An Evaluation Method for Multi-Agent Systems

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Abstract. The growing employment of Multi-Agent Systems (MASs) in several domains of everyday life has provided the impetus for much research into new tools and methodologies for their design and implementation. But up to now, few works have focused on evaluation of these MASs, and none of these considered characteristics such as the rationality, the autonomy, the reactivity and the environment adaptability of the agents in the MAS. We believe these characteristics affect the whole performance of these systems and are connected to the complexity of the environment where the agents act. In this paper we propose an evaluation method for static multi-agent systems. The method, based on the Goal-Question-Metric approach, allows evaluation of these same MAS characteristics and combines two analysis perspectives of these systems: intra-agent and inter-agent. We also report the use of the defined approach to evaluate the GeCo_Automotive system's MAS.

Keywords: Multi-Agent Systems, Goal-Question-Metric, MAS evaluation.

1 Introduction

In the last few years the Multi-Agent Systems (MASs) have been used in several domains such as logistics, networking, automation, simulation and robotics. The reasons for the success of MASs are mainly related to their capabilities of solving computationally difficult (or spatially distributed) problems and aptitude to develop social behaviors (one of the main conditions of agent intelligence). For all these reasons, MASs are today a consolidated research field where many interesting works about tools and design methodology have been presented. However, there are still few works addressing MAS evaluation. Moreover, often in the MAS evaluation process metrics are used that are defined on each individual agent. In this case, instead, it is important to take into account that a MAS is not only an aggregation of single agents, but is a complex system in which the agents interact in order to solve a problem.

Thus, the evaluation should be done according to other dimensions, such as the organizational structure or the type of interaction among the agents. A reliable method for MAS evaluation allows both estimation of the success of applications of the multi-agent paradigm in different domains, and the development of guidelines in order to design adequate solutions for the specific degree of environmental complexity. This paper presents the definition of a metric plan for the evaluation of static multi-agent systems using the Goal-Question-Metric (GQM) approach. The

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defined method enables evaluation of the complexity of the environment where the agent acts and the level, both individual and aggregate, of rationality, autonomy, reactivity, and adaptability to the environment that the agents exhibit in the MAS. This because the evaluation of the internal characteristics of the MAS agents has an impact on the overall performance of the system itself, and because the environment where the agents act cannot be ignored. The innovative aspect of the proposed method is that it merges two different approaches to the analysis of multi-agent systems: intra-agent and inter-agent. The first analyses the MAS agent as individual system highlighting the internal structure, the beliefs, the goals, and the perceptions related to its environment. The second considers each single MAS agent as a part of a society and analyses the interaction with the other agents of the system and its environment.

The paper is organised as follows: section 2 discusses some related works about the evaluation of multi-agent systems, section 3 presents the defined metric plan; section 4 describes the application of the defined method to the GeCo_Automotive multi-agent system and the results obtained. Finally, some conclusions and future research directions are outlined.

2 Related Works

Analysis of the literature about the evaluation of MASs has identified two main trends. The first considers the agent-based paradigm as the evolution of the object-oriented programming. In this case, the need for metrics to evaluate MASs has led to use and adaptation of object-oriented metrics such as the coupling between object classes, depth of the inheritance tree and so on [1]. Nevertheless, [2] states that these metrics are too low-level to be meaningful for agent-based software. The other trend consists of considering MASs mainly as distributed systems, thus, the aspects mostly considered in the evaluation are the architectural ones and the communication among the agents. In [3] several metrics are proposed such as the connection cost metric that can, if applied to real systems, predict how suitable the different Java RMI implementations are to the different environments and network configurations. In [4] an approach to evaluating the communication in MASs is proposed. The authors implement an evaluation tool that captures the messages exchanged among the MAS agents and extracts the data that depict a communication (directed) graph where the agents are the nodes and the arcs represent the communication links. The graph allows calculation of the value of metrics such as: communication level, number of the agents involved, the number of connections, and so forth. In [5] a set of metrics is suggested, serving to measure the communication and to detect the reasons for an unbalanced communication. In [6] Lee and Hwang assert the need to design agent-based systems in order to allow the agents to interact efficiently. They define metrics that allow evaluation of the organisation (complexity, extendibility and availability of the organization) and the MAS agents behaviour (processing time or cost). Instead, Lass et al. in [7] analyse several metrics for MASs like the environment/host metrics and system metrics. The first describes the aspects of the environment in which the system is tested; the second evaluates the performance of MAS in performing a specific task. In addition, the authors suggest the use of Basili's GQM approach [8] to evaluate multi-agent systems, but they do not define any metric plan.

