for supply chain systems that are difficult to manage, and coordinate is addressed. An efficient fuzzy inference system (FIS) model has been proposed and incorporated into the

Table 1
The responsibility table of the SA, DBA, and DMA.

Agent	Responsibilities
SA	(1) Serve as user-agent interaction facility to receive supplier's input data.(2) Sends the sustainable supplier evaluation input data to the DBA.(3) Receives a confirmation from the DBA regarding input data being received.(4) Requests the DMA about the results of the evaluation.(5) Receives the sustainability performance score from DMA.
DBA	(1) Receives the supplier evaluation data from the SA.(2) Saves the received data from the SA in the Database.(3) Inform the SA that the sent data is saved.(4) Receives the supplier evaluation input data request from the DMA.(5) Sends the supplier evaluation input data to the DMA.(6) Receives the sustainable supplier evaluation results from DMA and saves them in the database.
DMA	(1) Initiate the supplier evaluation process.(2) Request the evaluation data from DBA.(3) Receive the evaluation data from DBA.(4) Evaluate the suppliers by the proposed sustainable supplier evaluation algorithm.(5) Inform the evaluation results to the DBA.(6) Inform the evaluation results to the involved SAs.

developed MAS approach to model the internal behavior of the decision maker agent integrating the three dimensions of sustainability (environmental, economic and social aspects) in the periodic supplier evaluation process to ensure a seamless continuous evaluation of suppliers' performance toward the defined sustainable sub-themes. The application of the developed MAS architecture has been tested through an assumed scenario in a real-world industry setting adopted from a medical device manufacturer in Ireland and their suppliers around the world.

3. The proposed MAS approach for sustainable supplier evaluation and selection problem

The sustainable supplier evaluation process considered in this study can be described in four steps as follows. (i) Problem formulation: defined the product(s) and components to be supplied; (ii) Sub-theme and influencing factors formulation: identify the required sub-theme and their influencing factors regarding each sustainability dimension. These are usually defined based on manufacturer company's requirements and are utilized in the sustainable supplier evaluation phase. (iii) Requirement gathering: involves the supplier firm's participations in collecting the required data mandated by manufacturer company for the periodic and continuous assessment of each supplier. This information is to be exactly based on the identified IFs in step (ii). (iv) Sustainable supplier evaluation: to quantify each supplier's performance capabilities toward the sustainability dimensions resulting in an evaluation score for each using a proposed evaluation model (detailed in Section 3.2). The multi-agent realization of this entire process is detailed in the following.

To design a valid and reliable MAS, a literature review was performed on identifying MAS development and design methodologies (Adam, Berger, Sallez, & Trentesaux, 2011; Cossentino, Gaud, Hilaire, Galland, & Koukam, 2010; Ghadimi et al., 2018; Leitão & Restivo, 2006; Nikraz, Caire, & Bahri, 2006). These studied methodologies had generic nature and incorporated object-oriented programming into their agent design and implementation steps. In this current paper, the design framework proposed by Nikraz et al. (2006) and Ghadimi et al. (2018) has been adopted. The design and analysis phases of these frameworks are based on the Foundation for Intelligent Physical Agents (FIPA) standards. FIPA compliant JADE (Java Agent Development Framework) platform has been deployed to implement the developed MAS approach in this paper. Sustainable supplier evaluation can be characterized as a dyadic relationship between buyer-seller in a sustainable SC where these two upstream members of SC should collaborate effectively to make better sustainable sourcing decisions. The manufacturing company is regarded as the buyer of this SC sub-process, and respectively the suppliers are distinguished as sellers. In the considered sustainable supplier evaluation problem, there exists one buyer (manufacturing company) who is collaborating with multiple sellers (suppliers). Therefore, this process is considered as a one-to-many interaction. In the proposed MAS, software agents are designed to represent various members (buyer and suppliers) and various functional processes such as requirement gathering and evaluation processes. The architecture of the proposed MAS for the considered sustainable supplier evaluation problem is depicted in Fig. 1.

A three-layer system architecture is used, with the developed architecture consisting of three types of layers, i.e., interface layer, technical layer and data resources layer. The interface layer is about the web/local forms that help the suppliers and manufacturer to update their information regarding the data required for the evaluation process. The database in data resources layer stores each supplier's evaluation input data, the initial setting of the manufacturing company and computation results regarding each supplier's sustainable evaluation performance score. Decision rules and ontologies can also be represented in the data resource layer. The technical layer is interconnected with the other layers to accomplish retrieving the required data and knowledge required to progress the sustainable supplier evaluation process. For more clarifications, the three designed layers are described in the following.

Technical layer: three agents were designed to implement the sustainable supplier evaluation process namely, Supplier Agent (SA), Data Base Agent (DBA), Decision Maker Agent (DMA). The functions and responsibilities of the SA, DBA and DMA agents are described in Table 1. The behavior definition of each agent is then designed using this responsibility table. An agents' behavior is an actual job that it has to do internally.

Interface layer: the interface layer is placed on the top of the other layers in the system. The agent-user interactions can be done by an agent in the designed MAS. The agents that have any type of interactions with users should be identified in the analysis phase and should be expressed in the agent network/diagram by an actor element. Based on this methodology, two means of representing agent-user interactions could be a local Java Swing-based GUI which is an abstract windowing toolkit (AWT) or a web JSP-based (Java Server Pages) GUI. In this layer, an agent-user graphical interface is developed for the SA using Java Swing. This interface is accessed by a human user in any of the supplier's company to input the needed information related to the defined sets of influencing factors related to each sustainability dimension sub-theme.

Data resources layer: The data resources layer is composed of the supplier knowledge base, supplier database, manufacturer database and results database. Manufacturer database is designed to store the specifications and requirement of products and components provided by each supplier for each planning period. Supplier database is associated with storing the periodic evaluation information sent by each supplier with regards to the defined evaluation sub-themes and their influencing factors. Results database stores the calculated results from periodic implementations of the MAS, and finally, supplier knowledge base deals with the supplier evaluation decision rules provided by the manufacturer to be used in the evaluation model.

