A Multi-Agent based Decision Framework for Sustainable Supplier Selection, Order Allocation and Routing Problem

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Abstract: Supply chain decisions should aim for sustainability, in order to meet the global market needs, as well as the Industry 4.0 requirements, therefore they should consider beyond economic and environmental, societal dimensions as well. The complexity in decision making increases, moreover, supply network relationships become important, including inter-relationships and those developed with the suppliers. Agent technology is compatible with Industry 4.0, whereas multi-agent systems (MAS) can provide decision support for supply chain management and model the relatationships and interactions between entities in the supply chain environment. Therefore, in this paper, a MAS-based framework is proposed to address sustainability focused decision making in supplier selection, order allocation and routing. Fuzzy Multi Criteria Decision Making (MCDM) approaches and multi-objective programming are used by the agents in the MAS in order to adress sustainability requirements. Futrhermore, developed agent services for the supply chain business processes are integrated with web services, in order to facilitate business process execution as web services.

1 INTRODUCTION

From the perspective of a network, supply chain entities must collaborate in order to supply, produce, deliver and recover products, therefore, relationships including coordination and collaboration, between supply chain partners, as well as with suppliers and customers affect the network performance. Furthermore, globalisation has shifted the focus of supply chain performance from pure economic profitability or even economic and environmental aspects to sustainability. The performance of supply chains with respect to sustainability is measured in terms of operations that meet the needs of current population which do not compromise future needs (Krysiak, 2009). Sustainability dimensions, labelled as Triple Bottom Line (TBL) dimensions (Elkington, 1997), include economic, environmental and social ones. Economic sustainability refers to fiscal performance, whereas environmental sustainability relates to green supply chain management and the management of scarce environmental resources. Social sustainability refers to fair practices at work, occupational health and safety, as well as social welfare (Aktin and Gergin, 2016). Globalisation is a key driver for integration of sustainability in supply chain management. Global supply chains face increased risks, whereas sustainability integration could address these risks (Giannakis and Papadopoulos, 2016).

Global supply chains consist of distributed and autonomous business entities which collaborate with each other, whereas they communicate with the Internet. Agent technology is increasingly being used in supply chain business processes, due to its distributed artificial intelligence origin and the capability of enabling interactions between the different autonomous, distributed software agents (Woolridge and Jennings, 1995), connected in a network. Agents can represent various supply chain entities, business processes, machines, vehicles, as well as information and material elements. Business entities in global supply chains use negotiation, coordination and cooperation mechanisms in order to jointly deliver supply chain services and products, whereas these interaction features are inherent in agent technology (Swaminathan, 1998; Long, 2011). In the context of the supply chain, multi-agent systems (MAS) enable decision support by using individual agents, each one with local knowledge,

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capable of interacting to achieve the global supply system goal. Collaborative manufacturing decision support including supplier selection (such as Jiao et al., 2006, Trappey et al., 2007; Yu et and Wong, 2015; Ghadimi et al., 2018), and vehicle routing as well as intelligent transportation has been provided by MAS and agent technology (such as Davidsson et al, 2005; Martin et al., 2016). Collaboration in sustainable supply chain management aims to meet the sustainability goals. However, the impact of logistics in sustainability has not been well explored. Logistics, including transportation, contribute to the total carbon footprint, therefore, efficient planning and execution of logistics and transportation network can positively affect the carbon footprint of supply chains as well the long-term sustainability goals (Reefke and Sundaram, 2017). Hofmann and Rusch (2017) explore the potential of Industry 4.0 in logistics management. They argue that Industry 4.0 will result in the deployment of autonomous knowledge-based, self-regulating production systems, as well as the emergence of new services and business models. They suggest a physical supply chain model which includes autonomous, self-controlled logistics sub systems, such as transport units, or order processing units, interacting with each other. The digital supply chain model includes different types of data, transferred via a connectivity layer, such as in the cloud, in order to be processed, delivering value-added business services. Just-in-Time systems, which focus on buyer-supplier relationships, will benefit, since suppliers will receive real-time production order information at buyer sites via cloud-based ERP systems, thereby, triggering their production.

