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Highlights:

- The sustainable supplier selection and order allocation problem is considered.
- The issues in establishing long-term buyer-supplier relationships are addressed.
- A multi-agent system approach is proposed to address the identified gap.
- The applicability of the approach is tested by a real-world case application.

A Multi-Agent Systems Approach for Sustainable Supplier Selection and Order Allocation in a Partnership Supply Chain

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Abstract

Recently, incorporating sustainability into the buyer-supplier sourcing decisions has achieved a considerable amount of attentions among researchers and industrial enterprises who are attempting to move towards sustainable production. Moreover, by investigating further in the buyer-supplier relationships, the literature suggests that proper communication and structured information exchange are important components in establishing a long-term partnership and maintaining such a relationship. Toward this end, a Multi-Agent Systems (MASs) approach is proposed as a mean of automating and facilitating the process of sustainable supplier selection and order allocation (SSS&OA) resulting in a more co-operative partnership. This research shows that financial performance of manufacturing companies adopting environmental and social sustainability in their operations strategy enhanced their competitive advantage that can lead to long-term sourcing relationships for the buyer-supplier dyad. Additionally, it was also shown that applying MASs to the SSS&OA problem can be utilized as an approach to facilitate communications and automate information exchange processes in Supply Chains (SCs) where suppliers and manufacturer are looking to maintain a long-term SC partnership. The applicability of the developed MAS approach and its incorporated sustainable supplier evaluation and order allocation models is demonstrated using an adopted practical scenario from an industrial case study operating in the electronics sector in medical device industry.

Keywords: Multi-agent systems, supply chain management, sustainability, sustainable supplier selection, order allocation

1 Introduction

Almost every decision to be made in the management of supply network are affected by supplier evaluation and selection (Tan *et al.*, 2011; Mishra *et al.*, 2012; Ghadimi and Heavey, 2014; Brandenburg *et al.*, 2014; Fazlollahtabar, 2016). Besides, the lot-sizing problem, firstly introduced by Wagner and Whitin (1958) to deal with sourcing decisions, is also among the most important challenges that most firms are faced with (Rezaei and Davoodi, 2012). Recently, many researchers tried to combine the supplier selection and order lot-sizing problems in order to align various strategies that are available for buyers (Weber *et al.*, 2000; Aissaoui *et al.*, 2007; Demirtas and Üstün, 2008; Songhori *et al.*, 2011; Fazlollahtabar *et al.*, 2011; Şenyiğit, 2012; Tavana *et al.*, 2012; Azadnia *et al.*, 2015; Sodenkamp *et al.*, 2016; Ghadimi *et al.*, 2017). The supplier selection and order allocation problem considers qualitative and quantitative criteria and influencing factors for supplier selection, and product purchasing and inventory costs for order allocation, and utilizes mathematical modelling techniques to incorporate the constraints of the combined systems (Mafakheri *et al.*, 2011; Rezaei and Davoodi, 2012; Jaehn, 2016).

Recent awareness and advancements in sustainable supply chain management (SSCM) has motivated many researchers and industrial practitioners to practice the integration of sustainability Triple Bottom Line (TBL) attributes (environmental, economic and social) in production and supply

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chain activities of manufacturing organizations (Seuring and Müller, 2008). By manufacturing organizations focusing on the SSCM, traditional supplier selection approaches which considered mostly price and quality in the supplier evaluation process have also been affected (Degraeve and Roodhooft, 1999) in that sustainability practises have been incorporated into their supply chain and manufacturing activities leading to a more competitive edge in the market. As a result, the traditional supplier selection and order allocation problem has now been transferred into a sustainable supplier selection and order allocation problem where environmental and social measures and influencing factors are incorporated in the selection and sourcing processes (Azadnia *et al.*, 2015).

Responding to the diverse customer demands requires buyer's ability to link and work effectively and efficiently with suppliers which makes the buyer–supplier relationship to become critical for all organizations in a SC (Prahinski and Benton, 2004; Mettler and Rohner, 2009). An important factor in achieving a succescful and profitable supply chain and less uncertainty and increased information flow relies on establishing a supply chain parnership (Fiala, 2005). Co-operation is an importatnt element in charactrizing todays buyer-supplier relationship models. In contrast with the competitive environment in the past, more up-to-date models deemed to be focusing on more operative intearctions and high amount of information exchange resulting into joint efforts in value creation and total cost reductions (De Toni *et al.*, 1994; Cho *et al.*, 2012). Developing long-term cooperative relationships with critical suppliers are emphasized by managers and practitioners in today's business environment (Soh et al., 2016). A partnership requires building a solid and powerful foundation, which can be sustainable based on suppliers with competitive potential and effective management. At present, many enterprises have reduced the number of suppliers and have developed a partnership with competitive potential suppliers (Han, 2013).

In their partnership model, Lambert *et al.* (1996) stated that an appropriately managed and established partnership among buyers and suppliers should eventually improve performance for both parties. Better communication in a partnership supply chain was emphasized by many researchers as one of the influencing factors in establishing a long term partnership among the suppliers and buyers (Ellram and Cooper, 1990; Mohr and Nevin, 1990; Lambert *et al.*, 1996; Fiala, 2005; Li and Lin, 2006; Bhagwat and Sharma, 2007; Lambert, 2008; Trapero *et al.*, 2012; Wei *et al.*, 2012; Wu *et al.*, 2012; Zarandi and Avazbeigi, 2012; Han, 2013; Gabler *et al.*, 2014). In a literature review conducted by Jain *et al.* (2009) regarding the buyer-supplier relationships, it was highlighted that integration of supply chain functions regarding the buyer-supplier relationships will be possible through use of advanced communication technology that allows the real-time flow of information among the participating members. Wei *et al.* (2012) concluded that partner co-operations, information technology (IT) based exchange relationships and information integration can contribute to the performance achievements in a supply chain.

Towards this end, agents can be established as stand-alone entities to perform certain capabilities. However, in most cases, an individual agent may not be able to solve complex problems. It is necessary to combine multiple interacting agents to accomplish complex tasks more effectively (Giannakis and Louis, 2011; Proch *et al.*, 2017). A multi-agent system (MAS) can be defined as a loosely-coupled system composed of multiple interacting agents that work collectively through cooperation or competition to solve problems that would be beyond their individual capabilities (O'Hare and Jennings, 1996). In MASs, agents can provide reliability and robustness, and can be modularized and scaled as required. They have concurrent and parallel operation capabilities, and are usually heterogeneous and geographically distributed (Jennings *et al.*, 1998). MASs are especially suitable for application domains that are modular, distributed, dynamic and complex. Many agent-based industrial distributed systems have been developed to support automatic and dynamic collaborations for systems with distributed and complex behaviours (Camarinha-Matos *et al.*, 2009; Wu and Barnes, 2011; Yeung, 2012; Negahban *et al.*, 2014; Kumari *et al.*, 2015).

In this research study, the use of MASs for such supply chain systems that are complex and difficult to monitor, manage and coordinate is highlighted. To date, the literature provides little guidelines on the application of MASs for addressing sustainable sourcing decisions where appropriate information flows and exchange of the correct information in a structured manner is an important element. There is limited research on addressing an integrated problem of sustainable supplier selection and order allocation and a lack of guidelines for DMs of how to incorporate the emerging sustainability paradigm in their sourcing decisions.

The rest of this paper is organized as follows. Section 2 provides more details on the problem under study and also our research design in order to address the problem. Section 3 introduces the proposed MAS approach for SSS&OA process and its various constituents. The computational elements in this MAS approach are the sustainable supplier selection and order allocation sub-models which are presented in Section 4. Experiments are conducted in Section 5 to prove the capability and applicability of the proposed MAS for the SSS&OA problem using numerical representation of a real-world case study in a medical device sector. Section 6 discusses research findings together with various theoretical and managerial implications of the current research activity. Finally, some remarks are concluded and topics for future works are presented in Section 7.

2 Problem statement and research design

There are many studies that investigated the effect of incorporating environmental and economic aspects of sustainability into the process of supplier selection (Mafakheri et al., 2011; Ghadimi *et al.*, 2013; Kannan *et al.*, 2014; Brandenburg *et al.*, 2014; Girubha *et al.*, 2016; Fallahpour *et al.*, 2017; Yazdani *et al.*, 2017; Jauhar and Pant, 2017). Besides, few studies have also considered the social aspect of the TBL in the process of supplier selection either combined with environmental and economic dimensions or in a separate manner (Amindoust et al., 2012; Dai and Blackhurst, 2012; Azadnia et al., 2015). However, the number of research activities that tried to address the sustainable supplier selection problem, with an integrated consideration of sustainability issues in the process of supplier evaluation and multiple products and multiple sourcing order allocations, are still in an early stage and limited (Ghadimi et al. 2016a; Zimmer et al., 2016).

The agent technology has been applied by a number of researchers to address issues in the buyer-supplier relationships. In a well-known research activity conducted by Valluri and Croson (2005), a game-theoretic supplier selection model was developed where neither the suppliers nor the buyer possesses full information. Reinforcement learning (RL) was utilized in an agent named "leaner agent". Soroor et al. (2012) developed an evaluation agent that utilizes the concepts of Quality Function Deployment (QFD) and Fuzzy Analytical Hierarchy Process (FAHP) to calculate the final rankings of suppliers. Wang et al. (2012) designed an ontological intelligent agent platform to establish an ecological virtual enterprise (VE). The developed platform helps supply partners and manufacturer to communicate with each other in a coordinated manner within a VE platform. Mohebbi and Li (2012) proposed an agent-based e-supply network system that uses a multi-objective linear model in order to maximize the profit of buying an optimal amount of items from supplier. Recently, Yu and Wong (2014) designed a MAS in order to incorporate the synergy effect between products in a multi-product supplier selection model.

To our knowledge, none of the above works considered the TBL attributes in their model. Besides, there is no research study that investigates the applicability and suitability of the MASs on the problem of SSS&OA in enhancing the communication and information exchange components of a partnership type relationship supply chain. The primary contribution of this work is to develop a MAS approach for sustainable supplier selection and order allocation problem in order to provide better communication and structured information exchange processes which helps the industrial

practitioners and decision-makers inside manufacturing organizations to make better sustainable sourcing decisions in more prompt and less human-interacting manner resulting in maintaining a long-term partnership among manufacturer and its suppliers.