The MAS realization of the developed architecture for the sustainable supplier evaluation process is done using the JADE platform. The programming environment in JADE platform consists of one more container that can be located on various hosts, often in geographically dispersed firms, leading into establishing distributed networks of physical firms each represented as one or sets of agents. Upon launching the

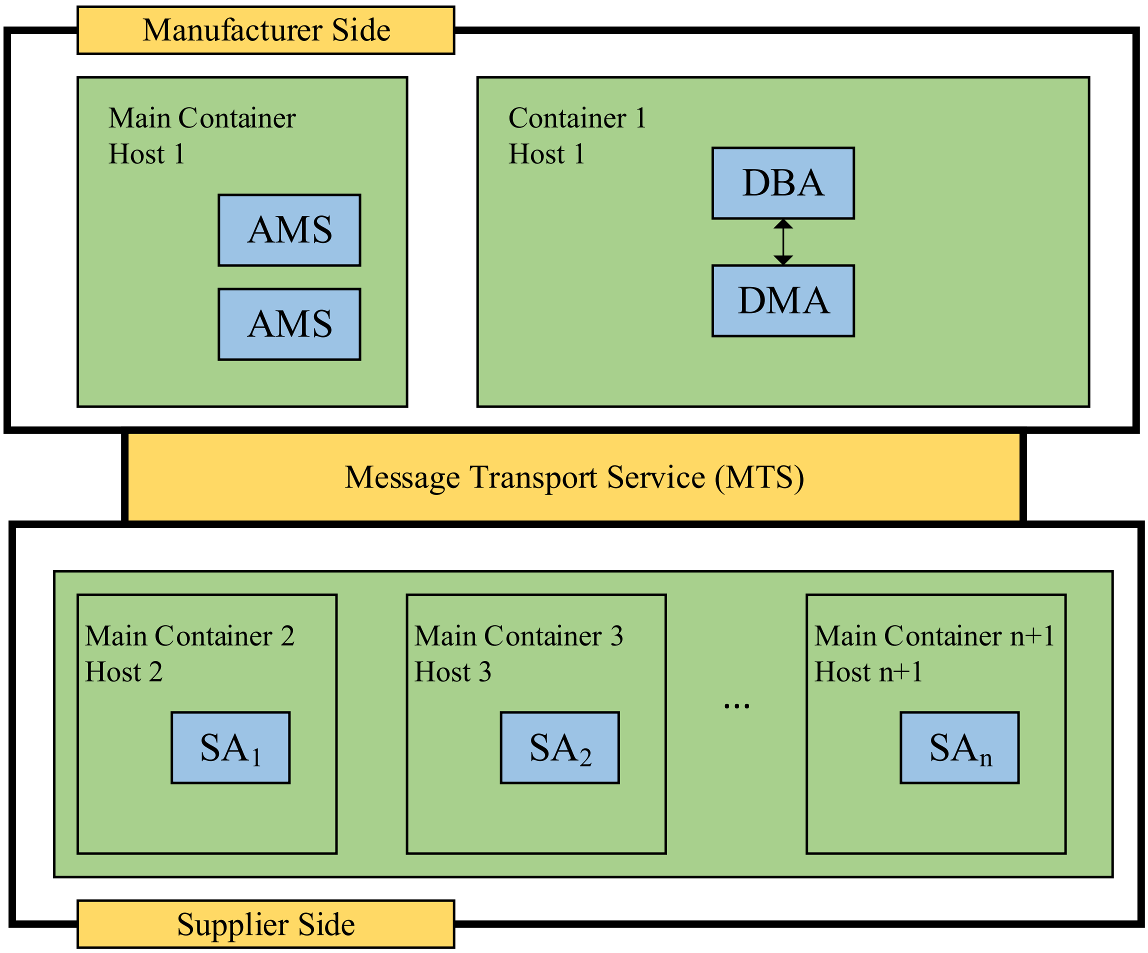

Fig. 2. Configuration of the MAS.

main-container, the JADE platform instantiates the Agent Management System (AMS) agent responsible for supervising the entire platform and also the Directory Facilitator (DF) agent who initiates the yellow pages service offered to other active agents to either access available services registered by other agents or catalogue their own services. Using the distributed capabilities of the JADE platform, the designed MAS approach for the sustainable supplier evaluation problem also consists of the main container and other containers distributed in various hosts over the SC network. Ideally, the main container can be hosted by a manufacturing company, and supplier firms would maintain their own containers connected to the manufacturer's main-container. As illustrated in Fig. 2, the instances of the DMA and DBA containers are located in the manufacturing company nested in the same host where AMS and DF are instantiated but generally in a different container (container 1). The possession of the SA instances is handled by suppliers' organizations each located in different host and container. Agents of the proposed system realize the sustainable supplier evaluation process through message passing. In this research activity, all of the designed agents are embedded in the main container and communicate with each other through the local host established by JADE.

3.1. Agent interaction specifications

The communication and external relationship activities happening among the registered agents are done through some form of specifications and interaction protocols (IPs). Each message content will be encoded and decoded by sender and receiver, respectively. FIPA Agent Communication Language (ACL) specifications, content language representations, and message exchange interaction protocols are utilized to deal with message exchange activities. FIPA Semantic Language (SL), a human readable content language, can be deployed in handling the MAS interactions. In this stage of designing the MAS, an interaction table is produced by mapping each agent's defined responsibilities in Table 1. Each row of Table 1 presents various interactions. The interaction tables related to the SA, DBA, and DMA are presented in Table 2.

After defining the agents' interaction tables, requirement gathering scheme and sustainable supplier evaluation interaction scheme are designed. These schemes enable the agent interaction processes. FIPA interaction protocols can be utilized to implement the developed schemes on the JADE platform. Owing to space limitation of this article, the sustainable supplier evaluation interaction scheme is presented briefly in Fig. 3. FIPA Request and Inform IPs can be used to implement this interaction scheme.

Moreover, the concrete states and semantics of the DMA are displayed in Fig. 4. The external relationships of the DMAs are governed based on this state transition diagram.