Digital integration as well as servitisation add value in smart supply chains. Supplier selection is a critical component of supply chain performance (Ghadimi and Heavy, 2014). Ho et al. (2009) emphasize that supply chain management goals include long term partnerships with suppliers, therefore a few but reliable suppliers are prefered. Govindan et al. (2015) further consider suppliers as the fifth echelon in the sustainable order allocation and supply chain network design. Sustainable supplier selection and subsequent order allocation is crucial in supply chain management, therefore organisations must cooperate with suppliers on sustainable practices. Besides, in the sustainable supplier selection process, long-term relationship-continuity has been identified as a sustainability criterion (Gören, 2018). The critical decisions in supplier selection include the types of products, identification of suitable suppliers, order quantities and time periods for order allocation (Songhori et al., 2010). Order allocation refers to the decisions regarding the order quantities to order from each selected supplier. Traditional supplier selection has focused on economic criteria, such as cost, quality, delivery times and has been summarised in reports (such as Ho, 2009). Sustainable supplier selection considers the tripple-bottom line dimensions (Gören, 2018). Research on sustainable supplier selection considering economic, environmental, as well as the social dimension (such as Kuo et al., 2010; Govindan et al., 2013) is growing. However, sustainable supplier selection with order allocation has been the focus of a limited number of studies (such as Aktin and Gergin, 2016; Gören, 2018; Govindan et al., 2015; Ghadimi, 2018). Transportation and distribution decisions affect logistics performance. Vehicle Routing Problem (VRP) optimises routes for vehicles from a set of depots to a set of destinations (Laporte, 1995). VRP is a supply chain optimisation method including optimisation of routes between suppliers and customers (Wang et al., 2018). Songhori (2010) consider supplier selection with order allocation and optimal selection of transportation alternatives. Supplier selection with order allocation and vehicle routing has been studied in the literature only recently (Govindan et al., 2017; Nasiri et al., 2018). Nasiri et al. (2018) address supplier selection and order allocation and vehicle routing for the multi-cross-dock problem with mixed integer linear programming. Govindan et al. (2017) present a closed loop supply chain network design which integrates decisions on supplier selection, order allocation, vehicle selection and routing. However, the authors have not addressed sustainability in their method. Ghadimi et al. (2018) develop a MAS method for sustainable supplier selection and order allocation. The authors argue that the proposed MAS enhanced structured communication and information exchange in the partnership, and therefore, enhanced the long-term relationships between buyer and suppliers as well as their partnership.

In this paper, an intelligent MAS is presented to assist in the integrated decision making in sustainable supplier selection with order allocation and routing. MAS agents represent supply chain entities such as project managers, information elements such as knowledge manager, business processes, such as supplier selection, order allocation and vehicle routing suppliers, as well as vehicles. Agent types are categorized to execution, information, outsourcing partner and mobile agents. Individual agents use different methods for local decision making include fuzzy MCDM and optimization. The MAS global goal is to make decisions in supplier selection, order allocation and vehicle routing taking into account logistics oriented Industry 4.0 concepts including sustainability. The proposed approach facilitates cooperation and communication between different supply chain members and enhances supply chain IT performance, since it can integrate with web services.

In the following, the proposed method is presented next, followed by a description of the proposed method. Finally, conclusions are drawn.

2 THE PROPOSED METHOD

2.1 The MAS

The MAS is developed in order to achieve the following tasks:

a) to evaluate and select appropriate supplier(s) taking into account sustainability dimensions,
b) to allocate orders to the selected suppliers, and
c) to configure product pickup vehicle routing starting from the depot and visiting suppliers in order to collect purchased products.