3. The constituents of the proposed MAS approach for SSS&OA

The SSS&OA process starts with the manufacturing company where the required products will be determined to be procured from potential suppliers. Then, the manufacturer company will be asked to formulate their desirable supplier evaluation criteria regarding the TBL attributes. Thereafter, the proposed MAS model utilizes two sub-models i.e. supplier evaluation sub-model and order allocation sub-model. As depicted in Figure 1, the main objective of the sustainable supplier evaluation sub-model is to utilize the proposed Fuzzy Inference System (FIS) model in order to evaluate the sustainability performance of the potential suppliers. On the other hand, the order allocation sub-model is to obtain the optimal order quantities.
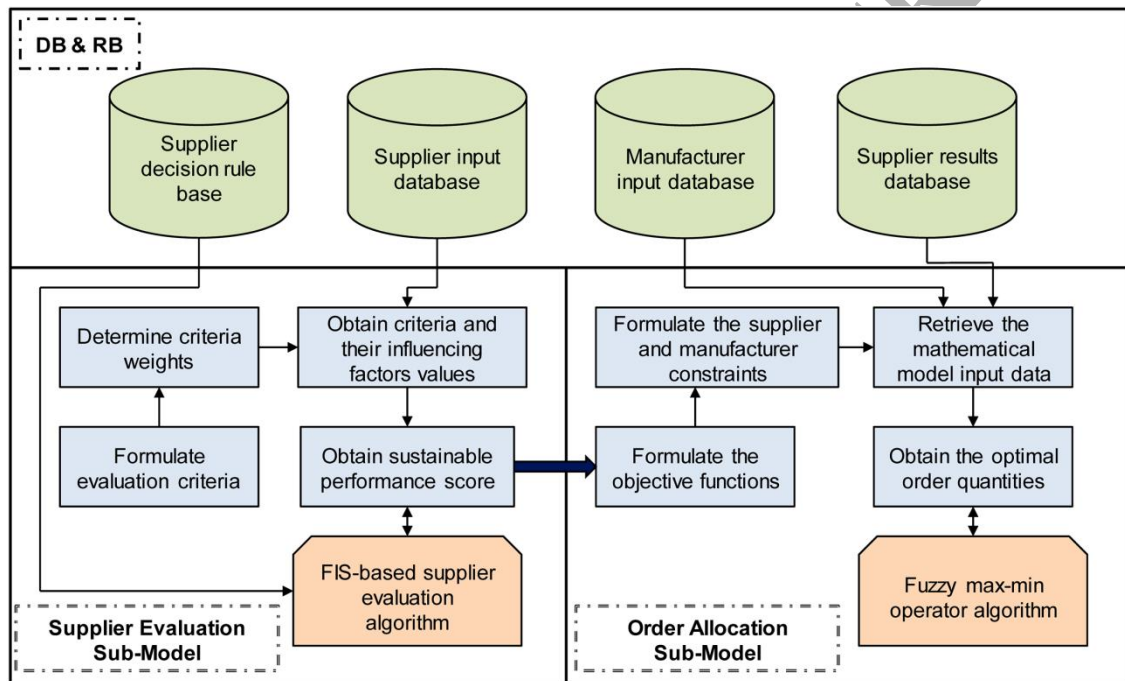
Figure 1. The sustainable supplier evaluation and order allocation sub-models.

3.1 MAS design methodology

Multi-agent technology has become a feasible solution for large-scale industrial and commercial applications. Brazier *et al.* (1997) highlighted that the developers and system designers need to make sure that a developed MAS is robust, reliable and fit to purpose. Therefore, following a rigorous design methodology capable of providing broad a priori specification of the agents can facilitate the analysis and design processes. Jennings *et al.* (1998) developed a general analysis and design methodology called "Gaia methodology" to help an analyst to systematically design a detailed and easy to implement MAS from a statement of requirements from a real system. Leitão and Restivo (2006) proposed a MAS design architecture called ANACOR in order to provide an environment for knowledge and skills distributions together with the capability to adapt to environment changes. Adam *et al.* (2011) developed a framework called HoloMAS using roles to provide an adaptive control system that can be applied on manufacturing systems.

In this current paper, the methodology in Nikraz *et al.* (2006) has been followed. The analysis and design phases of this methodology are based on the Foundation for Intelligent Physical Agents (FIPA) standards. Identification and refinement of agent types are performed in the analysis phase by applying a number of considerations. These considerations are: (i) support: which is related to check how, when and where is the required information retrieved/stored. (ii) discovery: which defines how each agent is going to find the other agents. Naming convention and yellow pages mechanism are two easily implementable approaches to solve the agent discovery problem. Each of these approaches has their own benefits and limitations. (iii) management and monitoring: where some agents need to be tracked or created on demand (Nikraz *et al.*, 2006).

3.1.1 Agents in the proposed MAS

The proposed MAS comprises agents that represent various functions and parties in the SSS&OA process. Four types of agents are defined: Data Base Agent (DBA), Supplier Agent (SA), Decision Maker Agent (DMA) and Order Allocator Agent (OAA). Agents involved in the supplier evaluation sub-model are the SAs, DBA and DMA; agents involving in the order allocation sub-model are SAs, DBA and OAA. A network of agents is modelled for the proposed MAS as shown in Figure 2. In this diagram, the actual agent types are represented as web services. People that must interact with the system are represented by a UML actor symbol. As instructed in Nikraz *et al.* (2006), the functions and responsibilities of these agents are defined in the analysis phase and are described in Table 1. This responsibility table is then utilized in defining the agents' behaviour(s). An agent behaviour is the actual job that it has to do internally.

Table 1. The responsibility table

Agent	Responsibilities	Agent	Responsibilities
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 order allocation input data request from the OAA. 7) Sends the order allocation input data to the OAA. 8) Receives the sustainable supplier evaluation results from DMA and saves them in database. 9) Receives the order allocation results from OAA and saves them in database.	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 evaluation. 5) Receives the sustainability performance score from DMA. 6) Requests the OAA about the results of order allocation. 7) Receives the optimal order quantities from the OAA.
OAA	1) Initiate the order allocation process. 2) Request the order allocation data from DBA. 3) Receive the order allocation data from DBA. 4) Calculates the optimal order quantities using the order allocation mathematical model. 5) Request the order quantities to be saved to in the database by DBA.	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

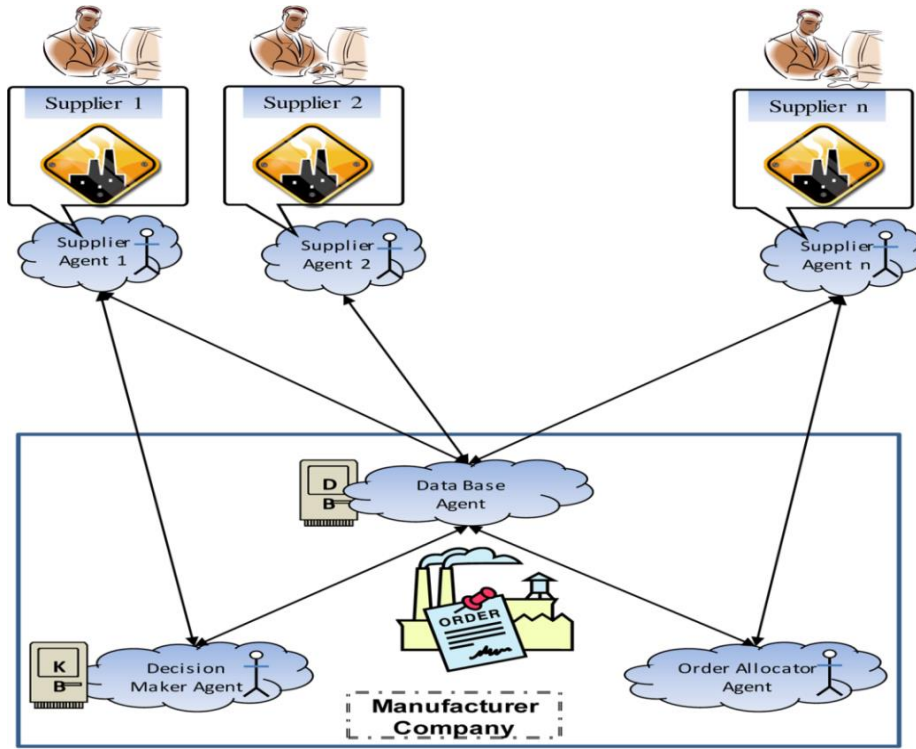| 6) Inform the allocation results to the involved SAs.	DBA. 6) Inform the evaluation results to the involved SAs.

Figure 2. The network of agents

3.1.2 Agent Interactions Specification

The external relationships of agents are mostly specified through a form of communication and interaction with each other. The message contents can be mostly encoded and decoded by sender and receiver. Agent Communication Language (ACL) messages can be based on FIPA Agent Communication specifications. Besides, the MAS interactions can be performed using FIPA Semantic Language (SL) content language which is a human-readable string-encoded content language.

In this step of the MAS design phase, all various responsibilities defined for each agent in the agent responsibility table (Table 1) are mapped into an interaction table produced for each agent. Various interactions are presented in each row of the table providing information about: (1) The interaction descriptive name. (2) The responsibility that originates this interaction which makes sure that the analysis artefacts are consistence with the design artefacts. (3) An interaction protocol (IP) that is suitable for implementing the interaction. (4) The role that the agent will fulfil in the IP which can be either Initiator (I) or Responder (R). (5) Name and type of the other agent that is fulfilling the role in conjunction with the agent in consideration. (6) A descriptive presentation of the condition that an agent triggered. (7) A message template to receive incoming messages based on the conversation ID (Conv-id) in the agent behaviours that are implementing an initiator role. Table 2 shows the interaction table for the DMA.

Table 2. Interaction table for the DMA

Interaction	Resp.	IP	Role	With	When	Template
Retrieve the supplier	2	FIPA	I	DBA	The user initiates	Conv-id

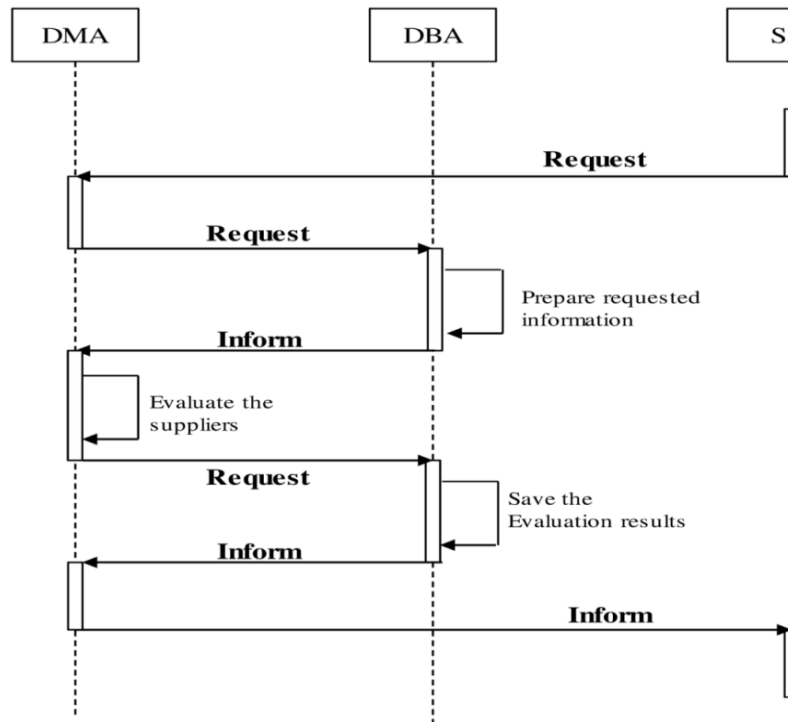| evaluation data		Request			the sustainable supplier evaluation process	
Respond to a sustainable supplier evaluation task	5	FIPA Inform	R	DBA	The required data are received.	Performative = Request
Respond to a "send the supplier evaluation result" request.	6	FIPA Inform	R	SA	The sustainable supplier evaluation process is done.	Performative = Request

Figure 3. Sustainable supplier evaluation interaction scheme

After defining the interaction tables for each of the agents, three interaction schemes which are requirement gathering scheme, sustainable supplier evaluation interaction scheme and order allocation interaction scheme are proposed to support the sustainable supplier evaluation and order allocation process. These schemes are implementable by the FIPA interaction protocols which are provided by the JADE platform. The sustainable supplier evaluation scheme is presented in this paper for illustration purposes. The sustainable supplier evaluation interaction scheme governs the interaction of agents supporting the sustainable supplier evaluation sub-model. It is used to evaluate the suppliers in order to allocate order quantities of the multiple required products based on the TBL attributes. This interaction scheme is depicted in Figure 3. In JADE, this interaction scheme can be implemented by the FIPA Request Interaction Protocol (IP) and FIPA Inform IP.