This paper presents an evaluation method that differs from the other approaches cited in literature in terms of three main aspects. Firstly, it proposes the use of high-level metrics in order to evaluate MASs and emphasizes the measurements of agent characteristics such as rationality, autonomy, reactivity and the environment's adaptability. Secondly, the defined method merges two MAS evaluation perspectives: inter-agent and intra-agent. The inter-agent evaluation considers the whole MAS aspects (cooperation and communication among agents), whereas the intra-agent evaluation considers the internal structure of each single agents (in terms of ability to learn, planning capabilities, and so on). Thirdly, it provides a metric plan in order to assess a MAS.

3 Definition of the Metric Plan

The evaluation of a static agents MAS is an overall process that needs to be defined independently of any specific implementation field and context of use. For this reason the metric plan was established using the GQM approach. Five goals were defined, related to fundamental aspects of the design of multi-agent systems, namely: the complexity of the environment, the rationality, the autonomy, the reactivity, and the adaptativity to the environment. For each goal, questions and metrics were identified that could firstly assess the agents as single entities and secondly, evaluate the entire MAS from a global viewpoint. Each MAS characteristic examined was quantitatively evaluated so as to make a numerical estimate of its autonomy, reactivity, rationality and adaptativity. These estimates were then compared with the environment complexity to determine the adequacy of the internal characteristics of the MAS to the environment where it acts. In [9] the environment is defined as the problem the agent must solve; it is clear that without an accurate analysis of the environment in which it operates, no evaluation of the MAS characteristics could be possible. One of the problems encountered in defining the metric plan was the different definitions found in literature not only of the environment but also of the internal characteristics of the MAS. To avoid the risk of ambiguity in defining the metric plan, a definition of the characteristic considered for each goal is provided, as well as the measurements to be made (or calculated) to estimate it.

3.1 Goal 1: The Environment Complexity

According to Russell and Norvig [9] an environment can be classified on the basis of various lines: its observability (complete/partial), the effect the agent's actions have on the environment (deterministic/stochastic), the time (discrete/continuous), the number of agents (single/multi-agent), the history of the perceptions (episodic/sequential) and the way it evolves (static/dynamic). The number and subjectivity of these lines make it difficult to characterize the environment. It is easy to identify which is the most complex environment, but if it presents other combinations of these properties it will be difficult to define their complexity.

Moreover, these properties are not always enough to characterize the environment and the effect of the agents' interactions on it. In the proposed method the complexity of the environment has been assessed on the basis of three different characteristics, namely: the inaccessibility of the environment, the instability, and the behavior of the agents. Each of these has been directly measured using a three-point scale: high, medium and low. To evaluate the inaccessibility of the environment two questions were defined, one assessing the inobservability of the environment (*EnvUnobs*: measured in terms of the agent's inability to access the complete state of the environment at any instant), and the other the inaccessibility of the resources (*ResInacc*: calculated as the trend of the inaccessibility level of each single resource).

Both metrics are expressed on the 3-point value scale (high, medium, low). The instability of the environment was defined using specific metrics based on time (*Time*: discrete or continuous), the possibility that the environment may change without any direct action of the agent (*Dynam*: static or dynamic) and the number of effects of the actions executed by the MAS agents (*NumEffeAct*: one or more effects). A value of 1 is assigned if the time is continuous, the environment dynamic, or the agent's action has more than one effect, otherwise 0. The instability (*TotInstab*) is high if the sum of the three metrics is more than 2, medium if it is equal to 2, and low in all other cases. To assess the behavior of the agents in the environment, two metrics were used, one to measure the degree of competition (*CompGrad*) among the MAS agents, and one to measure the presence of trust and reputation models (*Tr&RepMod*). For the first of these questions the value is "high" in cases in which the agents compete throughout the life cycle, "medium" if the agents alternate moments of competition with moments of cooperation, "low" if they cooperate throughout the life cycle. Instead, as regards the presence of trust and reputation models, a subjective assessment (as low/medium/high) is made of the presence of environment logics requiring an agent to assess the information sources from which to obtain the data needed to accomplish the goal. The complexity of the environment is calculated using the formula: $EnvCompl = \alpha H + \beta M + \gamma L$ where α, β and γ are the number of high, medium and low scores, respectively and H, M, L the values 2,1,0. The value of *EnvCompl* can range between [0-14]. If $EnvCompl \in [0\text{-}4]$ then the value is low, if $EnvCompl \in [5\text{-}9]$ it is medium, and if above, the complexity is high.