The MAS has been developed with Java Agent Development Framework (JADE) (Bellifemine et al., 2007). Agents interact with the FIPA-ACL Interaction Protocol (IP). The MAS agents are classified as execution, information, outsourcing partner and mobile agents. Agents located in different sites and JADE platforms communicate with the HTTP Message Transport Protocol. Lim and Zhang (2004) have classified agents such as information and execution. Wang and Lin (2009) classified agents as soft agents, namely information and execution ones as well as mobile ones. In this paper, execution agents are responsible for carrying out procedures and making decisions. Information agents are responsible for giving information including data to other agents upon request. Ousourcing partner agents represent suppliers, whereas mobile agents represent vehicles, Outsourcing partner agents represent outsourcing partners, they can make decisions as well as provide data upon request and include the supplier agents. Mobile agents can move according to a scheduling and routing plan, provide information upon request and include vehicle agents. However, mobile agents could represent different mobile elements such as data or products. The MAS consists of a project manager agent (PMA), a coordinator agent (CA), a supplier selection agent (SSA), a knowledge manager

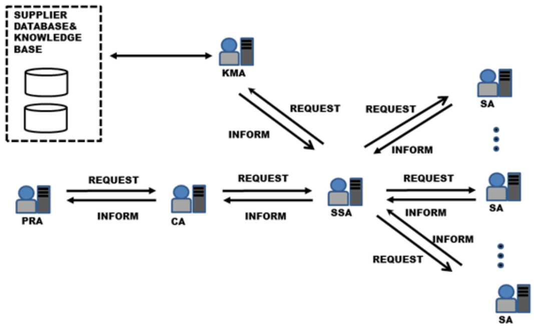

Figure 1: The MAS agent interaction diagram for the supplier selection process.

Table 1: MAS agents and their respective goals.

Agent	Goal
Project Release Agent (PRA)	Releases sequentially the supplier selection, order allocation and vehicle routing tasks to be executed by the MAS. Communicates with the CA.
Coordinator Agent (CA)	Coordinates task executions. Communicates with the SSA, OAA and VRA.
Knowledge Agent (KMA)	Retrieves and stores data and knowledge to the databases. Communicates with the SSA, OAA and VRA.
Supplier Selection Agent (SSA)	Executes the supplier selection task, evaluates and ranks potential suppliers. Communicates with the SAs, KMA and CA.
Supplier Agent (SA)	Represents potential suppliers. Each SA provides supplier data necessary for the supplier selection task. Communicates with the SSA.
Order Allocator Agent (OAA)	Executes the order allocation task. Communicates with the CA, KMA and OA.
Optimisation Agent (OA)	Communicates with the OAA and KMA.
Vehicle Routing Agent (VRA)	Executes the vehicle routing task. Communicates with the CA, KMA, VAs and OA
Vehicle Agent (VA)	Represents vehicles to be used for routing. Each VA provides vehicle data necessary for the vehicle routing task. Communicates with the VRA.

agent (KMA), supplier agent(s) (SA), vehicle agent(s) (VA), an order allocation agent (OAA), an optimisation agent (OA) and a vehicle routing agent (VRA). Execution agents include the project manager agent (PMA), the coordinator agent (CA), the supplier selection agent, the order allocation agent, the optimisation agent and the vehicle routing agent. Information agents include the knowledge manager agent, supplier agent and product agents. Table 1 shows the agents of the MAS. Figure 1 shows the MAS agent interaction diagram for the supplier selection process and Figure 2 shows the agent IP for the presented MAS focusing on supplier selection and order allocation processes.

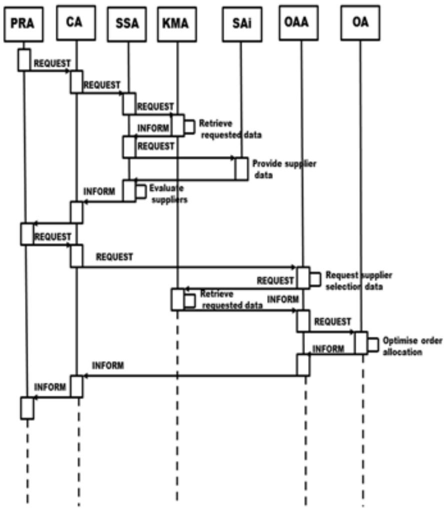

Figure 2: The agent interaction protocol for the presented MAS for the supplier selection and order allocation processes.

2.2 Elements of the MAS

Project Release Agent (PRA)

PRA decides on outsourcing tasks based on information received from project managers and releases project tasks to the coordinator agent. Tasks include supplier selection, order allocation and vehicle routing, taking into account sustainability (TBL) dimensions. PRA requests from CA to initiate supplier selection process. Upon receiving notification from CA that the task has been completed, he requests from CA order allocation execution. Upon receiving notification from CA that the task has been completed, he requests from CA vehicle routing execution. PRA communicates with the FIPA-Request IP.