3.2. Sustainable supplier evaluation model for the DMA

This sub-section details the developed sustainable supplier evaluation model that governs the internal behavior of the DMA. Each supplier's performance is evaluated according to the evaluation sub-themes and influencing factors (IFs) using a designed FIS model. The FIS model measures the magnitude of IFs and provides a numerical score for each of the sustainability sub-theme leading to an enhanced evaluation process. Moreover, the developed FIS model has the capability to deal with qualitative data where providing a quantitative value for the Ifs would be cumbersome and difficult. These types of qualitative data are

Table 2
Interaction table for the SA, DBA, and DMA.

Agent	Interaction	Responsibility	Interaction protocol	Role	With	When	Template
SA	Acquire the input data provided by a user	2	FIPA Request	Initiator	DBA	The user keys in the input data.	Conversation-ID
	Ask for the sustainable supplier evaluation results	4	FIPA Request	Initiator	DMA	This will happen whenever this agent is up.	Conversation-ID
DBA	Respond to a "save data in database" task	3	FIPA Inform	Responder	SA	The required data are received.	Performative = Request
	Respond to a "retrieve data from the database" task	5	FIPA Inform	Responder	DMA	The request for sustainable supplier evaluation data is received.	Performative = Request
DMA	Retrieve the supplier evaluation data	2	FIPA Request	Initiator	DBA	The user initiates the sustainable supplier evaluation process	Conversation-ID
	Respond to a sustainable supplier evaluation task	5	FIPA Inform	Responder	DBA	The required data are received.	Performative = Request
	Respond to a "send the supplier evaluation result" request.	6	FIPA Inform	Responder	SA	The sustainable supplier evaluation process is done.	Performative = Request

often expressed as opinions based on expert's knowledge which can be converted to linguistic expressions using the FIS model. Accordingly, Mamdani's compositional rule of inference (Mamdani, 1974) is used to design a FIS model that can address uncertainty and lack of magnitude involved with IFs. This contains four stages in the fuzzy evaluation of the input data.

- Fuzzification: Here, the input data being periodically provided by the SA_j are transformed into different grades of membership. A target range, being the maximum or minimum values possible, is set for each of these input variables. These scales range differently for each of the sustainability sub-theme, with each membership function falling within these scales. It is notable that a definitive input variable target ranges are not pre-defined in this proposed FIS and can be defined based on several factors such as decision maker's expert opinions, case country's regulations and region's environmental standards. In this research work, a triangular membership function is incorporated in the proposed FIS model for the input variables. Each input variable will be associated to three types of membership functions based on the defined target ranges namely, low, medium and high.
- Fuzzy rule base: Once the membership functions are created, the rule base governing them is developed. The number of rules can be calculated based upon the Equation (1).

$$R = n^{v} \tag{1}$$

where,
R – Number of potential rules.
n – Number of grades of membership function for input variable.
v – Number of input variables for each sub element.

The knowledge base will be comprised of a series of IF_THEN rules. The influencing factors are combined using IF statements, resulting in a THEN value for the related sub-theme within each sustainability dimension.

- Fuzzy evaluation mechanism: this step is consisted of implication and aggregation stages of fuzzy inference process. The fuzzy conclusion for each rule is defined by the implication process. Various fuzzy operator such as AND, OR and NOT would be utilized as a logical connector to obtain the output of the implication process. Afterwards, these output fuzzy conclusions of each rule are combined into a single fuzzy set as part of the aggregation process. The implication process output functions are used as inputs to the aggregation process. The fuzzified result of each rule will be used as the input to this mechanism. The output of this mechanism is used for the defuzzification process.
- Defuzzification: Using a 0–1 target range, the output membership functions are created, and are low [0 0 0.25], low to medium [0 0.25 0.5], medium [0.25 0.5 0.75], medium to high [0.5 0.75 1] or high [0.75 1 1]. A value of 0 is categorized as low sustainability performance and 1 is categorized as high sustainability performance. The output membership function is the aggregation of the fuzzy inference mechanism results transformed into a crisp output of the supplier evaluation score for each sustainability dimension.

Fig. 5 illustrates the details of the FIS model utilized by the DMA as its internal behavior mechanism which results in the sustainability performance score (sp_i) of each evaluated supplier. Eqs. (2)–(4) calculate the score of each sustainability dimension for each of the considered suppliers. Finally, the calculation of supplier sustainability performance score which is the aggregate value of the three sustainability dimensions weighted scores is performed using Eq. (5).

