Modeling of Complex Multiagent Behavior Using Matrix Representation

Sebastian Meszyński, Oleksandr Sokolov
Faculty of Physics, Astronomy, and Informatics
Nicolaus Copernicus University
Toruń, Poland
email: {sebcio, osokolov}@fizyka.umk.pl

Abstract— **Multi-agent systems are systems that solve complex problems by dividing them into smaller problems and imparting each of them to specialized programs called agents. The reliability of such systems strongly depends on the correctness of agents' communication and interaction. Unfortunately, the analysis of the whole system is not an easy task as its component parts, in the form of agents, work in an asynchronous way. An additional problem causing the difficulty in this analysis is the fact that each agent is an autonomous being, therefore, having received information from another agent existing in the same environment, it does not have to change its internal condition. In the following paper, matrix representation and equations, describing dynamics of the multiagent system were implemented by using the basic elements of graph theory and theory of compartment modeling. The analysis of equations and examples presented below, confirm the validity of the thesis that the adopted description is sufficient to describe the interactions between agents in the multiagent system.**

Keywords- multiagent system; agent; linear algebra; matrix.

I. INTRODUCTION

The models used for modeling of any kinds of physical phenomena are the tools utilized to obtain an answer to questions concerning the tested system, without the need for performing the actual experiment. Among the variety of models, i.e., psychological, word or physical models, there are also mathematical models whose relations observed in the system are described by mathematical formulas. The possibility to perform such experiments is called simulation (lat. simulare – simulate). It is a cheap and safe alternative or a complement to experiments with the system.

The quality of simulation's results depends entirely on the quality of the model. Fundamentally, there are two approaches to building a model representing a particular system. The first type of approach is based on the knowledge taken from literature or experience of experts in a given domain and could be used for building more and more precise description of the investigated phenomenon (more complex models are generated). The second one is based on observation of the phenomenon and its behavior on one level of description (using similar agents) and after that building the model and identification of parameters (agent-based approach).

The created model in both approaches needs to be described in a handy form, especially if one wants to analyze it with the use of digital machines. Having the model built, it is necessary to verify the correctness of obtained results. The credibility of the results provided by the model can be acquired using verification or validation.

This paper focuses on the use of a multi-agent system for the modeling of the insulin-glucose system responsible for the blood glucose homeostasis. Even by designing the simplest model based on the multi-agent paradigm, one must rely on a complex analysis of interactions between agents. For this reason, there is not one general formalism of description of these interactions, which would additionally allow for an easy analysis of the functioning of such a multi-agent system. In most cases, the approaches used are chosen depending on the category of problem that is solved by the system. It should be understood that if the multi-agent system was designed to address the issues of game theory, then this formalism would be used to analyze multi-agent system. In case multi-agent system was created for optimization problems, such problems will be used to analyze this system [7][8]. What is presented in this paper is a demonstration of the use of two modeling techniques for the general description of a multi-agent system. On one hand, the theory of compartment models has been used to describe the interaction between the different body regions, called compartments. On the other hand, there is a graph theory, which introduces a general and universal tool for describing the interaction between beings that can represent any mathematical or physical concept. Combining these two techniques allows us to describe the interaction between agents in a multi-agent system (MAS) in two ways. Firstly, it could help to describe the dynamics of the entire multi-agent system, showing the connections between agents, their behavior, and the ability to investigate the whole system. Secondly, it makes possible to include in the same formalism the information associated with each agent. This should be understood as the ability to get information about what behavior is implemented in the body of the agent, which behavior is used to communicate with the environment, and which are only the internal behavior of the agent. One can also get information about which agent is a receiver of the messages and which agents are senders of those messages.

The proposed approach allows describing MAS in two complexity scales - the system as a whole and the agent and its impact on the system. We illustrate now the MAS description and communication on the glucose homeostasis. The selected analytical model (Stolwijk-Hardy model [9]) was converted to a multi-agent system in a lossless fashion. As a result, individual members of this model became the determinants of behavior of individual agents, and in

Copyright (c) IARIA, 2017. ISBN: 978-1-61208-576-0

addition, the analysis of such model was maintained by compartmental methods.

The structure of the paper is following. Section II gives a short introduction to multi-agent systems and draws attention on components of agents and their communication standards. In the next section, the matrix representation of multi-agent system is proposed. Section IV illustrates the authors' approach with two simple examples. The conclusion and references summarize the article.

II. MULTI-AGENT SYSTEMS

We present primary ideas concerning multi-agent systems.