Coordinator Agent (CA)

CA coordinates the execution of the tasks issued by PRA. He receives requests for task execution from PRA. When he receives request from PRA for supplier selection, the agent requests from SSA to evaluate and rank suppliers, taking into account sustainability. After SSA informs CA that he finishes the task, CA informs PRA of the results. When he receives request from PRA for order allocation, he requests from OAA to allocate orders to the suppliers. After CA receives results from OAA, he informs PRA of the results. When CA receives request from PRA for vehicle routing execution, he requests VRA to do the vehicle routing. After he receives the vehicle routing results from VRA, the agent informs PRA of the results. CA communicates with the FIPA-Request IP.

Knowledge Manager Agent (KMA)

KMA receives requests for information regarding the list of potential suppliers and sustainability criteria from the SSA and informs SSA on the requested information based on information, he retrieves from the databases. The agent has access to supplier database. KMA receives requests for information regarding ranking of suppliers from OAA and informs OAA about the results. He receives order allocation results from OAA and informs the supplier and manufacturer databases. KMA receives requests for order allocation information from VRA and informs VRA about the results. He receives vehicle routing results from VRA and informs the supplier and manufacturer databases. KMA communicates with the FIPA-Request IP.

Supplier Selection Agent (SSA)

SSA receives request for sustainable supplier selection from CA. SSA communicates with KMA to receive list of suppliers and list of sustainability criteria for supplier evaluation. Next, he communicates with the potential supplier agents (SAs) in order to obtain the necessary data for supplier evaluation. He may use Contract Net Protocol (CNP) for communicating with the suppliers. A supplier agent (SA) may refuse to enter into negotiation with SSA. Alternatively, he may communicate with potential suppliers with FIPA Request IP. He applies different fuzzy MCDM approaches such as AHP, TOPSIS etc. to evaluate and rank suppliers. SSA sends evaluation results to CA and KMA. SSA communicates with the FIPA-Request IP and FIPA-CNP.

Order Allocation Agent (OAA)

OAA receives request for order allocation from CA. OAA requests from KMA supplier supplier ranking results and product data. OAA executes a bi-objective model to allocate orders to potential suppliers. When the agent receives optimisation results from OA, he informs both CA and KMA about the vehicle routing results. OAA informs order allocation results to the CA and KMA. OAA communicates with the FIPA-Request IP or FIPA-CNP.

The Bi-objective Model for Order Allocation

Multiple products and multiple periods are assumed in the model which is adapted from Gören (2018).

Indices:

i: index of a supplier
j: index of a product
t: index of a period

Parameters:

S: number of suppliers
P: number of products
T: number of periods
C_i: capacity of supplier *i*
P_{ij}: Purchasing price of product *j* from supplier *i*
W_i: Supplier rating value
O_{ij}: Ordering cost of product *j* from supplier *i*
H_j: holding cost for product *j*
q_{ij}: Average defect percent of supplier *i* for product *j*
Q_j: Maximum acceptable defect ratio for product *j*
p_{ij}: production time of supplier *j* for product *j*

Decision Variables:

X_{ijt}: Quantity of product *j* delivered by supplier *i* in period *t*.
Y_{ijt}: Binary variable equal to 1 if an order is placed to supplier *i* for product *j* in period, else 0.
I_{jt}: Available inventory of product *j* at the end of period *t*.