$$\psi_i = \sum_j w_{s_{ij}} s_{ij} \tag{2}$$

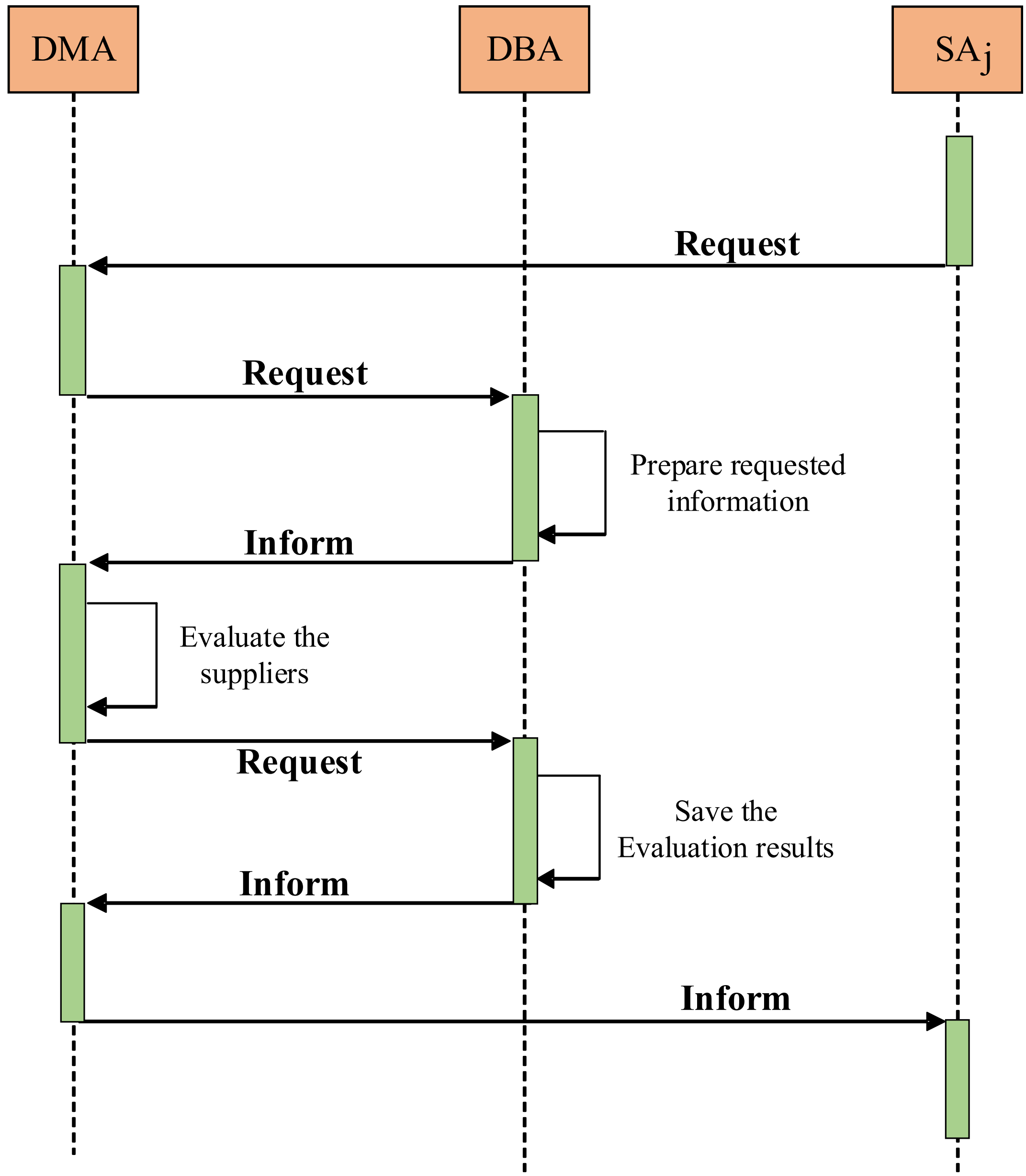

Fig. 3. The sustainable supplier evaluation interaction scheme.

$$Q_i = \sum_j w_{ec_{ij}} ec_{ij} \quad (3)$$

$$E_i = \sum_j w_{en_{ij}} en_{ij} \quad (4)$$

where,

- s_{ij} – supplier i score in j^{th} sub-theme of the social dimension
- ec_{ij} – supplier i score in j^{th} sub-theme of the economic dimension
- en_{ij} – supplier i score in j^{th} sub-theme of the environmental dimension
- ψ_i – supplier i performance score in social sustainability dimension
- Q_i – supplier i performance score in economic sustainability

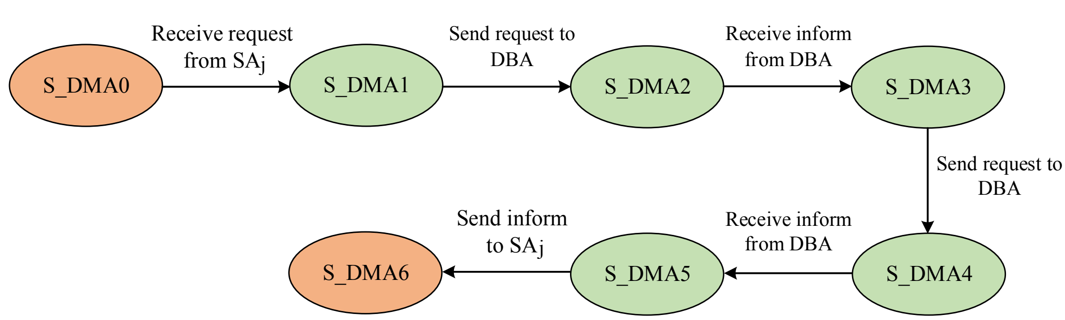

Fig. 4. State transition diagram of the DMA.