A. Concept of multi-agent system and agent

Multi-agent systems are complex systems of agents communicating and cooperating with each other. This construction of the systems enables solving problems of a diffuse or complex calculation. In the studies applying multi-agent systems, the concept of an agent is presented as an autonomous object having the initiative of action based on the observation of the environment, in which it is located. It also has the ability to use the resources of the environment and the motivation to solve the problem it has to face. Such definition of the agent forces him to have inputs called sensors (through which it will be able to receive signals from the environment) and effectors, which can be used to influence the surrounding environment. The most important task of the agent is to decide which of the possible courses of action is best, at the time of acquired knowledge about the problem, in order to achieve the goal.

The issue „agent" is wide and diverse. Nowadays the term is so broadly used that is best described as comprising a heterogeneous body of research and development [1]. Different communities refer to it in various ways. Some scientists will characterize agents as initiatives and reactivity of objects; others emphasize independent learning and communication skills. What can also be invoked is the characteristic that unifies modeling agent the most – it is their decentralization. An extensive discussion of multi-agent systems can be found in positions [2][3]. In contrast to the dynamic system or actions based on models, the multi-agent system does not have a special place of centralization where the dynamics of the system is fixed. What is more, global behavior of the whole system is defined on the basis of the individual behavior of all agents. Each agent has its own inner behavior as a set of rules and behavior for interaction with the environment and other agents. Such description produce a dynamic interaction of agents based on rules.

In many situations, there is a doubt linked to the lack of understanding of the philosophy of using multi-agent systems and returning toward object-oriented programming. What is characteristic of multi-agent systems can be presented in the following subparagraphs:

- Agents possess internal awareness and defined goals to be achieved. The goals can, but do not have to be identical to the objectives of the other agents who are in the same environment. In such case, information obtained from another agent can be taken into account only if it is coincident with its own objective.
- The agent is a dynamic instance which adapts its activity to instantaneous changes in the environment and has certain fixed parameters and characteristics only for him that do not change regardless of the extent of the changes observed in the environment.
- Each agent possesses at least one strand which is responsible for its behaviorism.

The general difference between instance of an agent and the object lies in the fact that the object has variables that change, while the agent variables can be changed only when the agent accepts the request of the sender to change the value of a variable in an immediate way or after the act of negotiation.

B. Communication in multi-agent system

In an environment where there is more than one agent, there must be a mechanism for the exchange of information between the environment and the agent, and between agents. Communication mechanisms are essential for the agents grouped in structures that facilitate co-operation so that they could achieve their goals. Since the multi-agent environments [4][5] are dynamic environments, it is necessary to introduce a mechanism that would allow for informing the agents of the existence of other participants in the system. The literature [6] distinguishes the following approaches:

- Yellow pages, where agent can place information about services it provides
- White pages – the list of all agents in the environment
- Broker – intercessory agent.

In order to create a message and then send it to another agent, so it can receive it and understand it, it is necessary to define common, to all the participants of the act, language of communication and terminology. It should be noted that the language of communication, which is independent of the field, is separated from the language of messages content. Among the communication standards the most popular include:

- KQML (Knowledge Query and Manipulation Language)
- ACL (Agent Communication Language)

Among the examples of the language of message content, the following should be distinguished:

- KIF (eng. Knowledge Interchange Format)
- FIPA standards:
  - — SL (Semantic Language)
  - —CCL(Content Language)

Having a tool for communication, agents can communicate with each other to achieve a common or an opposing goal. In the first case, we have to deal with the concept of co-operation, in the second case with the concept of competition. As a rule, multi-agent systems are designed to solve complex problems in which agents have control (or can observe), only a certain part of the environment (Figure

Copyright (c) IARIA, 2017. ISBN: 978-1-61208-576-0

1). In order for the multi-agent system to solve the problem, the agent has to have knowledge and control over the entire environment. To do so, agents are organized in the structure where then interact with each other. Interactions between structures and agents are supposed to bring them benefits. Each agent has its preferences for the state in which environment it should be (this is its goal). In order to describe this preference, the concept of utility ν, which causes an alignment state of the environment Ω due to the preferences of the agent, is introduced.

$$\nu : \Omega \rightarrow \Re \quad (1)$$

The environment that corresponds to preferences of the agent will have greater utility value (in other words: the agent will "feel better").