Objective Functions and Constraints

The first objective function aims to minimise the total cost of purchasing (TCP) from the suppliers.

$$Min(TCP) = \sum_{i=1}^{S}\sum_{j=1}^{P}\sum_{t=1}^{T}(P_{ij} * X_{ijt} + (H_j * I_{jt} + (O_{ij} * Y_{ijt}) \tag{1}$$

The second objective function aims to maximise the total sustainability value (TSV) of the suppliers.

$$Max(TSV) = \sum_{i=1}^{S}\sum_{j=1}^{P}\sum_{t=1}^{T}(W_i * X_{ijt}) \tag{2}$$

Constraints:
Demand constraint:

$$\sum_{i=1}^{S} X_{ijt} = D_{jt} \quad \forall\, j, t \tag{3}$$

Quality constraint:

$$\sum_{i=1}^{S} X_{ijt} * q_i = D_{jt} \quad \forall\, j, t \tag{4}$$

Supplier capacity constraint:

$$\sum_{j=1}^{P} X_{ijt} * p_{ij} \le C_i \quad \forall\, i, t \tag{5}$$

Non-negativity constraint:

$$X_{ijt} \ge 0 \quad \forall\, i, j, t \tag{6}$$

Each objective function subject to the constraints is solved separately. Results of each objective function are sent to the optimisation agent (OA). The bi-objective model is finally optimised and solved by OA.

Optimisation Agent (OA)

OA receives requests for optimisation from OAA and VRA. He informs the results of optimisation to OAA and VRA. The objective of OA is to find a set of optimal solutions that satisfy multiple objectives which could be conflicting, subject to a set of constraints.

OA follows the procedure adopted in (Hamdan and Cheaitou, 2017). OA receives from either OAA or VRA the solution to each objective function solved separately. A weighted approach is followed by OA in order to merge the two objective functions in a single objective function, *f*, which is shown below in response to OAA requests

$$f_1 = \frac{TCP - TCP_{min}}{TCP_{min}} \tag{7}$$

$$f_2 = \frac{TSV_{max} - TSV}{TSV_{max}} \tag{8}$$

$$minf = \alpha_1 f_1 + \alpha_2 f_2 \tag{9}$$

where α_1 and α_2 are relative weights. Their sum is equal to 1. Equation (9) gives the optimized solution for the order allocation. OA informs OAA with the results.

Vehicle Routing Agent (VRA)

VRA receives request for vehicle routing from CA. VRA requests from KMA order allocation results as well as product data and from vehicle agents data regarding vehicle parameters. VRA executes a bi-objective model for vehicle routing. Each objective function subject to the constraints is solved separately. Results of each objective function are sent to the optimisation agent (OA). The bi-objective model is finally optimised and solved by OA. When the agent receives optimisation results from OA, he informs both CA and KMA about the vehicle routing results. VRA communicates with the FIPA-Request IP or FIPA-CNP. Heterogeneous vehicles with different capacities, costs and carbon emission rates are represented by the vehicle agents.

The Bi-objective Model for Vehicle Routing

The problem is formulated such that each route starts and ends at the depot. The load of each vehicle should not exceed its capacity. Each supplier is visited once by one vehicle during each period.

Indices:

i: index of a supplier
j: index of a product
t: index of a period
v: index of a vehicle

Parameters:

S: number of suppliers
P: number of products
T: number of periods
V: number of vehicles
W_j: weight of product *j*
CP_v: capacity of vehicle *v*
FC_v: Fixed cost for vehicle *v*
VC_v: Variable cost for vehicle *v*
CE_v: Carbon emission of vehicle *v* per km
dn_in_j: Distance between suppliers (nodes) *i* and *j*

Decision Variables:

X_{ijvt}: Quantity of product *j* of supplier *i* in period *t* delivered by vehicle *v*.
y_{ninjtv}: : Binary variable equal to 1 if arc (n_i, *nj*) is part of the route of vehicle *v* in period *t*.
c_{0ijtv}: Binary variable equal to 1 if vehicle *v* starts from depot and visits immediately after supplier *i* in period *t*.

Objective Functions and Constraints

The first objective function aims to minimise the total cost of transportation activities (*TCT*).