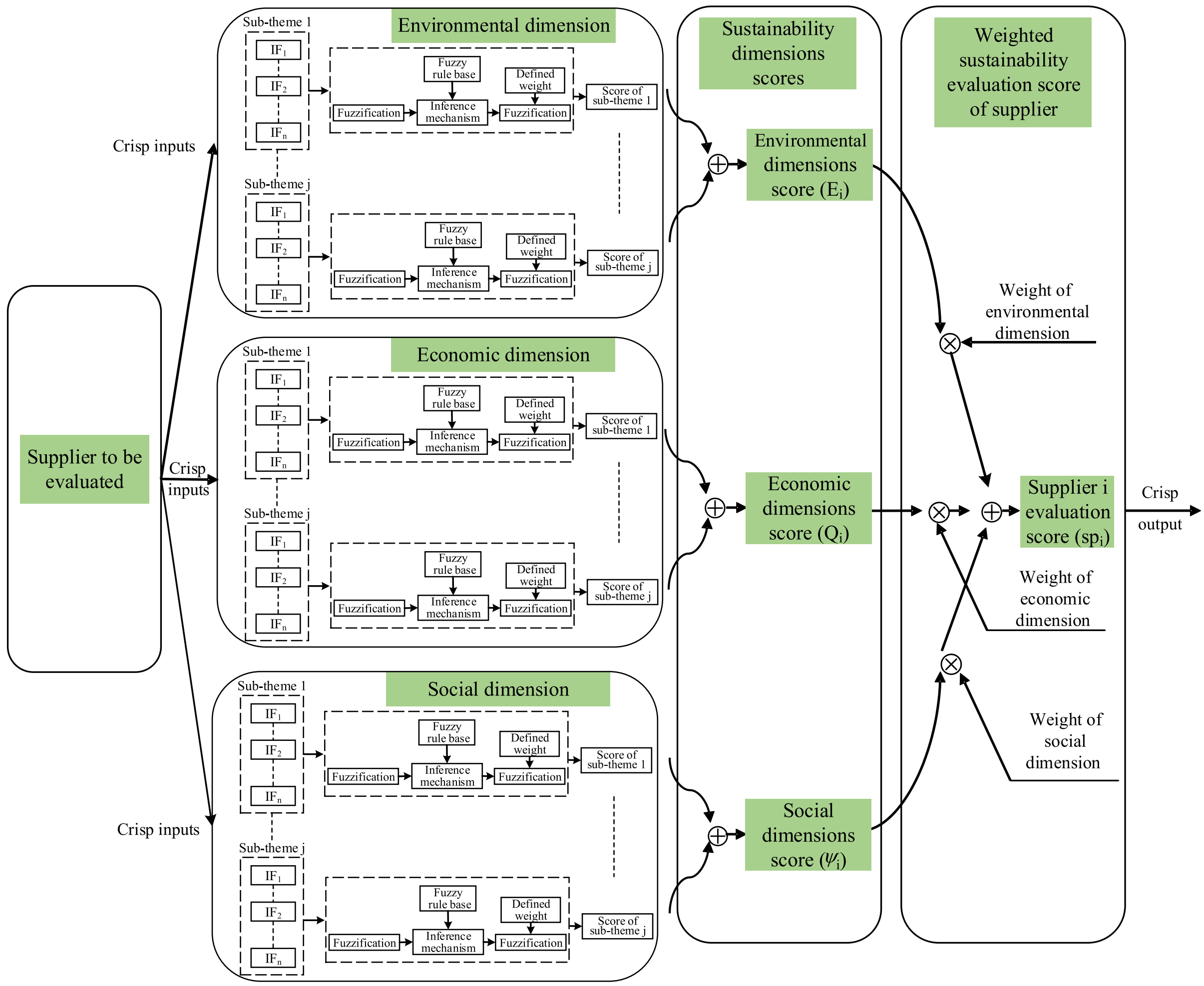

Fig. 5. The DMA's internal behaviour model.

dimension

- E_i – supplier i performance score in the environmental sustainability dimension

$$sp_i = \sum w_{Q_i} Q_i + \sum w_{E_i} E_i + \sum w_{\psi_i} \psi_i \tag{5}$$

where

- sp_i – the sustainability performance score of i^{th} supplier
- w_{Q_i} – the importance weight of economic sustainability dimension
- w_{E_i} – the importance weight of environmental sustainability dimension
- w_{ψ_i} – the importance weight of social sustainability dimension.

Based on the opinion of decision-makers in the manufacturing company, the importance weights can be defined. In some occasions, equal weighting would be defined for all stages of the evaluation that incurs no priority on the sub-theme and sustainability dimensions.

4. Implementation details and results

In this section, a scenario was assumed from a case study in the electronics sector of a medical device manufacturing network to prove the suitability of the developed MAS (Ghadimi and Heavey, 2014). The scenario for this implementation is presented briefly in the following description. In this supply network, a manufacturer is contracted to procure electronic medical devices to an Original Equipment Manufacturer (OEM) who handles the end-customer weekly demands. Nine suppliers are involved in supplying nine different assembly components. Suppliers are in sites in Germany, Taiwan, and the United States. US Food and Drug Administration (FDA) regulates the medical devices market where all companies involved in manufacturing medical devices products need to be complied with ISO13485 including both the OEM and the contract manufacturers. This restricts the contract manufacturer to select its suppliers from preapproved list of suppliers of various required components. This means that the contract manufacturer cannot select any component vendor outside of this list. Therefore, the contract manufacturer will need to improve the performance of the selected suppliers on a continuous manner.

In this paragraph, the description of the assumed scenario for the implementation of the proposed MAS approach is presented. This scenario is based on the presented supply chain network in the previous paragraph. The contract manufacturer establishes a partnership relationship with its suppliers requiring prompt information exchange and accuracy to satisfy the weekly demands. On the other hand, the contract manufacturer forces its vendors to regularly enhance their production activities to produce more sustainable products. Therefore, the suppliers require to provide the evaluation data based on a previously defined weekly basis structure for a planning period of 24 weeks. For illustration purposes, the number of suppliers for procuring components required for assembling the end-product for the OEM are assumed to be three suppliers (Supplier 1, Supplier 2, and Supplier 3) instead of originally nine suppliers in the original case.

4.1. Requirement gathering

The supplier evaluation sub-themes and IFs for each of the sustainability dimensions adopted in this work are related to the medical device manufacturing industry. For instance, environmental sustainability contains three sub-themes namely, green image, pollution control and green competencies. Each of these sub-themes consists of their own IFs. For example, market reputation and customer reputation are IFs related to the green image. Economic sustainability consists of four sub-themes namely, quality, delivery/service, cost and technical capability together with their respective IFs. Finally, health and safety, and employment practices are social sustainability related sub-themes. Owing to the limitation of space, the complete data set (24 planning period) of the information used by the DMA for obtaining the sp_i (sustainability performance of each supplier) values are not presented in this paper. For providing more detailed information, the type of procured data from the associated suppliers and the considered sub-themes and IFs related to each sustainability dimensions are briefly presented in the following.

– Environmental sustainability input data

The input data regarding each of the influencing factors related to the three selected sub-themes (green image, pollution control, and green competencies) of environmental sustainability dimension has been gathered. Table 3 tabulates the environmental sustainability dimension input data for the three potential suppliers that were considered for implementing the MAS approach. As can be seen, most of the input data are provided in a qualitative manner which gives the DMs more flexibility regarding providing input data. Table 4 provides a ranking order of market reputation level, customer reputation level, the level of using hazard materials in manufacturing the requested component, percentages of solid waste in manufacturing 1 KG of the product, level of using recyclable materials in the packaging process and level of capabilities of the supplier companies in committing to green processing. The provided ranking orders in Table 4 were used as input for the fuzzy process and accordingly the developed GUI for each SA instance regarding environmental, economic, and social sustainability dimensions.

– Economic sustainability input data

The input data regarding each of the influencing factors related to the four selected sub-themes of economic sustainability dimension has been gathered. Table 3 tabulates the input data for the three potential suppliers that were considered for implementing the MAS approach. Table 4 provides a ranking order of various influencing factors involved in the economic sustainability dimension.