III. MATRIX DESCRIPTION OF MULTI-AGENT SYSTEM

The key consideration in this paper is to propose a modeling paradigm glucose-insulin in the form of a multi-agent system starting with a mathematical description and finishing the implementation of the program. This solution shows how we can implement features of agents for both the macro and micro processes in homeostasis of glycemia. Moreover, at the same time, we can allow operating on two scales: organs and cells scale. This results in a new quality of information. To describe the multi-agent system, the authors used the approach presented in the chapter describing compartment modeling and using the rationality of graph theory (Figure 1). This approach simplifies the interpretation of what is happening in the multi-agent system, therefore, the behaviors of individual agents and their influence on other agents in the considered system can be easily identified.

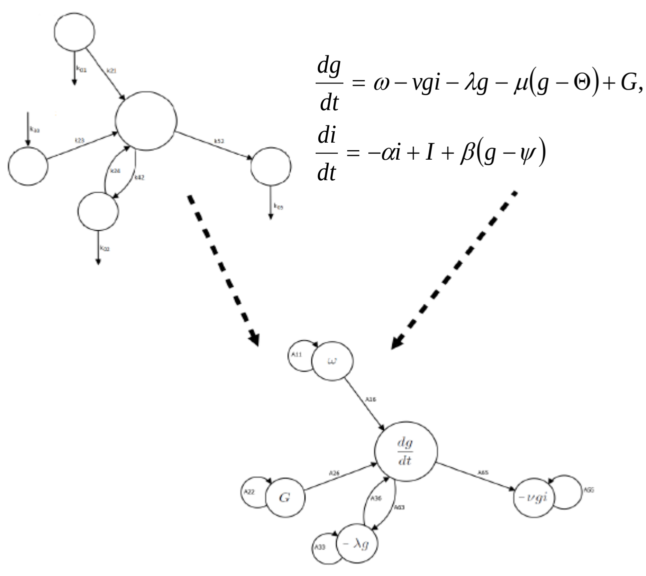

Figure 1. A new concept of describing a multi-agent model.

The analysis of multi-agent system is a difficult task to implement due to the existence of the asynchronous relationships between agents occurring in the system. Additionally, each agent which takes an active part in the multi-agent system has at least two behaviors: the one receiving incoming messages from other agents, and the other one used by it to send the information to the chosen agent. By verification of the model, one can understand two aspects. The first aspect concerns information about acceptable range of internal parameters of model, which guarantees the stability of the model for the incoming information/extortion from outside. The second is the range of input set, which ensures the correct stability and expected representation of the behavior of the modeled system.

We propose to describe multiagent system by using a comparison of network connections between the agents to the connections between vertexes forming a graph. Nomenclature of the vertex is extended by the occurrence of behaviors that identifies the agent's behavior. In this perspective of the problem, the graph which describes the interactions between agents with their associated behaviors is obtained. The assumptions are:

- Behaviors implemented in a given agent create a set of behaviors for the agent, which is a subset of behavior occurring in the multi-agent system:

$$\sum A \in \Phi \quad (2)$$

$$\Phi \subseteq \Omega \quad (3)$$

where:
A - represents some behavior of agent, Φ - represents a set of behaviors of a given agent, Ω - represents a set of behaviors of multi-agent system.

- Agents who pose the same behaviors are not identical with each other. It results from independent activities in terms of time and each agent using the same behavior performs them in various time slots.

- Graph A=(V,E); |V|=n, |E|=m represents multi-agent system basing on the assumption that:
  - n: number of graph vertexes (number of agents),
  - m : number of behaviors appearing in MAS.

- Adjacency matrix K∈M(n×n;N) is defined in such way that value in i-th line and in j-th column equals:
  - 0: if there is no communication between agents (connection),
  - 1: if there is communication between agents (connection).

  Whereby:
  - k_{ii} represents cyclical route of agent i-th,
  - k_{ij} represents route from agent i-th to agent j-th.
- The sum of the same behavior is the same behavior:

$$\sum_i A_{1i} = A_1 \quad (4)$$

- Behavioral Matrix $A \in M(n \times n; B)$ (where B designates set of behaviors within the scope of the multi-agent system) is defined in a such way that value in i-th line corresponds to behavior responsible for communication between agents i-th and agent j-th , whereby:
  - Behavior A_{ii} represents internal behavior (cyclical) of agent i-th,
  - Behavior A_{ij} represents information exchange from agent i-th to agent j-th.