4 Computational elements in the proposed MAS approach for sustainable supplier selection and order allocation

In this section, the two main analytical modelling sub-models of the developed MAS approach are explained. The first sub-model (Section 4.1) deals with evaluating the suppliers that are contracted with manufacturing organization towards sustainability TBL attributes and the second sub-model (Section 4.2) deals with allocating optimal order quantities based on evaluated suppliers'

sustainability performance by considering the objectives, total purchasing cost, and the suppliers' sustainability performance value. The sustainable supplier evaluation sub-model is utilized as the internal behaviour activity of the DMA and the order allocation sub-model is used as the internal behaviour activity of the OAA. In Sections 4.1 and 4.2, the detail algorithm and solution approach of these sub-models are described.

4.1 Sustainable supplier evaluation sub-model

The functions of this sub-model involve; formulating the evaluation criteria and their influencing factors for each dimension of sustainability (environment, economic and social); determining criteria weights; obtaining the influencing factors' values; and calculating the suppliers' sustainability performance score based on the defined evaluation criteria and influencing factors. These functions support the internal activity of the DMA and SAs. This calculation is based on a Fuzzy Inference System (FIS) model (Ghadimi and Heavey, 2014; Ghadimi *et al.*, 2017) that has been designed and implemented on a case study in the medical device sector. The details of the designed FIS for sustainable supplier evaluation together with the justification of utilizing such approach are presented in the following.

The proposed FIS is applicable to this research work as it can provide a way to the managers characterizing the inputs (influencing factors) and the decision threshold (supplier's sustainability performance score). The FIS process simplifies the suppliers' performance evaluation process by fuzzifying the magnitude of influencing factors and quantifies each of the sustainability sub-criteria by providing a single number score in order to show the level of performance of each of the suppliers towards each of the sustainability dimensions and their respective sub-criteria. As a result, the proposed FIS approach increases the degree of aggregation of the identified influencing factors (Gagliardi et al., 2007; Herva et al., 2012; Hesami *et al.*, 2013) into defuzzification value which can result in an enhanced selection process leading to select the suppliers that are taking initiatives towards incorporating sustainability principles into their operations and manufacturing activities. Moreover, in many industries or organizations, some activities are very complex in nature where providing a quantitative metric for them would not be possible or would be cumbersome, therefore, these metrics can be expressed qualitatively using linguistic expressions defined by the experts' opinion and knowledge in the field. Another important characteristic of the proposed FIS could be its capability to deal with quantitative and qualitative influencing factors simultaneously.

4.1.1 The designed fuzzy inference system (FIS)

In this research, Mamdani's compositional rule of inference (Mamdani, 1974) has been applied to build the proposed FIS model. It consists of four operational steps that are described in the followings.

(a) Fuzzification: this is the step performed to assess the input data. Gathered crisp data are converted into grades of membership. Purchasing manager or a CEO inside the organization sets these grades of membership based on the importance and criticality of input variables. Next, a target range is to be set for each input variable. A target range would be the minimum and maximum values that the input variable value can obtain. The source of selecting a target range might be various depending on the nature of the input variable. A common source for defining a target range could be set by local authorities, the manufacturer and national agencies. These target ranges are then utilized in constructing the membership functions. In this FIS model, three fuzzy sets are applied for the inputs that are the influencing factors. The linguistic rating variables assigned to each of these fuzzy sets are "low", "medium" and "high" as shown in Fig. 4. The input variables membership function developed

for the proposed FIS is considered using a triangular form. A triangular form fuzzy number can be shown as $\tilde{T} = (a, b, c)$ and defined as Equation 1.

$$\mu_{\tilde{M}} = \begin{cases} 0, & x < a, \\ (x-a)/(b-a), & a \leq x \leq b \\ (c-x)/(c-b), & b \leq x \leq c \\ 0, & x > c \end{cases}$$
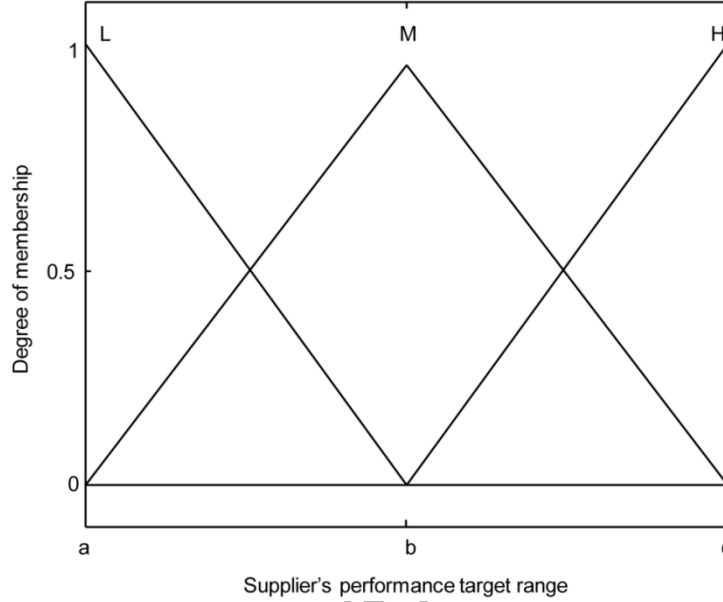
Eq. 1

Figure 4. Membership function for each criterion

(b) Knowledge base (rules): the rule base will be defined after the input variables membership functions are constructed based on DMs' knowledge inside the organization. The number of rules in the fuzzy rule base can be calculated based on Equation 3 (Cornelissen et al., 2001):

$$R = n^v$$

Eq. 2

where the numbers of the input variables membership function are represented by n and v is the number of input variable for each criterion and R stands for the number of potential rules. Knowledge base will be populated with a series of IF-THEN rules where various influencing factors are combined with each other to form the IF part and THEN part of the respective criterion.

(c) Fuzzy inference mechanism: the inputs for this fuzzy mechanism are the fuzzified result of each rule and the output of this mechanism will be used as an input for the defuzzification process.

(d) Defuzziefication: the output membership functions are constructed using zero to one target range. The zero value is an indication of a low sustainability performance while one is interpreted as a high sustainability performance. This membership function is set out for aggregating the results of the fuzzy inference mechanism into crisp output which would be the supplier performance score towards the measured criterion. In the developed FIS model, five fuzzy sets of membership functions are applied for the output variable that is, each of the criteria. The linguistic rating variables assigned to each of these fuzzy sets are "low", "low to medium", "medium", "medium to high" and "high" as shown in Figure 5.
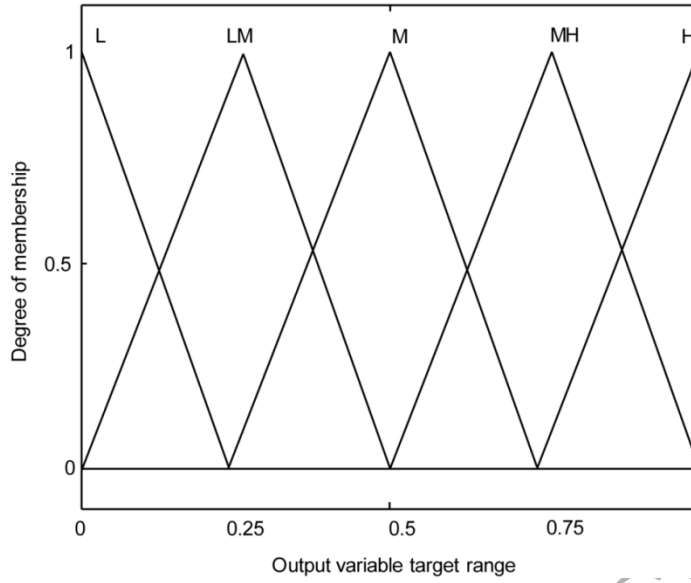
Figure 5. Membership function for defuzzification process

The output results of the defuzziefication are the scores of the defined criteria regarding the evaluated supplier. In the next step, these scores are utilized in the calculation of supplier sustainability performance score (Equation 6) which is the aggregate value of the criteria scores using Equation 3, Equation 4 and Equation 5:

$$\psi_i = \sum_j w_{s_j} s_{ij} \qquad \text{Eq. 3}$$

$$q_i = \sum_j w_{ec_j} ec_{ij} \qquad \text{Eq. 4}$$

$$E_i = \sum_j w_{en_j} en_{ij} \qquad \text{Eq. 5}$$

where,

s_{ij} Value of supplier i in j^{th} criterion of social dimension calculated by the FIS

ec_{ij} Value of supplier i in j^{th} criterion of economic dimension calculated by the FIS

en_{ij} Value of supplier i in j^{th} criterion of environmental dimension calculated by the FIS

w_{s_j} Weight of jth criterion of social dimension

w_{ec_j} Weight of jth criterion of economic dimension

w_{en_j} Weight of jth criterion of environmental dimension

q_i Score of supplier i in economic sustainability dimension

E_i Score of supplier i in environmental sustainability dimension

ψ_i Score of supplier i in social sustainability dimension

$$sp_i = \sum w_{ec} q_i + \sum w_{en} E_i + \sum w_{so} \psi_i \qquad \text{Eq. 6}$$

where sp_j is the sustainability performance score of jth supplier. w_{ec} is the importance weight of economic sustainability dimension, w_{en} is the importance weight of environmental

sustainability dimension and w_{so} is the importance weight of social sustainability dimension.

Defining the importance weights in calculating q_i, E_i, ψ_i and sp_j is an option that can be considered by manufacturer company as they might want to consider equal weighting for all stages of the evaluation which means there would be no priority on the criteria and sustainability dimensions. The jFuzzyLogic open source Java library (Cingolani and Alcalá-Fdez, 2013) is utilized for performing the designed FIS which provides a programming interface (API) and an Eclipse plugin in order to allow integration with the JADE platform.

4.2 Order allocation sub-model

The function of this sub-model is to support the order allocation process between the OAA and the SAs resulting in obtaining the optimal order quantities regarding each supplier. This function is performed by developing a bi-objective programming model. The proposed model was developed to deal with a sustainable supplier selection problem with multiple products and multiple sourcing decisions in a required decision period. The constituents of the order allocation mathematical model are presented in the following sub-section. Owing to the space limitations, further details of the bi-objective function mathematical model and its solution approach are not presented in this paper and are available in Ghadimi et al. (2016b) (published by the authors of current research work).

4.2.1   Decision variables and indices

n	Number of suppliers
m	Number of products
i	Product indices
j	Supplier indices
X_{ij}	Numbers of product i allocated to supplier j.