– Social sustainability input data

Table 3 tabulates the input data for the three potential suppliers that were considered for sustainable evaluation. Table 4 provides a ranking order of various influencing factors involved in the social sustainability dimension. Disciplinary and security practices can be measured as the percentages of total numbers of oral warning, written warning, suspension without pay, transfer to another task, demotion, dismissal over all of the procedures concerning aspects of human rights that are relevant to the organization's operations. Employee training can be measured as the average number of hours that would be spent by the employer to train each employee regarding their awareness of social and cultural sustainability practices.

For verification purposes, the agents' interactions with each other with regards to suppliers 1 and 2 is illustrated in Fig. 6. FIPA Inform and Request interactions protocols are utilized in these interactions. In this implementation, two types of FIPA communicative acts are involved:

- Request: The S1, S2, and S3 send to the DBA to request for storing the input data for sustainable supplier evaluation in the database. This information was gathered using the developed GUI as a means for the user to interact with the supplier agents.
- Inform: The DBA sends the reply to each of the supplier agents (S1, S2, and S3) to inform them that the sustainable supplier evaluation input data are saved in the database.

4.2. Results analysis and discussion

Table 5 presents the sustainable evaluation results for the three suppliers related to 24 evaluation periods. The requirement gathering, and sustainable supplier evaluation models embedded as the internal behaviors of the SAs (supplier agent) and the DMA (decision maker agent) are utilized in obtaining the sustainable performance scores of the supplier 1, supplier 2 and supplier 3 at the beginning of each evaluation week.

As mentioned earlier, stockholders and European laws and legislations force the contract manufacturer to manufacture more sustainable products. Otherwise, the OEM could incur complications in marketing these medical devices to end-customers that are mostly from health sector. The contract manufacturer can consider this matter by forcing its supplier to enahce their operations towards producing more sustainable products. For illustration purposes, it was assumed that the supplier 2 did improve its production operations resulting a decrease in the purchasing price of its procured component from currently 18 dollars to 13 dollars (13th evaluation week onwards). Because of this improvement, a positive effect was experienced on the economic sustainability score of the supplier 2 improving it from 0.437 to 0.5 for the second half of the evaluation periods. Therefore, the supplier 2 sustainability performance score was improved from 0.592 to 0.613. Using the developed MAS tool, the entire supplier evaluation process was implemented over the internet and resulted in managing the cooperation of the geographically disperse suppliers and manufacturers in an automated and digitized manner. The right information was provided to the right supply chain member at its right time and format.

This case application was designed and conducted to prove that the developed MAS tool can contribute towards realizing Industry 4.0 SCs with specific reference to sustainable supplier selection problem. The developed MAS approach has several advantages when compared with previous implementation frameworks in Industry 4.0 SC settings. These advantages are described and mapped into the four design principles for the Industry 4.0 components.

- Interconnection: using MAS technology, upstream supply chain members i.e. suppliers and manufacturer are connected over the internet and via the designed agents. This forms the basis for interactions and collaboration in a jointly manner. Various suppliers and other supply chain members can be added/removed from the network using a designated agent in a modular manner. This enables the presented Industry 4.0 SC to adapt to the dynamic nature of the markets and business environment.
- Real-time information transparency: various agents in the supply chain will send and receive information on real-time and via using pre-defined information exchange protocols. A well-defined message passing structure for exchanging various information among the involved agents adds to the information transparency principle of Industry 4.0.
- Decentralization: the JADE platform and its distributed nature, the capability of agents to communicate with each other on a web server, autonomous decision-making capability of each agent to achieve a local goal supports the decentralization feature of Industry 4.0 SCs. The decentralized, interconnected and real-time decision-making capabilities ultimately contributes to increase the overall SC productivity.
- Technical assistance: one of the objectives of this research study was to illustrate the applicability of MAS in automating the process of sustainable supplier evaluation for the involved Industry 4.0 SC

Table 3
Environmental, economic and social sustainability dimension input data.

Category	Sub-theme	Influencing factor	Unit	Supplier 1 Input	Supplier 2 Input	Supplier 3 Input
Environmental dimension	Green image (GI)	Market reputation (MR)	Qualitative	Medium	Medium	High
		Customer reputation (CR)	Qualitative	Low	High	Medium
	Pollution Control (PC)	Solid waste (SW)	Percentage per 1 kg	7	10	5
		Use of hazard materials (UHM)	Qualitative	Medium	Medium	Low
	Green competencies (GC)	Green packaging (GP)	Qualitative	Medium	High	Medium
		Green process (GPr)	Qualitative	Medium	Medium	High
Economic dimension	Quality (Q)	Document control procedure (DCP)	Qualitative	Medium	High	Medium
		Requirement of Medical Device Directive (MDD)	Qualitative	Medium	High	Low
		Medical device vigilance (MDV)	Qualitative	High	Medium	High
		Internal quality audit (IQA)	Numbers of internal audits per year	2	4	3
	Service/Delivery (SD)	Handling and preservation of product (HPP)	Qualitative	Have but not being implemented completely	Have and being implemented well	Don't have
		Product identification and traceability (PIT)	Qualitative	Have and being implemented well	Have but not being implemented completely	Don't have
		Customer complaint handling (CCH)	Qualitative	Have and being implemented well	Don't have	Have and being implemented well
		Post market surveillance (PMS)	Qualitative	Have but not being implemented completely	Don't have	Have and being implemented well
	Cost (C)	Production (Pr)	Qualitative	Higher than the market average	Market average	Lower than the market average
		Transportation (Tr)	Qualitative	Market average	Higher than market average	Market average
		Ordering (Or)	Qualitative	Lower than the market average	Market average	Lower than the market average
	Technical Capability (TC)	Failure Mode Effects & Critical Analysis (FMECA)	Qualitative	No	yes, but not systematically	Yes
		Technology level (TL)	Qualitative	New	Fairly new	Fairly new
Social dimension	Quality (Q)	Document control procedure (DCP)	Qualitative	Medium	High	Medium
		The requirement of Medical Device Directive (MDD)	Qualitative	Medium	High	Low
		Medical device vigilance (MDV)	Qualitative	High	Medium	High
		Internal quality audit (IQA)	Numbers of internal audits per year	2	4	3
	Service/Delivery (SD)	Handling and preservation of product (HPP)	Qualitative	Have but not being implemented completely	Have and being implemented well	Don't have
		Product identification and traceability (PIT)	Qualitative	Have and being implemented well	Have but not being implemented completely	Don't have
		Customer complaint handling (CCH)	Qualitative	Have and being implemented well	Don't have	Have and being implemented well
		Post market surveillance (PMS)	Qualitative	Have but not being implemented completely	Don't have	Have and being implemented well
	Cost (C)	Production (Pr)	Qualitative	Higher than the market average	Market average	Lower than the market average
		Transportation (Tr)	Qualitative	Market average	Higher than market average	Market average
		Ordering (Or)	Qualitative	Lower than the market average	Market average	Lower than the market average
	Technical Capability (TC)	Failure Mode Effects & Critical Analysis (FMECA)	Qualitative	No	yes, but not systematically	Yes
		Technology level (TL)	Qualitative	New	Fairly new	Fairly new