3.2 Goal 2: Rationality

Russell and Norvig in [9] define the rationality of an agent as its ability to take actions that can maximize its success. This ability varies according to the performance metrics, the perception sequence, the knowledge of the environment and the actions the agent can accomplish. In the proposed metric plan the degree of rationality of the MAS agents was evaluated according to the following aspects: mode of choice of the actions and maximization of the success. The mode of choice of the actions was assessed using the metrics: agent type (simple, stimulus-response, goal-based agent, etc.), ability to build plans of action, ability to learn, and possession of an internal model of the actions and intentions of the other MAS agents. The metric agent type (*AgType*) assigns a value of 0 if the agent is simply reactive or model-based, 1 if it is goal or utility-based. The metric capacity to build plans of action (*PlaConstr*) attributes to each MAS agent a value of 1 if it is able to build plans, 0 if not. The same logic is employed for the metrics capacity to learn (*LearAb*) and possession of an internal model of the actions and intentions of the other MAS agents (*InsMod*). Maximization of the success was evaluated as the capacity to maximize the expected result of the actions (*ActMax*). To calculate this metric, for each agent n intervals of observation lasting t seconds are defined. For each interval, the agent's perception sequence is derived, as well as the knowledge of the environment possessed. The possible agent actions are defined as a function of the state it is in and the expected results on the environment in the observation interval. These results must be expressed in numerical terms. After establishing the expected metric, the result on the environment caused by the agent's action is observed. The expected result is compared with the obtained result using the following expression: (|*val.expect-val.obtain.*|)/*base* where *base* is a numerical value that can normalize the value on a scale from 0 to 1. The result of this expression is defined as the gap between the expected result and the result obtained. It is important to choose as expected value an optimal but realistic estimate of the agent's performance. The *base* value depends on the choice of the range of expected and obtained results.

After calculating the gap, the mean gap for each agent is calculated on the basis of the number of intervals considered. The capacity of the MAS to maximize the expected result is the one’s complement of the mean of the *MeanGap* values calculated for all the MAS agents. The rationality value for each agent (*AgRatio*) is the mean of the values of all the defined metrics. The mean of the rationality values for all the MAS agents yields the rationality value for the entire MAS (*MASRatio*).

3.3 Goal 3: Autonomy

According to Wooldridge [10], autonomy is the property that characterizes the agent. This consists of its ability to act without the need for human intervention or actions by other agents. A key element of autonomy is proactivity, in other words the ability to “take the initiative” rather than simply acting in response to the environment. Proactivity includes the agents' capacity to exhibit behavior both directed to satisfying their goals, and to anticipating future situations, making predictions. We believe that in the case of MAS agents assessment of the autonomy must also take into account the agent's role in the MAS organization. For this reason, the degree of autonomy of each agent was evaluated on the basis of its proactivity and the role it has in the organizational structure. To assess proactivity, various questions were asked (and relative metrics) probing the agent's ability to learn new knowledge (*LearAb*), ability to diagnose errors and/or problems (*DiaErPrAb*) during execution of the tasks, and the ability to undertake and autonomously conduct a communication (*ComAutAb*) with the other MAS agents. A value of 1 was assigned if this capacity was present, 0 otherwise. Assessment of the role of the agent in the organizational structure considers for each agent: its position in the MAS structure (*PosStr*) that is 0 if the agent occupies a subordinate position, and 1 otherwise; the ability to take on several roles (*MoreRol*: with a value of 1 for more than one role, 0 otherwise); the ability to negotiate with other agents (*NegAg*: value 1 if present, 0 otherwise); and sharing tasks or resources (*SharTask&Res*). Since sharing makes the agent less autonomous, a value of 0 is assigned if it can share, 1 otherwise). The level of autonomy of each agent (*AgAuto*) is the mean of the values of the metrics for proactivity and the role played in the organizational structure. The level of autonomy exhibited by the MAS (*MASAuto*) is equal to the mean of the levels of autonomy of its agents.