$Y_j \begin{cases} 1 & \text{if an order allocated to supplier } j \\ 0 & \text{otherwise} \end{cases}$ for all j

4.2.2   Parameters

V_{ij}	Capacity of jth supplier for i^{th} product.
P_{ij}	Purchasing price of product i delivered by supplier j.
d_i	Total demand of product i.
T_{ij}	On-time delivery rate of product i offered by supplier j.
t_i	Manufacturer's minimum acceptable on-time delivery rate of product i.
η_{ij}	Defective rate of product i delivered by supplier j.
η_i	Manufacturer's maximum acceptable defective rate of product i.
o_j	Fixed ordering cost for supplier j.
o_j'	Variable ordering cost for supplier j.
tc_j	Transportation cost of supplier j per vehicle.
n_j	Number of vehicles assigned for supplier j.
v_j	Vehicle capacity for supplier j in *KG*.
ψ_i	Weight occupied by each unit of product i in KG.

s_i Space occupied by each unit of product i in m^3.

S Manufacturer's total storage capacity in m^3.

h_i Holding cost ratio of product i.

sp_j Sustainability performance value of supplier j calculated in Section 4.1.

4.2.3   Bi-objectives functions

- Total purchasing cost (TPC)

$$Min \ Z_1 = \sum_{i=1}^{m}\sum_{j=1}^{n} P_{ij} X_{ij} + \sum_{j=1}^{n} o_j Y_j + \sum_{i=1}^{m}\sum_{j=1}^{n} o_j' X_{ij} + \sum_{i=1}^{m}\sum_{j=1}^{n} h_i P_{ij}(X_{ij}/2) + \sum_{j=1}^{n} tc_j n_j$$

Eq. 7

where:

$$n_j = \frac{\sum_{i=1}^{m} \psi_i X_{ij}}{v_j} \qquad \forall j \in n \qquad \text{Eq. 8}$$

- Supplier's sustainability performance value (SSPV)

$$Max \ Z_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} sp_j X_{ij} \qquad\qquad \text{Eq. 9}$$

4.2.4   Operational constraints

- Demand constraint

$$\sum_{j=1}^{n} X_{ij} = d_i \qquad \forall i \in m \qquad\qquad \text{Eq. 10}$$

- Supplier capacity constraint

$$X_{ij} \le V_{ij} \qquad \forall i \in m, \forall j \in n \qquad\qquad \text{Eq. 11}$$

- Quality constraint

$$\sum_{j=1}^{m} \eta_{ij} X_{ij} \le \eta_i d_i \qquad \forall i \in m \qquad\qquad \text{Eq. 12}$$

- Delivery constraint:

$$\sum_{j=1}^{n} (1 - T_{ij}) X_{ij} \le (1 - t_i) d_i \qquad \forall i \in m \qquad\qquad \text{Eq. 13}$$

- Manufacturer Storage Capacity

$$\sum_{i=1}^{m}\sum_{j=1}^{n} s_i X_{ij} \le S \qquad\qquad \text{Eq. 14}$$

In this current research, GAMS 24.1.2 has been utilized to optimize the developed order allocation bi-objectives mathematical model to identify the optimal order quantities to the evaluated sustainable suppliers. In order to be able to utilize GAMS inside the JADE environment, the GAMSJavaAPI was used providing the possibility of using GAMS execution libraries in in order to perform optimization tasks.

5 Implementation and experimental results

In this section, we adopted a practical scenario from an industrial case study operating in the electronics sector in medical device industry. The main motivation of such adoption is to demonstrate the applicability of the developed MAS approach using a real supply chain structure along with relevant supply chain policies such as the frequency of demand fulfilments. From the perspective e of a manufacturer, satisfying market demand on time and with the right quantity can be considered as one of the main factors in maintaining the competitive advantage in the market (Mirzapour *et al.*, 2011). Therefore, we decided to study the applicability of the proposed MAS approach for the SSS&OA process in a situation where different sourcing decisions need to be taken based on variable demands for each planning period. The description of the case study and our assumed scenario for this experiment is presented in the Section 5.1 adopted from Lanning (2014).

5.1 Case study description

The case study focal partner is a contract manufacturer, who was contracted to supply electronic devices to an Original Equipment Manufacturer (OEM). The OEM, as part of a wider product offering runs a healthcare diagnostics, monitoring and management division broken down into 6 subdivisions, one of which sells 9 different product types in the area of diabetes monitoring. The end-item modelled in this case study was one of these monitoring kits. The contract manufacturer is motivated to meet demand but is also motivated by a desire to analyse and refine the inventory control policies to reduce their costs. Information was obtained from both the plant general manager and the inventory planning manager in one of the company's European production facilities. On the supply side there were 9 suppliers furnishing 9 different component types. Suppliers were located in areas such as Germany, Taiwan and the United States. Each of the suppliers was contracted for a single component for this unit. The market for medical devices is quite highly regulated, particularly by the US Food and Drug Administration (FDA) and both the OEM and contract manufacturer were ISO13485 compliant. One of the consequences of this was the establishment of a turnkey arrangement in the supply chain. According to the contract manufacturer this involved accepting a list of preapproved vendors of component parts as being a requirement of assenting to the contract. The arrangement constrained the contract manufacturer's ability to seek out component suppliers which it may determine as best for business from its point of view. However, the contract manufacturer will seek to improve the performance of the selected suppliers.
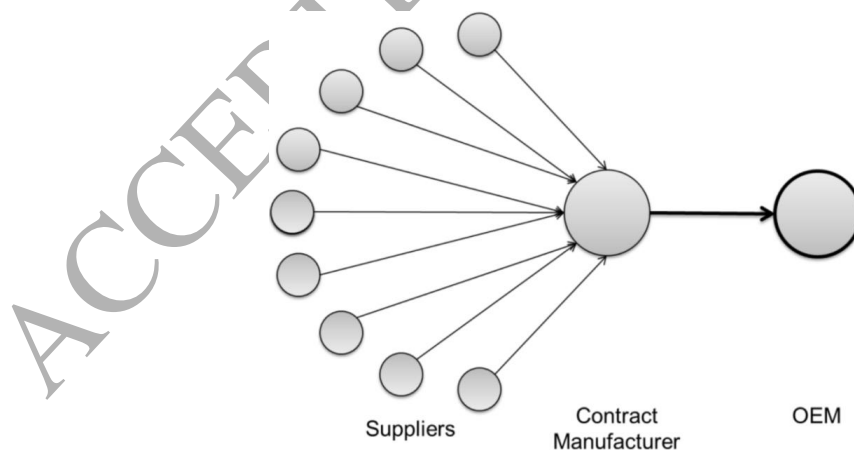

Figure 6. Case study sourcing network (Adopted from Lanning (2014))

The contract manufacturer places an order with its suppliers on a weekly basis. A period or week is defined as 5 working days. These orders will be placed 1 week ahead of their required scheduled launch to production at the contract manufacturer regardless of lead time to supplier. Demand for the

unit was just over 10% of the total annual demand of units sold by the OEM and is approximately 1.31 million units per year. This was based upon a 52-week production year, demand per week was simply averaged at 25,208 (D) units per week as of the current OEM delivered long term forecast. The OEM had expressed its primary concern to the contract manufacturer in terms of "robustness of supply under unpredictable demand contingencies", and the risk of not meeting demand. Figure 6 shows the network of the suppliers, the contract manufacturer and the OEM in this case study.

In their demand data analysis section, Lanning (2014) used the demand data provided by the contract manufacturer and identified the type of distribution. Using a series of tests on the provided data sets such as goodness of fit test using the Minitab statistical software, it was indicated that the Gamma distribution could be an appropriate probability distribution to model the demand at the contract manufacturer. Apart from defining the type of distribution, the shape and variability characteristics such as coefficient of variations (CV) was also studied. CV refers to the relationships that exist between a distribution's standard deviation and its mean (Walsh *et al.*, 2008). The Gamma distribution probability density function is defined as (Yeh *et al.*, 1997):

$$f(x) = \frac{(\alpha x)^{\beta-1}}{\Gamma(\beta)} \alpha e^{-\alpha x}, \quad 0 \le x < \infty \qquad \text{Eq. 15}$$

where

$$\Gamma(\beta) = \int_0^\infty t^{\beta-1} e^{-t} dt \qquad \text{Eq. 16}$$

where α is the scale parameter, β is he shape parameter and $\Gamma(\beta)$ is the gamma function evaluated at β. Table 3 tabulates the input parameters for generating random Gamma demand values. These inputs are characterized based on various CV values which defined the level of variability in demand output values. The CV of zero means that the demand values are deterministic and the demand outputs generating from CV of one have the most variability.

Table 3. Gamma inputs for scale and shape parameters (Lanning, 2014)

Mean value required	α	β	CV value required	Mean value required	α	β	CV value required
25208	1.20	21006.67	0.01	25208	4000.00	6.30	0.40
25208	10.00	2520.80	0.02	25208	4604.00	5.48	0.43
25208	20.00	1260.40	0.03	25208	5000.00	5.04	0.45
25208	50.00	504.16	0.04	25208	5104.00	4.94	0.45
25208	250.00	100.83	0.10	25208	6000.00	4.20	0.49
25208	500.00	50.42	0.14	25208	6302.00	4.00	0.50
25208	750.00	33.61	0.17	25208	7000.00	3.60	0.53
25208	1000.00	25.21	0.20	25208	7500.00	3.36	0.55
25208	1151.00	21.90	0.21	25208	8000.00	3.15	0.56
25208	1276.00	19.76	0.22	25208	9000.00	2.80	0.60
25208	1875.00	13.44	0.27	25208	10000.00	2.52	0.63
25208	2000.00	12.60	0.28	25208	11000.00	2.29	0.66
25208	1575.50	16.00	0.25	25208	15000.00	1.68	0.77
25208	2500.00	10.08	0.31	25208	18416.00	1.37	0.85
25208	3000.00	8.40	0.34	25208	22000.00	1.15	0.93
25208	3500.00	7.20	0.37	25208	25208.00	1.00	1.00

5.2 Experiment Scenario

In this section, the description of the assumed scenario for this experiment is presented. We use the real case description presented in the previous section as the base line of this assumed scenario. As stated in Section 5, the main objective in developing a scenario is to demonstrate that the research conducted in this paper has the capability to be applicable in an industrial application.

In this experiment, similar to the case description in the previous section, the contract manufacturer places an order with its suppliers on a weekly basis. For illustration purposes, a six month planning horizon consisting of 24 planning periods (weeks) is considered in this experiment for procuring the components for the contract manufacturer. As the suppliers are dictated from the OEM to the contract manufacturer based on a list of preapproved suppliers, therefore, the manufacturer cannot select new and possibly more capable suppliers to work with based on its own preferences. Consequently, the contract manufacturer and the suppliers established a partnership relationship that requires a high level of information exchange due to the weekly demands that needs to be satisfied. Besides, the contract manufacturer also wants its suppliers to constantly improve their operations towards sustainability TBL as they are members of a medical device manufacturing supply chain that see as a requirement to manufacture more sustainable products. Therefore, it is assumed that the suppliers need to provide their evaluation inputs based on a predefined structure on a weekly basis.

For illustration purposes, the numbers of suppliers for procuring the two components (component A and B) required for assembling the end-user product to be shipped to the OEM are assumed to be three suppliers (S1, S2 and S3) (originally nine components were required to be sourced from nine suppliers in the case study described in the previous sub-section). The weekly demands are generated for each of these two components using the EasyfitXL software for the CV = 0.5, α = 6302.00 and β = 4.00 (extracted from Table 3). This CV provides variability in the weekly demand inputs. Table 4 tabulates the randomly generated Gamma inputs for the demands of component A and component B on a weekly basis for 24 weeks (6 months).