Table 4
Ranking orders of environmental, economic and social sustainability.

Category	Degree	Ranking
Environmental sustainability	Low	1
	Medium	2
	High	3
Economic sustainability		
a. The ranking order of implementing *document control procedure* in supplier *i*	Don't have	1
	Have but not being implemented completely	2
	Have and being implemented well	3
b. The ranking order of *Meeting Requirements of MDD*	Low	1
	Medium	2
	High	3
c. The ranking order of implementing *medical device vigilance* in supplier *i*	Don't have	1
	Have but not being implemented completely	2
	Have and being implemented well	3
Social sustainability		
a. The ranking order of implementing *OHSAS 18001*	Don't have	1
	Have but not being implemented completely	2
	Have and being implemented well	3
b. The ranking order of the level of *Standardize health and safety conditions*	Low	1
	Medium	2
	High	3

Table 5
Sustainability performance values for supplier 1, 2 and 3 for 24 evaluation periods (weeks).

	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
sp_1	0.499	0.499	0.499	0.499	0.499	0.499
sp_2	0.592	0.592	0.592	0.592	0.592	0.592
sp_3	0.705	0.705	0.705	0.705	0.705	0.705
	Week 7	Week 8	Week 9	Week 10	Week 11	Week 12
sp_1	0.499	0.499	0.499	0.499	0.499	0.499
sp_2	0.592	0.592	0.592	0.592	0.592	0.592
sp_3	0.705	0.705	0.705	0.705	0.705	0.705
	Week 13	Week 14	Week 15	Week 16	Week 17	Week 18
sp_1	0.499	0.499	0.499	0.499	0.499	0.499
sp_2	0.613	0.613	0.613	0.613	0.613	0.613
sp_3	0.705	0.705	0.705	0.705	0.705	0.705
	Week 19	Week 20	Week 21	Week 22	Week 23	Week 24
sp_1	0.499	0.499	0.499	0.499	0.499	0.499
sp_2	0.613	0.613	0.613	0.613	0.613	0.613
sp_3	0.705	0.705	0.705	0.705	0.705	0.705

members. It was demonstrated that how software agents can be assigned to assist the users in suppliers and manufacturer firms. The utilization of developed MAS approach reduced the weekly involvement of the human resources that was required in the case application.

- Continuous sustainable performance evaluation: the proposed FIS

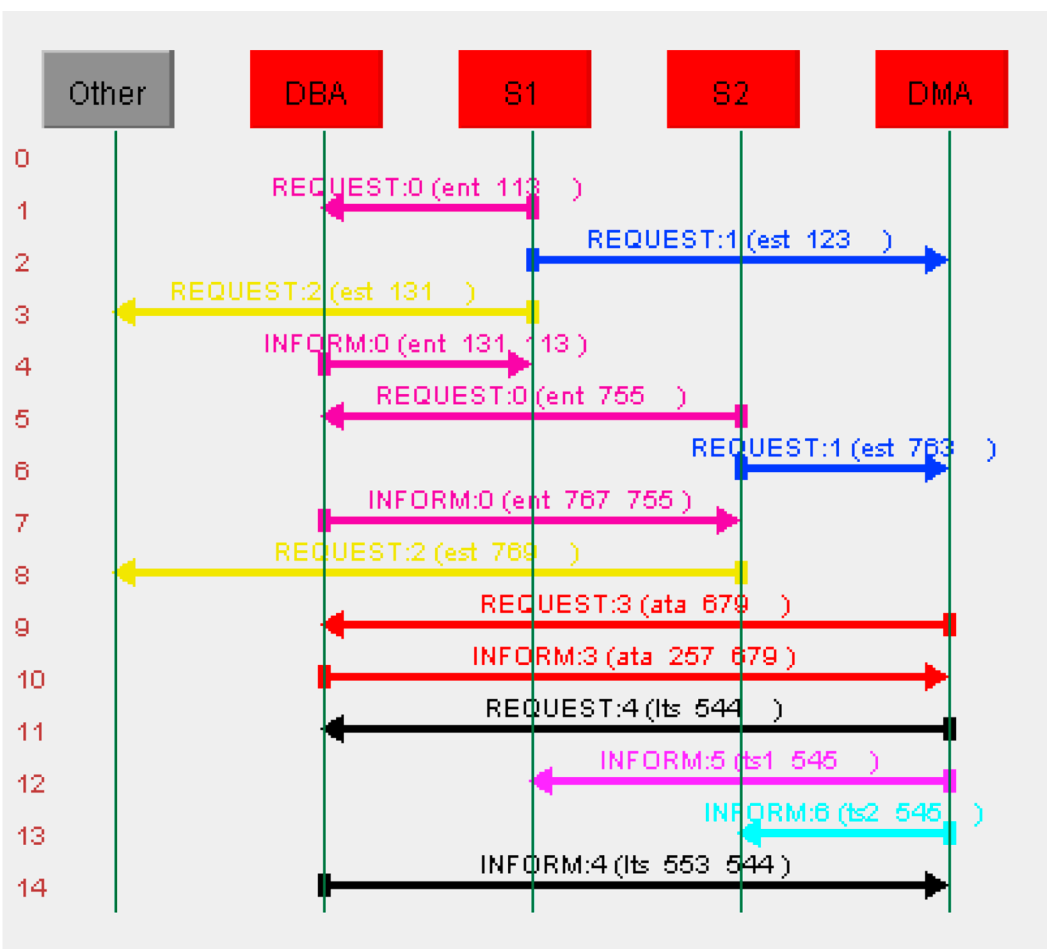

Fig. 6. Sustainable supplier evaluation interaction scheme tracing diagram.

approach has considered the ambiguity of existing selected influencing factors. The final supplier score provides a numerical magnitude of how well/bad the suppliers are performing towards sustainability TBL. This can be utilized in the order management decision making activities resulting in ordering higher quantities to the more sustainable suppliers on a weekly basis.