The second objective function aims to minimise total carbon emissions from the vehicles used to pickup and deliver the purchased products (*TCE*).

$$Min(TCT) = \sum_{i=1}^{S}\sum_{j=1}^{P}\sum_{j=1}^{T}\sum_{t=1}^{T}\sum_{v=1}^{V}(c_{0ijtv} * FC_v) + \sum_{ni=0}^{S}\sum_{nj=0}^{S}\sum_{t=1}^{T}\sum_{v=1}^{V}(d_{n_in_j} * y_{n_in_{jtv}}VC_v) \quad (10)$$

$$Min(TCE) = \sum_{ni=0}^{S}\sum_{nj=0}^{S}\sum_{t=1}^{T}\sum_{v=1}^{V}(d_{n_in_j} * y_{n_in_{jtv}}CE_v) \quad (11)$$

Constraints:
Vehicle load capacity constraint:

$$\sum_{i=1}^{S}\sum_{j=1}^{P}(X_{ijvt} * W_j) \leq CP_v \quad \forall\, v,t \quad (12)$$

Equation (13) states that each vehicle visits at most one node at the beginning of the pickup:

$$\sum_{i=1}^{S}\sum_{j=1}^{P}\sum_{j=1}^{T}\sum_{t=1}^{T} c_{0ijtv} \leq 1 \quad \forall\, v,t \quad (13)$$

Equations (14)-(16) state the degree constraints and route continuity:

$$\sum_{ni=0}^{S} y_{n_in_{jtv}} = 1 \quad \forall\, v,t \; and \; n_j = 1,2 \ldots.,S \quad (14)$$

$$\sum_{nj=0}^{S} y_{n_in_{jtv}} = 1 \quad \forall\, v,t \;\; and \; n_i = 1,2 \ldots.,S \quad (15)$$

$$\sum_{ni=0}^{S} y_{n_in_{jtv}} = \sum_{\substack{nj=0 \\ \neq n_j}}^{S} y_{n_jn_{itv}} \quad \forall\, v,t \;\; and \; n_i \quad (16)$$

The bi-objective model is solved following with the procedure adopted in (Hamdan and Cheaitou, 2017) by OA. VRA requests from OA optimisation, providing to the agent TCT, TCT_{min}, TCE and TCE_{min} results.

The Java API of CPLEX is used by the MAS for the multi-objective programming development.

2.3 Integration of MAS with Web Services

Agent services can be published as web services by using the Web Service Integration Gateway (WSIG) in JADE (Bellifemine et al., 2007). Figure 3 shows the integrated MAS with WSIG architecture. WSIG consists of two basic components, namely the WSIG Servlet and the WSIG Agent. The WSIG Servlet is the front-end to the internet. Its tasks include serving incoming HTTP/SOAP (Simple Object Access Protocol) requests, determining the requested agent action and informing the WSIG agent, as well as sending the HTTP/SOAP response to the client. The WSIG Agent is the gateway between the internet and the agent worlds. The tasks include forwarding requested agent actions to the agents in order to perform them and receiving the responses from the agents, as well as creating the Web Service Description Language (WSDL) corresponding to each agent registered service and publish it in a Universal Description, Discovery and Integration (UDDI) repository.

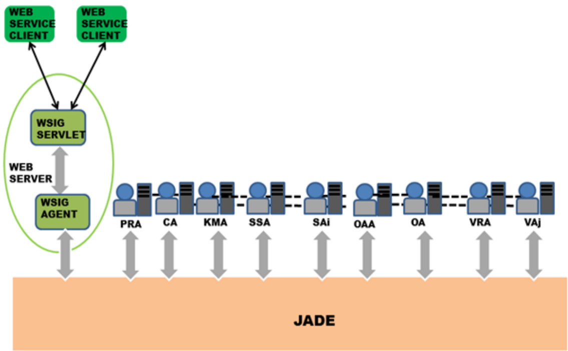

Figure 3: The integrated MAS with WSIG architecture.

3 CONCLUSIONS

Digital servitisation in smart supply chains requires synchronisation of business processes and real time information exchange between supply chain members. Challenges created by sustainability requirements lead to the emergence of new methods in order to address business processes. Therefore, in this paper, a MAS-based framework is proposed to address sustainability requirements and integrated decision making in supplier selection, order allocation and vehicle routing. Fuzzy MCDM approaches and multi-objective programming are used by the agents in the MAS. Agents represent different supply chain entities, business processes, information elements as well as vehicles. They are categorized as execution, information, outsourcing partner and mobile agents. Furthermore, developed agent services for the supply chain business processes are integrated with web services, in order to facilitate business process execution as web services. The proposed method will be tested on a real case study in the future studies.

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