Table 4. Weekly demand inputs

Week no.	Component A	Component B	Week no.	Component A	Component B
1	24760	25260	13	25160	25500
2	25535	24895	14	25285	25435
3	25140	25330	15	24910	25045
4	24990	25100	16	25205	25355
5	25280	25600	17	24890	25200
6	24365	24610	18	25530	25645
7	25280	25230	19	25520	25130
8	25045	25450	20	24760	24580
9	25650	25150	21	25205	24845
10	25140	24805	22	25255	25045
11	25770	24910	23	25570	25315
12	25565	25400	24	25340	25035

The supplier evaluation criteria and influencing factors for each of the sustainability dimensions adopted in this experiment are explicitly related to medical device sector extracted from Ghadimi and Heavey (2014) tabulated in Table 5. Moreover, Table 6 shows the input data that could be provided by the three suppliers for planning period 1 (week 1). These input data are utilized for sustainable supplier evaluation sub-model. Besides, Tables 7 and 8 provide the assumed input data required for the developed mathematical model for the order allocation sub-model related to planning period 1 (week 1).

Table 5. Dimensions, sub-criteria and influencing factors

Dimension	Criterion	Influencing factor
Environmental sustainability	Green image	Market reputation
		Customer reputation
	Pollution control	Solid control
		Use of hazard materials
	Green competencies	Green packaging
		Green process
Economic sustainability	Quality	Document control procedure
		Requirement MDD
		Medical device vigilance
		Internal quality audit
	Delivery/Service	Handling and preservation of product
		Product identification and traceability
		Customer complaint handling
		Post market surveillance
	Cost	Production
		Transportation
		Ordering
	Technical capability	Failure Mode Effects & Critical Analysis
		Technology level
Social sustainability	Health and safety	Safety audit and assessment
		OHSAS 18001
	Employment practices	Training
		Disciplinary and security practises

Table 6. Input data for sustainable supplier evaluation for week 1

Supplier	Input data					
	Environmental sustainability					
	Green image		*Pollution control*		*Green competency*	
	Market reputation	Customer reputation	Solid waste	Use of hazard materials	Green packaging	Green process
S1	2	1	7	2	2	2
S2	2	3	10	2	3	2
S3	3	2	5	1	2	3
	Economic sustainability					
	Quality				*Technical capability*	
	Document control procedure	Requirement MDD	Medical device vigilance	Internal quality audit	FMECA	Technology level
S1	2	2	3	2	1	3
S2	3	3	2	4	2	2
S3	2	1	3	3	3	2
	Service/delivery					
	Handling and preservation of product	Product identification and traceability	Customer complaint handling	Post market surveillance		
S1	2	3	3	2		
S2	3	2	1	1		
S3	1	1	3	3		
	Cost					
	Production	Transportation	Ordering			
S1	3	2	1			

S2	2	3	2		
S3	1	2	1		

Social sustainability

Health & safety | | | | *Employment practices* |

	Safety audit and assessment	OHSAS 18001	Standardize health and safety conditions	Disciplinary and security practices	Employee training
S1	5	2	2	5	15
S2	7	2	3	8	25
S3	6	3	3	5	35

Table 7. Data related to the components for week 1

Product(i)	t_i	η_i	w_i	s_i	h_i
Component A	0.92	0.02	0.38	0.0012	0.01
Component B	0.92	0.02	0.101	0.0005	0.021

Table 8. Other input data for week 1

Parameter	Product(i)	Suppliers		
		S1	S2	S3
V_{ij}	Component A	9500	9500	10500
	Component B	10000	10000	10000
P_{ij}	Component A	15	18	10
	Component B	12	13	12
η_{ij}	Component A	0.02	0.01	0.025
	Component B	0.02	0.01	0.25
T_{ij}	Component A	0.95	0.90	0.92
	Component B	0.95	0.90	0.92
o_j		15	15	15
$o_j^{'}$		0.1	0.12	0.09
tc_j		215	230	190
v_j		480	480	480
$S = 100$				

5.3 The MAS approach implementation steps and results

Agents involving in the MAS model are the DMA, DBA, OAA, S1, S2 and S3. The implementation procedure of the MAS model for sustainable supplier evaluation and order allocation is summarized as follows:

Figure 7. Supplier agent GUI

- Step 1: at the beginning of the first planning period, the three suppliers' designated agents (S1, S2 and S3) are registered in the JADE platform. These three agents *request* the input data provided by user to be saved in the database by DBA. The DBA receives this request, and then *inform* the S1, S2 and S3 as a confirmation that the data has been saved in the respective databases. These databases are realized in MySQL database management software. Figure 7 shows the GUI that is designed for the users in three supplier companies to interact with their designated agents. At the same time, these three agents send a *request* message to the DMA asking for the sustainable supplier evaluation results and also another *request* message to the OAA to provide the optimal order quantities

- Step 2: the DBA receives the data saving request by the S1, S2 and S3 and after saving their provided data sends *inform* message back to them.

- Step 3: The DMA receives the S1, S2 and S3 requests from step 1, and then through a user-agent interaction GUI the DMA initiates the sustainable supplier evaluation process by sending a *request* to the DBA to acquire the needed data. The acquired information from the database containing the sustainability influencing factors values needed for evaluating the suppliers is retrieved by the DBA and sent to the DMA by an *inform* message (see Table 6 as an illustration of these input data). The DMA then executes the proposed FIS-based sustainable supplier evaluation algorithm introduced in Section 4.1 to evaluate the suppliers. Figure 8 (generated from JADE platform runtime) is a sample of the message content that is passed between the DBA and DMA.

```
(REQUEST
 :sender  ( agent-identifier :name DMA@192.168.0.102:1099/JADE
 :addresses (sequence http://74LDM74J.ul.campus:7778/acc ))
 :receiver  (set ( agent-identifier :name DBA@192.168.0.102:1099/JADE ) )
 :content  "SupplierData"
 :reply-with  request11435659052679
 :protocol  fipa-request
 :conversation-id  "Evaluation Data" )

(INFORM
 :sender  ( agent-identifier :name DBA@192.168.0.102:1099/JADE
 :addresses (sequence http://74LDM74J.ul.campus:7778/acc ))
 :receiver  (set ( agent-identifier :name DMA@192.168.0.102:1099/JADE
 :addresses (sequence http://74LDM74J.ul.campus:7778/acc )) )
 :content  "SupplierData"
 :reply-with  DMA@192.168.0.102:1099/JADE1435659056257
 :in-reply-to  request11435659052679
 :protocol  fipa-request
 :conversation-id  "Evaluation Data" )
```

Figure 8. An example of message exchange between the DBA and DMA

- Step 4: Then, the DMA *requests* from the DBA to save the supplier evaluation results into the related database. The DMA then *informs* the suppliers' sustainability performance scores to the SA_j as it was requested in the beginning of the process. The results will be utilized as one of the inputs for implementing the order allocation mathematical model (see Section 4.2). Table 9 tabulates the output results of this step related to 24 weeks. For instance, sp_1 for week 1 indicates the sustainability performance value of supplier 1 at the beginning of the first planning week which is 0.499.

Table 9. Sustainability performance values for S1, S2 and S3 for 24 planning periods (weeks)

Supplier sustainable performance values					
sp_j	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

- Step 5: The OAA receives the S1, S2 and S3 requests from step 1, and then through a user-agent interaction GUI the OAA initiates the order allocation process by sending a *request* to

the DBA to acquire the needed data. The acquired information from the database containing the suppliers' sustainability influencing factors values, the products price, demand and etc. needed for performing the order allocation is retrieved by the DBA and sent to the OAA by an *inform* message (see Tables 7 and 8 as an illustration of these retrieved data). The OAA then executes the bi-objectives order allocation mathematical model introduced in Section 4.2 to calculate the optimal order quantities to be allocated to each supplier.

- Step 6: Then, the OAA *requests* from the DBA to save the results into the related database. The OAA then *informs* the suppliers' allocated order quantities to the SA_j as it was requested in the beginning of the process. Table 11 shows the obtained optimal order quantities for 24 planning weeks. For instance, X_{11} for week 1 means that the amounts of orders that are allocated for component A to supplier 1 at the beginning of week 1 are 9173 units.

Table 11. Optimal order quantities

Week	Order quantity					
	X_{11}	X_{12}	X_{13}	X_{21}	X_{22}	X_{23}
1	9173	5196	10391	6104	9156	10000
2	9500	5530	10500	6037	9056	9802
3	9482	5219	10439	6132	9198	10000
4	9383	5202	10405	6040	9060	10000
5	9500	5280	10500	6261	9392	9947
6	9002	5121	10242	5844	8766	10000
7	9500	5280	10500	6132	9197	9901
8	9390	5218	10437	6180	9270	10000
9	9500	5650	10500	6122	9183	9845
10	9500	5213	10427	5960	8939	9906
11	9500	5770	10500	6053	9079	9778
12	9500	5565	10500	6205	9308	9887
13	5864	8796	10500	8100	7400	10000
14	5914	8871	10500	8087	7348	10000
15	5764	8646	10500	8009	7036	10000
16	5882	8823	10500	8071	7284	10000
17	5756	8634	10500	8040	7160	10000
18	6012	9018	10500	8129	7516	10000
19	6008	9012	10500	8026	7104	10000
20	5704	8556	10500	7774	6806	10000
21	5882	8823	10500	7917	6928	10000
22	5902	8853	10500	8009	7036	10000
23	6028	9042	10500	8063	7252	10000
24	5936	8904	10500	8007	7028	10000

5.4 Results analysis and discussions

The order allocation results are shown graphically in Figure 9. As expected, the supplier 3 was allocated more orders than the other two suppliers due to its better overall sustainable performance leading to procuring more sustainable components to the contract manufacturer. Regarding supplier 2 and 3, it is worth highlighting that supplier 2 performed better in terms of social and environmental sustainability, however, its low performance score toward economic sustainability for the first 12 planning weeks (0.437) posed negative effects in the number of allocated items for Component A. In other words, this means that although supplier 2 is able to source environmental friendly and high quality components in terms of Component A, high purchasing price, transportation and ordering

costs leading to lower economic sustainability caused lower order quantities to be awarded to supplier 2 regarding Component A.
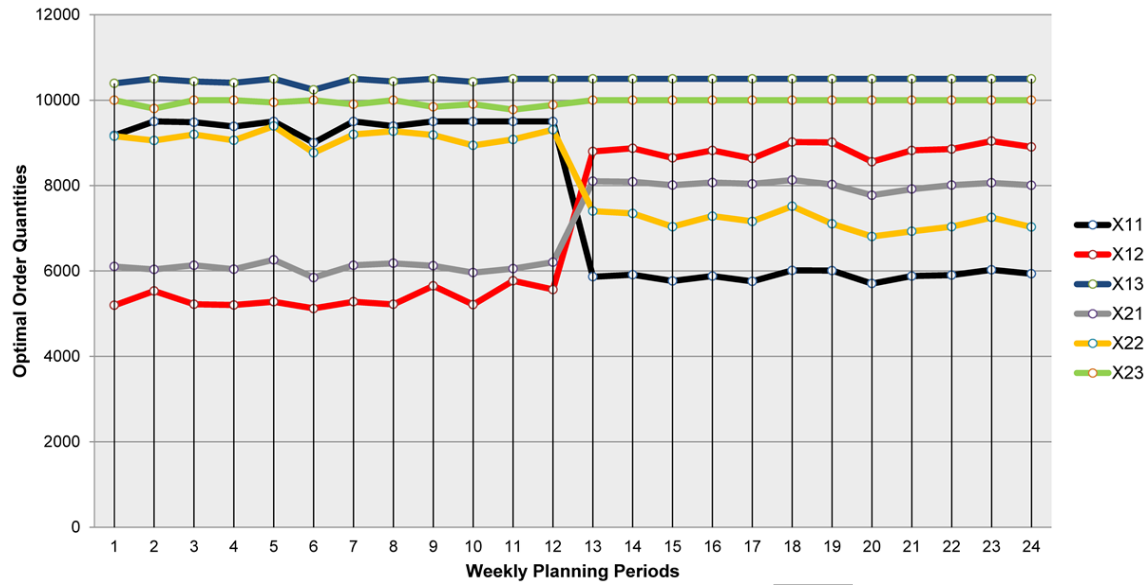