Finally, it is possible that larger instances of suppliers can be handled by the developed MAS tool. An agent can be registered to the networks of agents on JADE as the realization of a new supplier. The new supplier agent will then start to send and received messages with the DMA and DBA agents to perform its internal behavior. The developed interaction schemes would be utilized by each new supplier agent and the DMA to perform the periodic process of sustainable supplier evaluation. The new supplier data and evaluation results will then be saved by the DBA.

5. Theoretical implications and managerial insights

This research article contributes to the Industry 4.0 SCs and sustainable supply chain management literature by adopting the four design principles of Industry 4.0 originally developed in manufacturing (Hermann et al., 2016) and considering the same principles on an SC scenario using a MAS approach. The theoretical underpinning of the current work aims to justify the use of agent technology as one of the enabling technologies in moving towards Industry 4.0 SCs. Towards this end, the sustainable supplier evaluation and selection problem were addressed using a proposed MAS approach to automate and enhance this process providing information exchange accuracy and facilitated communications channels between these two members of a typical SC. In the literature of Industry 4.0 and manufacturing applications, the use of technologies such as IoT and radio-frequency identification (RFID) approaches in manufacturing and production are currently widely discussed topics, which aims to connect physical and cyber world wherein the machines, systems and products virtually and independently exchange and respond to information for managing end-to-end processes (Babiceanu & Seker, 2016; Monostori et al., 2016; Tu et al., 2018). However, the complexity of supply chain management, in general, is one of the major bottlenecks of the field (Ivanov et al., 2016). Understanding such complexity and processing appropriate information to corresponding supply chain partners play a critical factor to operate a smart supply chain. Decentralization, information readiness, and prompt information exchange channels, as some of the important principle of Industry 4.0, can be regarded as key criteria to enhance supply chain performance.

Building on these principles, the inherent characteristics of the software agents and the relevance of MASs as a proper means for managing information systems associated with SC members as a decentralized network of physical entities provides immense opportunities on extending the implications of Industry 4.0 and agent technology towards achieving a digital SC. The introduction of multi-agent technology, the utilization of its distributed, autonomous, mobile, intelligence and self-learning capabilities leads to the digitalization of SC processes such as sustainable supplier evaluation and selection process (Ghadimi et al., 2018; Li et al., 2018). In the current research activity, it is demonstrated that the developed MAS approach has the potential to provide interoperable and decentralized network system resulting in prompt information exchange between suppliers and manufacturer with considering the supplier evaluation process with regards to sustainability aspects. From a theoretical point of view, the developed MAS tool justifies the applicability of MAS technology in addressing the design principles of Industry 4.0 SCs focusing specially on supporting the sustainable supplier evaluation process.

From the managerial point of view, the findings obtained from the experimental and implementation results of the MAS-based Industry 4.0 SC prototype has demonstrated that the proposed approach can be applied on real world supply chain settings where various suppliers are geographically dispersed. Accordingly, the work in this article provides insights into the implementation steps of a continuous supplier evaluation mechanism serving as a proper tool for SC managers and industrial practitioners in a SC, specially the upstream members, to exchange appropriate information in an interoperable and decentralized manner within their supply network aligned with Industry 4.0 design principles. As final managerial remark, the merits of Industry 4.0 enabling technologies, such as the one discussed in this paper, in enhancing industrial management are being currently addressed by scholars and industrial practitioners. However, the ethical and legal aspects of the new working environments that these technologies create in terms of reduced human interactions within a digitalized SC and manufacturing settings must yet be addressed comprehensively.

6. Conclusions and future works

The application of multi agent technology as one of the enabling technologies for Industry 4.0 SCs with specific consideration of supplier evaluation and selection problem has been reported in this paper. The inherent characteristics of the software agents such as distribution, autonomy, mobility, intelligence, and self-learning have been utilized to address the issues of information readiness and poor communications channels between manufacturers and suppliers along the process of continuous and periodic supplier evaluation. An efficient FIS model has been developed and utilized as the internal behavior of the decision maker agent who holds the responsibility on evaluating the geographically dispersed suppliers in a periodic manner (weekly in the case application) resulting in reduced human interaction and time utilization along the entire process. The inherent subjectivity and uncertainty involved in sustainability evaluation information can be regarded as a justification of developing such evaluation method based on fuzzy-set theory. As a result of such implementation, the suppliers need to continuously advance their operations toward sustainability principles requested by the manufacturer to ensure their competitive advantage.

As future work, the capability of the proposed MAS architecture in being adaptable to other technologies already existing in a manufacturer's or supplier's company such as Enterprise Resource Planning (ERP) systems and Manufacturing Execution System (MES) can also be investigated aiming at incorporating dynamic system conditions in real-time which is a fundamental principle in moving towards Industry 4.0. Although the proposed tool reduces the human interaction along the process, the requirement gathering phase of the framework is still being done manually. Accordingly, the integration capability of agent technology with other technologies within industry 4.0 domain such as IoT and more specially RFID to automate and enhance the requirement gathering phase of the developed framework along the entire supply network is regarded as another future work on this Industry 4.0 SCs domain. With the recent dominance of sustainability considerations, most of the SC processes are transformed into sustainable processes. As future work, more academic research is required to draw scholarly and industrial practitioners' attentions on the incorporation of sustainability in Industry 4.0 SCs and manufacturing. Research activities are required to highlight the challenges and opportunities that the fourth industrial revolution (Industry 4.0) can cause and provide for sustainable consumption and production activities within manufacturing firms and along their entire SCs.

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