Taking the above assumptions into consideration, it is possible to describe multi-agent system with the use of matrix equation:

$$A^T K + D = \Phi \tag{5}$$

where:
A^T is the transpose of a matrix of agents' behaviors; K is a matrix of connections between agents; D is a matrix of agents' internal behaviors; Φ is a matrix representing multi-agent system.

Analysis of the above equation will be presented on 3 examples of multi-agent system. Both examples will rely on a different number of behaviors occurring in the multi-agent system.

IV. EXAMPLES

In this paragraph, authors demonstrate examples of the use of matrix to describe the multi-agent system and to select unknown behavior.

A. *The example of two-agent description based on the matrix representation*

Let us consider the multi-agent system, where two agents A1 and A2 have predefined behaviors and A11 and A22 are internal behaviors and A12 and A21 are external behaviors (Figure 2).

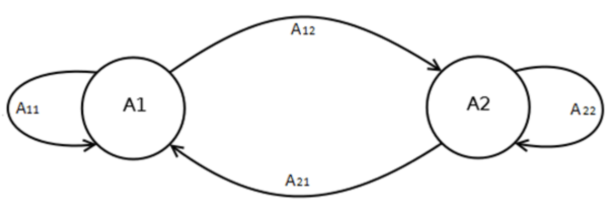

Figure 2. Two-agent system.

For the following example, adequate matrixes will be defined:

$$A = \begin{bmatrix} A_{21} - A_{12} & A_{12} \\ A_{21} & A_{12} - A_{21} \end{bmatrix} \tag{6}$$

$$A^T = \begin{bmatrix} A_{21} - A_{12} & A_{21} \\ A_{12} & A_{12} - A_{21} \end{bmatrix} \tag{7}$$

$$K = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{8}$$

$$D = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \tag{9}$$

Substituting to equation (5) we obtain representation of multi-agent system in the form of:

$$[\Phi] = \begin{bmatrix} A_{11} + A_{21} & A_{21} - A_{12} \\ A_{12} - A_{21} & A_{22} + A_{12} \end{bmatrix} \tag{10}$$

Conducting a detailed analysis of the matrix Φ we receive information about:

- First minor (φ_1) of a matrix Φ represents internal and incoming behaviors to agent $A_{1:}$

$$\varphi_1 = A_{11} + A_{21} \tag{11}$$

- Second minor (φ_2) of a matrix Φ represents behaviors of data exchange between agents A_1 and $A_{2:}$

$$\varphi_2 = A_{21} - A_{12} \tag{12}$$

- Third minor (φ_3) of a matrix Φ represents of data exchange between agents A_1 and $A_{2:}$

$$\varphi_3 = A_{12} - A_{21} \tag{13}$$

- Fourth minor (φ_4) of a matrix Φ represents internal and incoming behaviors to agent $A_{2:}$

$$\varphi_4 = A_{22} + A_{12} \tag{14}$$

- Trace of a matrix represents behaviors occurring in multi-agent system:

$$Tr[\Phi] = A_{11} + A_{21} + A_{22} + A_{12} \tag{15}$$

The above-mentioned examples were designed to show the application of (5) to describe the multi-agent system and the equivalence with the use of a graph. Description using matrixes is helpful in such a way that, in a compact form, it contains a representation of the dynamics of multi-agent system. It is not relevant what type of behaviors are written using matrix A. That is why the authors consider this record as universal. The results matrix Φ contains much information from which one can restore the functioning of the multi-agent system, basing solely on the content of individual cells of the matrix. Individual cells φ_i make it possible to obtain information on what types of behavior are present in the agent - whether they are its own internal behaviors (e.g., A_{11}) or behaviors associated with taking or receiving information to/from another agent (e.g., A_{21}). Additionally, the sum of the behavior of a given line (e.g., $\varphi_1 + \varphi_2$) is interpreted as the behavior occurring in the agent (e.g., for A_1). The results matrix can also determine

Copyright (c) IARIA, 2017. ISBN: 978-1-61208-576-0

whether, in a multi-agent system, there is at least one bidirectional communication between agents. In order to verify whether in the multi-agent system the exchange of information occurs, it is necessary to check whether the following identity is met:

$$Tr[\Phi] = \sum_i \varphi_i \tag{16}$$

In order to verify the above relationship the examples discussed earlier can be used:

$$A_{11} + A_{21} + A_{22} + A_{12} = A_{11} + A_{21} + A_{22} + A_{12} \Leftrightarrow Tr[\Phi] = \sum_i \varphi_i \tag{17}$$

B. The example of matrix representation for identification of desired behavior

The experiment is quite specific. This uniqueness is based on the use of the matrix record, introduced in Section III, to determine unknown behavior in a multi-agent system. The experiment was based on a two-agent representation of the glucose homeostasis system. The first agent represents the entire mechanism of normoglycemia in the case of type 1 diabetic patient. The second agent represents insulin delivery in the form of external administration (Figure 3). The purpose of this experiment is to define the behavior responsible for sending "information" from Agent A1 to Agent A2 so that the dose of insulin delivered contributes to the metabolism of glucose.