Figure 9. Trends in optimal order quantities

As mentioned in Section 5.3, the contract manufacturer might be required by stockholders and European laws and legislations to manufacturer more sustainable end-user products. Otherwise, the OEM could face difficulties in selling these end-user products shipped by the contract manufacturers to their customers such as hospitals and health organizations due to their environmental and sustainability issues. This matter can be considered by the contract manufacturer by asking its supply partners to constantly improve their operations towards manufacturing more sustainable products. For illustration purposes, we assume that supplier 2 did improve its production operations that resulted in decreasing the purchasing price for the component A from 18 to 13 (13th planning week onwards). Consequently, this improvement in production operations would have a positive effect on supplier 2 economic sustainability score improving it from 0.437 to 0.5 for the second half of the planning periods (13th planning week onwards). Therefore, the overall sustainability performance of supplier 2 was increased from 0.592 to 0.613. As the results of this slight improvement, the supplier 2 was awarded more order allocations from the manufacturer. This matter can be observed from the turning point depicted in Figure 11 after week 12 of the planning period.

Besides, it is worth to point out that the number of orders awarded to supplier 3 was always at an steady state in all planning periods as they have the best performance towards all three dimensions of sustainability with the best trade-offs regarding their various types of cost elements such as ordering, transportation and purchasing costs.

Figure 10 depicts the trend of the sustainability performance objective function value with variability in weekly demands (see Table 4). The objective function value is showing a gradually increasing trend which is due to the slight improvements in supplier 2's manufacturing and corporate operations resulting in performing in a better manner towards economic dimension of sustainability. One of the added values of optimized SSPV is the guaranteed optimal allocation of orders to the suppliers that are more sustainable. In situations where the buyer organization does not own the entire supply chain but is seeking to establish a partnership with its suppliers, using this objective function can encourage suppliers to improve their sp_j in order to maintain their relationship with the buyer organization which ultimately leads to improvement in their profitability and competitive advantages.
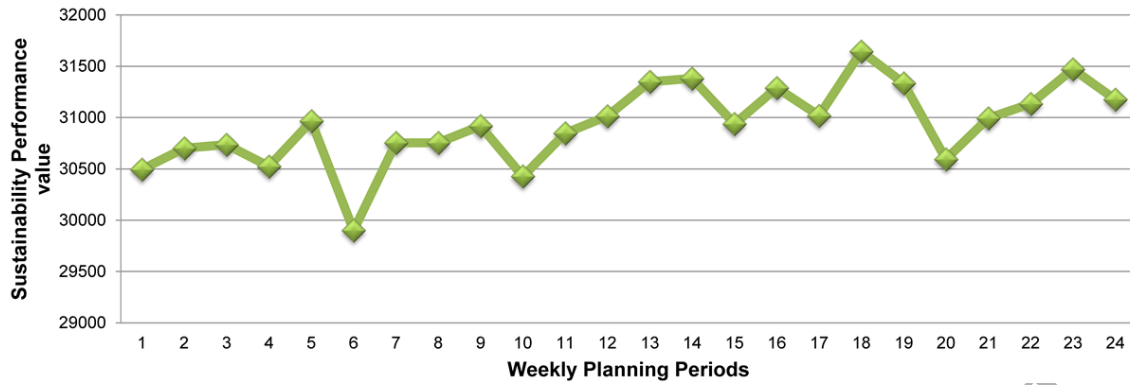
Figure 10. Sustainability performance objective function value

On the contrary, the trend for the total purchasing cost shows a sudden decrease after the second evaluation process as shown in Figure 11. This decrease in total cost is obviously incurred by reducing the purchasing prices for components A and B from supplier 2. Apart from the increasing and decreasing trends analysis for both of these two objective functions, another interesting point in analysing the results depicted in these two figures is the sensitivity of the bi-objective order allocation model towards various changes in the supply network. The findings from this experiment show that the proposed bi-objective order allocation model has the ability to handle variable changes in demand and supplier performance towards sustainability and provide appropriate results regarding the optimal order quantities to be allocated to each of the suppliers.
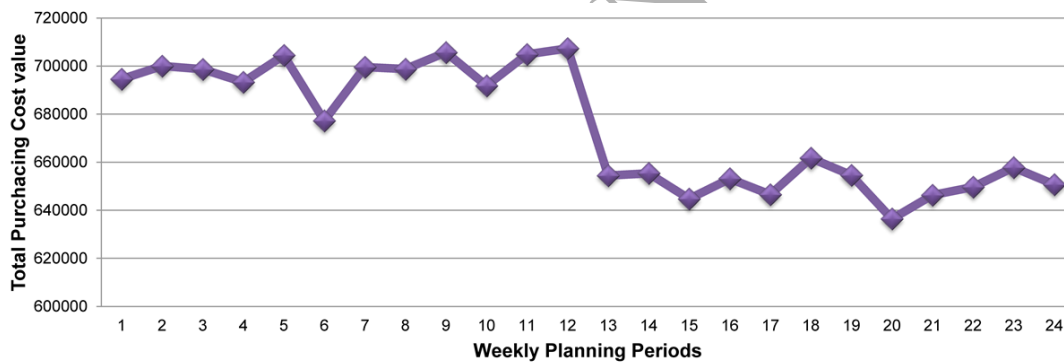

Figure 11. Total purchasing cost objective function value

5.5 Validation and Key Performance Indicators (KPIs)

In this section, we aim to briefly introduce various types of KPIs that can be utilized in the validation process of the developed MAS tool in this research work. In this paper, an experiment was developed and implemented to test and demonstrate the capability and applicability of the developed MAS approach for enhancing the SSS&OA process in terms of better communication and co-operation among supply partners operating in a partnership type relationship. Throughout this experiment, it was proven that the developed tool has the potential to be utilized in a real case study aiming to link the conducted research to a possible industry application where utilizing the developed MAS tool can contribute towards:

- Improving cost efficiency: optimal order quantities are calculated using the order allocation optimization model resulting in minimizing the total purchasing costs.
- Enhanced performance in terms of sustainability TBL attributes: the sustainability TBL attributes are incorporated in the supplier evaluation process using the sustainable supplier evaluation sub-model leading to contribute towards continuous improvement in the suppliers' operational and corporate activities resulting in sourcing more sustainable products to the manufacturers.

- Time consumption reduction: this experiment was based on a scenario of a real case study in the medical device industry which means that measuring the actual reduction in time consumption was not possible. However, the amount of time that the suppliers and contract manufacturer should spend on fulfilling the "weekly" demands and orders could be potentially high. Therefore, using the developed MAS tool with proper configurations in a real life situation aiming to automate and facilitate this process can be considered as one of the added values of such a tool.

 - Reducing human interactions: one of the main objectives of this paper was to demonstrate the applicability of MAS in facilitating the process of SSS&OA for the end-user. It was shown throughout an experiment that how intelligent agents can be designed and implemented to "do-the-job" for the users in suppliers and manufacturer organizations in cyclic manner (weekly) resulting in reduced human involvement, thereby reducing costs.

- Accuracy in information exchange: as the two encompassed sub-models (sustainable supplier evaluation and order allocation) in the designed MAS approach ensures high accuracy in timely collection of data.

- Structured communication channel: as mentioned in Section 5.2, the distributed nature of the JADE platform and the capability of agents to communicate with each other on a web server will support real-life utilization of the developed MAS tool.

- Improving the profitability of the SC: The main objective in any type of SC is to increase the profitability of the entire supply chain by sharing risks and benefits (Simatupang et al., 2002). In this paper, a novel approach is developed for the suppliers and the contract manufacturer to help them enhance and maintain co-operative and partnership in a long-term relationship by periodically sharing costs and benefits resulting in fulfilling the OEM demands by manufacturing cost efficient and sustainable products based on continuous improvement principles.

Finally, the developed MAS approach can be adopted for larger instances of components and suppliers. Each instance of new suppliers would be represented by an agent that would be registered on the Jade platform and will communicate with the OAA, DMA and DBA agents. These new supplier agents utilize the presented interaction schemes to take part in the sustainable supplier evaluation and order allocation processes to source the required periodic demand. The DBA will store the new data related to the new suppliers and components in the database. The DBA agent will access these data along with the other registered suppliers on the JADE platform to perform its internal behaviour. The results will be saved in the database and will be then utilized by the OAA to allocate the optimal order quantities to all registered suppliers.

6 Research Findings, Theoretical and Managerial Implications
6.1 Theoretical Implications

This study contributes to the SC partnerships and sustainable SCM literature by addressing the issue of inappropriate communication and inaccurate information exchange in a supply chain with the focus on the SSS&OA process. We proposed a multi-agent system approach aiming to facilitate the SSS&OA process for the suppliers and the manufacturers that are seeking to maintain a long-term partnership relationship. In the literature of SC partnership, information exchange among supply partners can improve order fulfilment rate, decrease demand uncertainty and eventually lead to better supply chain performance (Lin *et al.*, 2002; Jain *et al.*, 2009; Chang *et al.*, 2013). In their well-known partnership model developed by (Lambert *et al.*, 1996), it was stated that effective communication contributes to the success of a partnership and is one of the components that can have positive effects on the life of the partnership. From a theoretical point of view, Moberg *et al.* (2002) highlighted the importance of information exchange in performing successful SC operations. They conducted an empirical research where their results analysis demonstrated a significant relationship between the

importance of building a strong relationship with supply partners by improving accuracy, timeliness and information structure. In the same context, Mohr and Spekman (1994) also pointed out that communication strategies are one of the critical factors to partnership success. Similarly, Tan *et al.* (2002) investigated the effects of supply chain and supplier evaluation practices to firm's performance. They stated that communication and co-operation among suppliers and buyers in maintaining partnership relations would eventually lead to increase performance and lower total costs.