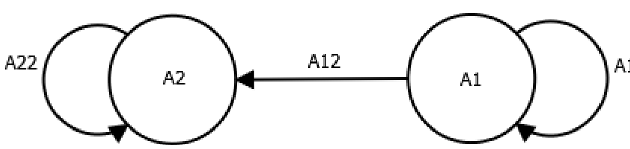

Figure 3. Diagram of multi-agent system for the experiment.

Based on the concepts introduced in the section above, we can define the appropriate arrays, and so the matrix A:

$$A = \begin{bmatrix} -A_{12} & A_{12} \\ 0 & A_{12} \end{bmatrix} \tag{18}$$

matrix K:

$$K = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \tag{19}$$

matrix D:

$$D = \begin{bmatrix} A_{11} & 0 \\ 0 & A_{22} \end{bmatrix} \tag{20}$$

The matrix of a multi-agent system is defined by the corresponding relation between the previously mentioned matrices so that the system matrix is:

$$\Phi = \begin{bmatrix} A_{11} & -A_{12} \\ 0 & A_{22} + A_{12} \end{bmatrix} \tag{21}$$

The trace of the matrix:

$$Tr\phi = A_{22} + A_{11} + A_{12} \tag{22}$$

In this particular case, the meaning of the individual behavior is as follows:

- Behavior A_{11} it is responsible for the insulin production that will eventually be introduced into the system. This behavior may also represent a buffer that stores a certain amount of insulin.
- Behavior A_{22} it represents all the phenomena occurring in the glycemic homeostasis system, along with the ways of insulin utilization.
- Behavior A_{12} it is responsible for the exchange of information (from agent A1 to agent A2) - this behavior should be determined.

The purpose here is to define the behavior A12 in such a way as to ensure insulin levels of φ_{A2}=7 [uIU/ml] for Agent A2. Below is a procedure to achieve our goal:

1. Simulation for the conditions specified for a person with type 1 diabetes (without insulin infusion) (Figure 4).

2. Transform the pattern (22) into a form that allows us to calculate the desired behavior. In this case, we get:

$$A_{12} = \varphi_{A2} - A_{22} \tag{23}$$

3. Perform curve fitting procedure (Figure 5) to the points obtained. This procedure was performed in MATLAB environment using the “fctool” command. The fit was done using a linear function. The following form of function is given:

$$f(A_{12}) = -0{,}0914t + 6{,}14 \tag{24}$$

4. The last step was to implement the equation described in Equation (24) into the body of the insulin dispensing agent. The simulation was started and a comparative analysis of data from the insulin-free model and from the model in which the found behavior A_{12}.

Below are the following drawings corresponding to the points mentioned above.

As can be deduced from Figure 6, the concept of using a matrix description to identify unknown behaviors is the most appropriate approach. Using (22), it is possible to select unknown behavior in such a way that the preset value can be maintained throughout the system under consideration. By focusing on the selected part of φ matrix, there is an opportunity to declare such an unknown behavior that will result in a given value from the agent the minor describes. This is the second case presented in this experiment. As a result of matching A_{12}, it has become possible to maintain insulin levels of 7 [uIU/ml] by the agent A2. Of course, the quality of the curve fitting to the measurement points (Figures 4 and 5) directly affects the quality of the results generated by the multi-agent system.

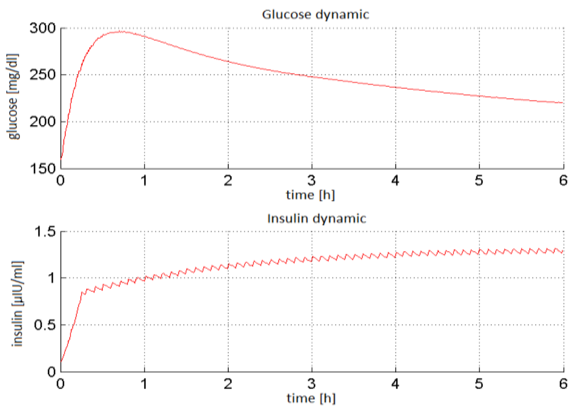

Figure 4. Simulation result for a person with type 1 diabetes - without insulin.