In the application of MAS in the SCM literature, many papers emphasized on the relevance of MASs as an appropriate information management technology for decision making in real-time and implementation of communication between various members of a supply chain (Moyaux *et al.*, 2006; Lee and Kim, 2008; Mohebbi and Li, 2012). The advantages of agents in SCs is defined as a reliable mean for collecting predefined information, being able to trace the information and data within the network and nodes and finally assisting the members of the network to make decisions (Mohebbi and Li, 2012). Jain *et al.* (2009) claimed that agent technology is very suitable to support partnership among SC actors. The introduction of multi-agent technology, the use of its distribution, autonomy, mobility, intelligence and self-learning and other characteristics can lead to improve the intelligence of supply chain management process, and to provide the support for the automation and intelligence of supplier selection and sourcing decisions (Mian, 2011) which can ultimately be consider as a suitable tool for supporting a long term partnership relationship among the buyers and their suppliers.

In this research paper, building on the aforementioned research activities, throughout conducting an experiment (see Section 5), we demonstrated that the developed MAS approach is capable of narrowing the communication and information exchange issues within the SSS&OA process by providing appropriate information to the right member of the SC in the right time and with the required formatting. In the developed MAS, each part of a decision making process is represented by each agent in the networks of the agents. This would create a tight decision makers network that can react to the designed real-time requirements by other agents. From the theoretical perspective, the implemented MAS approach in this paper demonstrates contributions of agent technology in addressing the communication and information exchange challenges in SC partnerships focusing specifically on suppliers and buyers relationship supporting the SSS&OA process.

6.2 Managerial Implications

SCs deal with operations and activities such as monitoring the flow of materials and transforming these materials to finished goods and deliver them to end-users. SC activities integration aiming at enhancing SC relationships that result in gaining competitive edge is an important research topic (Handfield and Nichols, 1999; Chang *et al.*, 2013; Bozarth and Handfield, 2015). Maintaining a long-term relationship is of great importance for senior managers; this mainly originates from high relationship termination and switching costs (Wu *et al.*, 2012). Hence, manufacturers will tend to maintain an already established partnership co-operation with their supply partners and commit to continuous improvement concepts rather than constantly switch to other suppliers (Li *et al.*, 2007; Prajogo *et al.*, 2012). Accordingly, the work in this paper provides insights into the implementation steps of the proposed MAS approach for the SSS&OA process which is targeted to provide an efficient tool for practitioners in manufacturing companies to exchange required information in a structured manner. Besides, owing to the autonomy characteristic of agents, the developed MAS has the capability to provide control over their internal behaviours and their actions which makes it less dependent on direct intervention of a user inside the manufacturing and suppliers organizations.

Another managerial implication that can be drawn is the capability of the developed MAS tool in being adaptable to other technologies already existed in manufacturer and supplier's company such as Enterprise Resource Planning (ERP) systems, Material Resource Planning (MRP) and Demand

Management Systems. Throughout the implemented experiment, it was demonstrated that the MAS tool can utilize the periodic demand values and output the final order sizes. In real-life implementations, an agent can be assigned to these enterprise planning systems in order to automatically read the demand figures and communicate with the agents in the MAS to achieve the final objectives of the entire system.

The research results and the implementation steps of the developed MAS show that although the developed tool can be a possible approach for better communication and information exchange as the main components of a partnership, establishing a real-life application of such technology requires both suppliers and manufacturer's willingness in providing the required technical and strategic infrastructures. Technical infrastructure refers to availability of Internet and constant support of IT department of the suppliers and manufactures company. Strategic infrastructures deals with managerial aspects of a partnership relationship as the CEO's and managers of both manufacturer and supplier sides should initially forge a strategic alliance so that these kinds of technologies can play their role and add value to their business.

Finally, it should be also mentioned that the real-life application of the developed MAS does not obligate the industry practitioners to apply the exact models that are proposed in various sub-models of this tool. The developed MAS approach for the SSS&OA process is flexible and customizable based on the actual needs of the case and has the capability to be extended or modified. The main purpose of this research work was to introduce such technology for the gaps identified and demonstrated the possibility of utilization of agent technology as an option for narrowing the communication and information exchange issues in a partnership type supply chain.

7 Conclusion, limitations and future works

The paper reports the application of agent technology on a combined problem of sustainable supplier selection and order allocation. The developed and implemented MAS approach in this paper demonstrates contributions of agent technology in addressing the communication and information exchange challenges in SC partnerships focusing specifically on suppliers and buyers relationship regarding the SSS&OA process. The capability and applicability of the proposed MAS has been successfully proven by conducting a comprehensive experiment inspired by a scenario adopted from a real case study in the medical device sector supply chain. The proposed system aims to improve the process of sustainable supplier selection and order allocation in terms of adding values such as less human interaction, facilitated communications and structured information exchange between all participating members of the supply chain. Finally, more detailed theoretical and managerial implications were drawn based on the results and findings of this paper. The following conclusions are drawn from this research work. We proposed a FIS model designed to evaluate supply partners in circumstances where sustainability evaluation information is uncertain, imprecise and difficult to be quantified. Besides, the evaluated suppliers were allocated based on their sustainability performance by considering the objectives, total purchasing cost, and the suppliers' sustainability performance. Therefore, they are constantly obligated to improve their sustainability practices in order to reduce the risk of gaining less profit and losing their competitive advantages, by not being selected as a supplier.

A limitation of implementing such an approach in real-life applications would be limited access of companies to gather validated input data required for the sustainable supplier evaluation and order allocation processes. This matter was also pointed out by other researchers in the field (Kannan *et al.*, 2014; Brandenburg *et al.*, 2014; Kumar *et al.*, 2014). Therefore, uncertainty and lack of imprecise input data are challenging limitations in sustainable development studies. More research is needed in the future to develop quantifiable indicators especially for environmental and social attributes of sustainability.

Based on the scope of this research work, the issues in maintaining the relationships in buyer-supplier dyad have been investigated and addressed using the developed MAS and its constituents. As future work, the issues and requirements in the other dyadic relationships of the supply chain such as manufacturer-retailer can also be studied and investigated. Furthermore, the implementation of the developed MAS using more appropriate and user-friendly GUI is being investigated for future works.

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Reference

Adam, E., Berger, T., Sallez, Y., Trentesaux, D., 2011. Role-based manufacturing control in a holonic multi-agent system. Int J Prod Res 49, 1455-1468.

Aissaoui, N., Haouari, M., Hassini, E., 2007. Supplier selection and order lot sizing modeling: A review. Computers & operations research 34, 3516-3540.

Amindoust, A., Ahmed, S., Saghafinia, A., Bahreininejad, A., 2012. Sustainable supplier selection: A ranking model based on fuzzy inference system. Appl Soft Comput 12, 1668-1677.

Azadnia, A.H., Saman, M.Z.M., Wong, K.Y., 2015. Sustainable supplier selection and order lot-sizing: an integrated multi-objective decision-making process. Int J Prod Res, 1-26.

Bhagwat, R., Sharma, M.K., 2007. Performance measurement of supply chain management: A balanced scorecard approach. Comput Ind Eng 53, 43-62.

Bozarth, C.C., Handfield, R.B., 2015. Introduction to operations and supply chain management. Prentice Hall.

Brazier, F.M.T., Dunin-Keplicz, B.M., Jennings, N.R. & Treur, J. (1997). Desire: Modelling multi-agent systems in a compositional formal framework. Int. Journal of Cooperative Information Systems, 6(1), 67-94.

Camarinha-Matos, L.M., Afsarmanesh, H., Galeano, N., Molina, A., 2009. Collaborative networked organizations–Concepts and practice in manufacturing enterprises. Comput Ind Eng 57, 46-60.

Chang, H.H., Tsai, Y.C., Hsu, C.H., 2013. E-procurement and supply chain performance. Supply Chain Management: An International Journal 18, 34-51.

Cho, D.W., Lee, Y.H., Ahn, S.H., Hwang, M.K., 2012. A framework for measuring the performance of service supply chain management. Comput Ind Eng 62, 801-818.

Cingolani, P., Alcalá-Fdez, J., 2013. jFuzzyLogic: a java library to design fuzzy logic controllers according to the standard for fuzzy control programming. International Journal of Computational Intelligence Systems 6, 61-75.

Cornelissen, A., Van den Berg, J., Koops, W., Grossman, M., Udo, H., 2001. Assessment of the contribution of sustainability indicators to sustainable development: a novel approach using fuzzy set theory. Agriculture, ecosystems & environment 86, 173-185.

Dai, J., Blackhurst, J., 2012. A four-phase AHP-QFD approach for supplier assessment: a sustainability perspective. Int J Prod Res 50, 5474-5490.

De Toni, A., Nassimbeni, G., Tonchia, S., 1994. New trends in the supply environment. Logistics Information Management 7, 41-50.

Degraeve, Z., Roodhooft, F., 1999. Effectively selecting suppliers using total cost of ownership. Journal of Supply Chain Management 35, 5-10.

Demirtas, E.A., Üstün, Ö., 2008. An integrated multiobjective decision making process for supplier selection and order allocation. Omega 36, 76-90.

Ellram, L.M., Cooper, M.C., 1990. Supply chain management, partnership, and the shipper-third party relationship. The International Journal of Logistics Management 1, 1-10.

Fallahpour, A., Olugu, E.U., Musa, S.N., Wong, K.Y., & Noori, S. 2017. A decision support model for sustainable supplier selection in sustainable supply chain management. Computers & Industrial Engineering.

Fazlollahtabar, H., Mahdavi, I., Ashoori, M.T., Kaviani, S., & Mahdavi-Amiri, N. 2011. A multi-objective decision-making process of supplier selection and order allocation for multi-period scheduling in an electronic market. The International Journal of Advanced Manufacturing Technology 52(9-12), 1039-1052.

Fazlollahtabar, H. 2016. An integration between fuzzy PROMETHEE and fuzzy linear program for supplier selection problem: Case study. Journal of Applied Mathematical Modelling and Computing 1, 1-16.

Fiala, P., 2005. Information sharing in supply chains. Omega 33, 419-423.

Gabler, C.B., Agnihotri, R., Moberg, C.R., 2014. Collaborative Communication between Sales and Logistics and Its Impact on Business Process Effectiveness: A Theoretical Approach. Journal of Marketing Channels 21, 242-253.

Gagliardi, F., Roscia, M., Lazaroiu, G., 2007. Evaluation of sustainability of a city through fuzzy logic. Energy 32, 795-802.

Ghadimi, P., Yusof, N.M., Saman, M.Z.M., & Asadi, M. 2013. Methodologies for measuring sustainability of product/process: a review. Pertanika Journal of Science & Technology 21(2), 303-326.

Ghadimi, P., Heavey, C., 2014. Sustainable Supplier Selection in Medical Device Industry: Toward Sustainable Manufacturing. Procedia CIRP 15, 165-170.

Ghadimi, P., Azadnia, A.H., Heavey, C., Dolgui, A. & Can, B. 2016a. A review on the buyer–supplier dyad relationships in sustainable procurement context: past, present and future. International Journal of Production Research, 54(5), 1443-1462.

Ghadimi, P., Dargi, A., Heavey, C, 2016b. Making Sustainable Sourcing Decisions: Practical Evidence from the Automotive Industry. International Journal of Logistics Research and Applications, 1-25.

Ghadimi, P., Dargi, A., & Heavey, C. 2017. Sustainable supplier performance scoring using audition check-list based fuzzy inference system: a case application in automotive spare part industry. Computers & Industrial Engineering 105, 12-27.

Giannakis, M., Louis, M., 2011. A multi-agent based framework for supply chain risk management. J Purch Supply Manag 17, 23-31.

Girubha, J., Vinodh, S., & KEK, V. (2016). Application of interpretative structural modelling integrated multi criteria decision making methods for sustainable supplier selection. Journal of Modelling in Management, 11(2), 358-388.

Han, W., 2013. Review of Supply Chain Partnership Process in Joint Ventures Example as Chinese Automotive Industry. 2013 International Conference on the Modern Development of Humanities and Social Science. Atlantis Press.

Handfield, R.B., Nichols, E.L., 1999. Introduction to supply chain management. prentice Hall Upper Saddle River, NJ.

Herva, M., Franco-Uría, A., Carrasco, E.F., Roca, E., 2012. Application of fuzzy logic for the integration of environmental criteria in ecodesign. Expert Systems with Applications 39, 4427-4431.

Hesami, M., Nosratabadi, H.E., & Fazlollahtabar, H. 2013. Design of a fuzzy expert system for determining adjusted price of products and services. International Journal of Industrial and Systems Engineering 13(1), 1-26.

Jaehn, F. 2016. Sustainable Operations. European Journal of Operational Research, 253(2), 243-264.

Jain, V., Wadhwa, S., Deshmukh, S., 2009. Select supplier-related issues in modelling a dynamic supply chain: potential, challenges and direction for future research. Int J Prod Res 47, 3013-3039.

Jauhar, S.K., & Pant, M. (2017). Integrating DEA with DE and MODE for sustainable supplier selection. Journal of Computational Science.

Jennings, N.R., Sycara, K., Wooldridge, M., 1998. A Roadmap of Agent Research and Development. Autonomous Agents and Multi-Agent Systems 1, 7-38.

Brandenburg, M., Govindan, K., Sarkis, J., & Seuring, S. 2014. Quantitative models for sustainable supply chain management: Developments and directions. European Journal of Operational Research 233(2), 299-312.

Kannan, D., de Sousa Jabbour, A. B. L., & Jabbour, C. J. C. 2014. Selecting green suppliers based on GSCM practices: Using fuzzy TOPSIS applied to a Brazilian electronics company. European Journal of Operational Research, 233(2), 432-447.

Kumar, A., Jain, V., Kumar, S., 2014. A comprehensive environment friendly approach for supplier selection. Omega 42, 109-123.

Kumari, S., Singh, A., Mishra, N., Garza-Reyes, J.A., 2015. A multi-agent architecture for outsourcing SMEs manufacturing supply chain. Robotics and Computer-Integrated Manufacturing.

Lambert, D.M., 2008. Supply chain management: processes, partnerships, performance. Supply Chain Management Inst, Business logistics.

Lambert, D.M., Emmelhainz, M.A., Gardner, J.T., 1996. Developing and implementing supply chain partnerships. The international Journal of Logistics management 7, 1-18.

Lanning, I., 2014. Modelling of information sharing in capacitated assembly supply chains using simulation.

Lee, J.H., Kim, C.O., 2008. Multi-agent systems applications in manufacturing systems and supply chain management: a review paper. Int J Prod Res 46, 233-265.

Leitão, P., Restivo, F., 2006. ADACOR: A holonic architecture for agile and adaptive manufacturing control. Comput Ind 57, 121-130.

Li, S., Lin, B., 2006. Accessing information sharing and information quality in supply chain management. Decision support systems 42, 1641-1656.

Li, W., Humphreys, P.K., Yeung, A.C., Cheng, T.E., 2007. The impact of specific supplier development efforts on buyer competitive advantage: an empirical model. Int J Prod Econ 106, 230-247.

Lin, F.-r., Huang, S.-h., Lin, S.-c., 2002. Effects of information sharing on supply chain performance in electronic commerce. Engineering Management, IEEE Transactions on 49, 258-268.

Mafakheri, F., Breton, M., Ghoniem, A., 2011. Supplier selection-order allocation: a two-stage multiple criteria dynamic programming approach. Int J Prod Econ 132, 52-57.

Mamdani, E.H., 1974. Application of fuzzy algorithms for control of simple dynamic plant. Proceedings of the Institution of Electrical Engineers. IET, pp. 1585-1588.

Mettler, T., Rohner, P., 2009. Supplier relationship management: a case study in the context of health care. Journal of theoretical and applied electronic commerce research 4, 58-71.

Mian, W., 2011. Comprehensive evaluation and selection model of supplier under e-business. Uncertainty Reasoning and Knowledge Engineering (URKE), 2011 International Conference on. IEEE, pp. 256-258.

Mirzapour Al-E-Hashem, S., Malekly, H., Aryanezhad, M., 2011. A multi-objective robust optimization model for multi-product multi-site aggregate production planning in a supply chain under uncertainty. Int J Prod Econ 134, 28-42.

Mishra, N., Kumar, V., Chan, F.T.S., 2012. A multi-agent architecture for reverse logistics in a green supply chain. Int J Prod Res 50, 2396-2406.

Moberg, C.R., Cutler, B.D., Gross, A., Speh, T.W., 2002. Identifying antecedents of information exchange within supply chains. International Journal of Physical Distribution & Logistics Management 32, 755-770.

Mohebbi, S., Li, X., 2012. Designing intelligent agents to support long-term partnership in two echelon e-Supply Networks. Expert Systems with Applications 39, 13501-13508.

Mohr, J., Nevin, J.R., 1990. Communication strategies in marketing channels: A theoretical perspective. The Journal of Marketing, 36-51.

Mohr, J., Spekman, R., 1994. Characteristics of partnership success: partnership attributes, communication behavior, and conflict resolution techniques. Strategic management journal 15, 135-152.

Moyaux, T., Chaib-Draa, B., D'Amours, S., 2006. Supply chain management and multiagent systems: An overview. Multiagent based supply chain management. Springer, pp. 1-27.

Negahban, A., Yilmaz, L., Nall, T., 2014. Managing production level in new product diffusion: an agent-based simulation approach. Int J Prod Res 52, 4950-4966.

Nikraz, M., Caire, G., Bahri, P.A., 2006. A methodology for the analysis and design of multi-agent systems using JADE.

O'Hare, G.M., Jennings, N., 1996. Foundations of distributed artificial intelligence. John Wiley & Sons.

Proch, M., Worthmann, K., & Schlüchtermann, J. (2017). A negotiation-based algorithm to coordinate supplier development in decentralized supply chains. European Journal of Operational Research, 256(2), 412-429.

Prahinski, C., Benton, W., 2004. Supplier evaluations: communication strategies to improve supplier performance. Journal of operations management 22, 39-62.

Prajogo, D., Chowdhury, M., Yeung, A.C., Cheng, T., 2012. The relationship between supplier management and firm's operational performance: A multi-dimensional perspective. Int J Prod Econ 136, 123-130.

Rezaei, J., Davoodi, M., 2012. A joint pricing, lot-sizing, and supplier selection model. Int J Prod Res 50, 4524-4542.

Şenyiğit, E., 2012. The optimization of lot sizing with supplier selection problem in multi-echelon defective supply chain network. Mathematical and Computer Modelling of Dynamical Systems 18, 273-286.

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. Journal of cleaner production 16, 1699-1710.

Simatupang, T.M., Wright, A.C., Sridharan, R., 2002. The knowledge of coordination for supply chain integration. Business process management journal 8, 289-308.

Sodenkamp, M. A., Tavana, M., & Di Caprio, D. 2016. Modeling synergies in multi-criteria supplier selection and order allocation: An application to commodity trading. European Journal of Operational Research 254(3), 859–874

Soh, K. L., Jayaraman, K., Yen, T. S., & Kiumarsi, S. (2016). The role of suppliers in establishing buyer-supplier relationship towards better supplier performance. International Journal of Productivity and Quality Management, 17(2), 183-197.

Songhori, M.J., Tavana, M., Azadeh, A., Khakbaz, M.H., 2011. A supplier selection and order allocation model with multiple transportation alternatives. The International Journal of Advanced Manufacturing Technology 52, 365-376.

Soroor, J., Tarokh, M.J., Khoshalhan, F., Sajjadi, S., 2012. Intelligent evaluation of supplier bids using a hybrid technique in distributed supply chains. J Manuf Syst 31, 240-252.

Tan, K.C., Lyman, S.B., Wisner, J.D., 2002. Supply chain management: a strategic perspective. Int J Oper Prod Man 22, 614-631.

Tan, W., Chai, Y., Liu, Y., 2011. A message-driving formalism for modeling and simulation of multi-agent supply chain systems. Journal of Systems Science and Systems Engineering 20, 385-399.

Tavana, M., Fazlollahtabar, H., & Hajmohammadi, H. (2012). Supplier selection and order allocation with process performance index in supply chain management. International Journal of Information and Decision Sciences 4(4), 329-349.

Trapero, J.R., Kourentzes, N., Fildes, R., 2012. Impact of information exchange on supplier forecasting performance. Omega 40, 738-747.

Valluri, A., Croson, D.C., 2005. Agent learning in supplier selection models. Decision Support Systems 39, 219-240.

Wagner, H.M., Whitin, T.M., 1958. Dynamic version of the economic lot size model. Management science 5, 89-96.

Wang, X., Wong, T. & Wang, G. (2012). An ontological intelligent agent platform to establish an ecological virtual enterprise. Expert Systems with Applications, 39(8), 7050-7061.

Walsh, P.M., Williams, P.A., Heavey, C., 2008. Investigation of rolling horizon flexibility contracts in a supply chain under highly variable stochastic demand. IMA Journal of Management Mathematics 19, 117-135.

Weber, C.A., Current, J., Desai, A., 2000. An optimization approach to determining the number of vendors to employ. Supply Chain management: An international journal 5, 90-98.

Wei, H.-L., Wong, C.W., Lai, K.-h., 2012. Linking inter-organizational trust with logistics information integration and partner cooperation under environmental uncertainty. Int J Prod Econ 139, 642-653.

Wu, C., Barnes, D., 2011. A literature review of decision-making models and approaches for partner selection in agile supply chains. J Purch Supply Manag 17, 256-274.

Wu, M.-Y., Weng, Y.-C., Huang, I.-C., 2012. A study of supply chain partnerships based on the commitment-trust theory. Asia Pacific Journal of Marketing and Logistics 24, 690-707.

Yazdani, M., Chatterjee, P., Zavadskas, E.K., & Zolfani, S.H. 2017. Integrated QFD-MCDM framework for green supplier selection. Journal of Cleaner Production 142, 3728-3740.

Yeh, Q.-J., Chang, T.-P., Chang, H.-C., 1997. An inventory control model with gamma distribution. Microelectronics Reliability 37, 1197-1201.

Yeung, W., 2012. Agent-based manufacturing control based on distributed bid selection and publish-subscribe messaging: a simulation case study. Int J Prod Res 50, 6339-6356.

Yu, C., Wong, T., 2014. A supplier pre-selection model for multiple products with synergy effect. Int J Prod Res, 1-17.

Zimmer, K., Fröhling, M. & Schultmann, F. (2016). Sustainable supplier management–a review of models supporting sustainable supplier selection, monitoring and development. International Journal of Production Research, 54(5), 1412-1442.

Zarandi, M., Avazbeigi, M., 2012. A multi-agent solution for reduction of bullwhip effect in fuzzy supply chains. Journal of Intelligent & Fuzzy Systems: Applications in Engineering and Technology 23, 259-268.