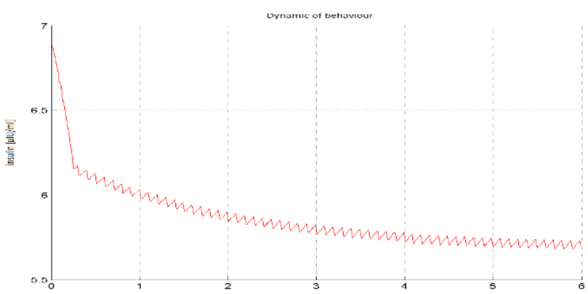

Figure 5. Chart for variability of behavior A_{12}.

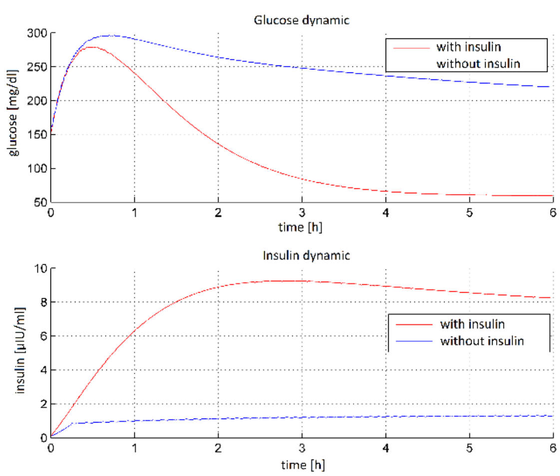

Figure 6. Simulation results for two cases: without insulin (blue curve), including the behavior of insulin dosing into the multiple agent system (red curve).

V. CONCLUSIONS

In this paper, we made the analysis of the multi-agent system with the use of graph theory and matrix calculus. This approach can help us analyze the operation of such system in two ways: quantitative and qualitative ones. The use of matrix record enables performance of analysis of internal multi-agent system involving assignment of behaviors to particular agents. External analysis of the multi-agent system with the use of introduced record allows for description of the relation between agents and for selection of such unknown behavior of agent which will meet the intended purpose or criterion implemented by the multi-agent system. In the second example, it is shown how using matrix equation allows finding the desired behavior of multi-agent system. For the general case in which the agents (and the multi-agent system) process several volumes, each of these factors must be represented by a separate graph of accurate dependency. Generally speaking, each value can represent different graph of connections between agents, and agents can have different numbers and behaviors intended to process these values. The matrix equation (5) proposed by authors, will be the subject of further work towards stability study of multi-agent system.

REFERENCES

1. H. S. Nwana, “Software agents: an overview,” *The Knowledge Engineering Review*, 1996, 11(3), pp. 205–244. doi: 10.1017/S026988890000789X.
2. M. Wooldridge, “An introduction to multiagent systems,” John Wiley& Sons, 2009.
3. P. Stone and M. Veloso, “Multiagent systems: A survey from a machine learning perspective,” Autonomous Robots 8.3: pp. 345-383, 2000.
4. A. Helleboogh, G. Vizzari, A. Uhrmacher and F. Michel, “Modeling dynamic environments in multi-agent simulation,” *Autonomous Agents and Multi-Agent Systems* 14.1 : 87-116, 2007.
5. T. Seth and U. Wilensky, “NetLogo: Design and implementation of a multi-agent modeling environment,” *Proceedings of agent*, vol. 2004.
6. F. Bellifemine, A. Poggi and G. Rimassa, “Developing multi-agent systems with JADE,” *International Workshop on Agent Theories, Architectures, and Languages*, Springer Berlin Heidelberg, 2000.
7. S. Parson and M. Wooldridge, “Game Theory and Decision Theory in Multi-Agent Systems,” Kluwer Academic Publisher, 2000.
8. P. J. Wangerman and F. R. Stengel, “Optimization and Coordination of Multiagent Systems Using Principled Negotiation,” Journal of guidance, control, and dynamics, vol. 22, No. 1, 1999.
9. S. Soylu, K. Danişman, I.E. Saçu and M. Alçi, "Closed-loop control of blood glucose level in type-1 diabetics: A simulation study." Electrical and Electronics Engineering (ELECO), 2013 8th International Conference on. IEEE, 2013.