3.4 Goal 4: Reactivity

Most of the proposals for classifying agents present in the literature [11] consider a reactive agent as an agent lacking internal states, programmed to make the action to be accomplished correspond to a perception sequence. In the metric plan we define reactivity is considered as the ability to perceive the environment and respond in a timely fashion to changes in it. This quality is assessed by taking into account the efficiency of acquisition of perceptions of the environment and the rapidity of accomplishment of its tasks or goals. The metric plan evaluates the ability of each agent to perceive the environment using a question and relative metric with three values. This metric (*EnvPercEff*) checks whether the agent's sensory system allows it to process perceptions in a satisfactory way, choosing the most significant perceptions or aggregating large perception sequences (value 1); or can process perceptions but not always adequately for the agent's goals (value 0.5); or else cannot process the perception sequence at all (value 0). Instead, the agent's rapidity of accomplishment of its tasks or goals (*RapReachGoals*) is assessed using various questions and defining the following metrics: predefined behavior of the agent, possession of a model of the environment, number of roles in the MAS and minimization of communication while carrying out the given tasks. The metric predefined behavior (*DefBeh*) ascertains whether the agent's reactions were pre-established by the designer (value 1 if so, 0 otherwise). The metric possession of a model of the environment (*EnvMod*) examines whether the agent bases the choice of actions to be executed on a model of the environment; if there is no model the actions will be faster (1 if it does not possess a model, 0 otherwise). The metric number of roles (*NumRol*) sees whether the agent has one or more roles. Because playing more than one role implies less reactivity, a value of 1 is assigned if the agent has a single role in the MAS, 0 otherwise. Finally, the metric minimization of communication (*ComMin*) assesses the MAS agent's ability to carry out its tasks or goals with minimal communication with other agents, since this increases the response times. For this purpose, n intervals of time are defined, each interval lasting time t and the number gr of gaols achieved in interval t. Then the mean number of messages exchanged to achieve the goal is calculated. If this value is equal to or less than the previously defined expected value, *ComMin* has a value of 1, otherwise 0. The level of reactivity of each agent (*AgReact*) is the mean of the values of the single metrics, while the overall reactivity value of the MAS (*MASReact*) is the mean of the reactivity levels of all its agents.

3.5 Goal 5: Adaptability to the Environment

Since the environmental conditions can change rapidly, the agent must be able to adapt to it. This involves being able to modify the plan of actions to be undertaken to achieve the goal and in some cases, also the possibility of changing the short term goal if pursuit of this would lead to failure to achieve the main goal. In a MAS, the environment each agent must adapt to includes other agents, so it is necessary to consider the adaptability of the entire system. In this work the ability to adapt to the MAS environment (*EnvAdapt*) was taken as the mean capacity of adaptation to the environment of each agent. To this end, the agent's ability to respond to new external stimuli was probed, as well as the ability to manage different situations. The ability to respond to new external stimuli was assessed by taking into account the agent's ability to choose the actions to be executed according to the goals to be achieved (*ChoAct*); the ability to take on more than one role (*DifRol*) and the ability to share tasks or resources with other MAS agents (*SharTask&Res*). The metric *ChoAct* was assigned a value of 1 if the agent is goal-based, 0 if it has simple reflexes; the metric *DifRol* was scored 1 if the agent can have several different roles, 0 otherwise; the metric *SharTask&Res* scored 1 if the agent shares tasks with other agents, 0 otherwise. The ability to manage different situations was evaluated in terms of the ability to learn (*LearAb*), efficiency in finding heuristics for achieving its goals (*EurFinAb*), and efficiency in handling exceptions (*ExcManAb*). The metric *LearAb* was given value 1 if the agent is able to learn, 0 otherwise. The metric *EurFinAb* was calculated by comparing the mean number of messages sent by the agent to obtain useful information (*vmr*) and the number of messages the agent sent in the environment expected by the assessor (*va*). If $vmr > va$ the metric *EurFinAb* has a value of 0, otherwise it will be 1. The metric *ExcManAb* is calculated by comparing the number of exceptions managed by the code of each single agent (*nem*) and the number of exceptions the agent is expected to manage (*ea*). If $nem \geq ea$ *ExcManAb* has a value of 1, otherwise 0. The adaptability of each agent to the environment (*AgAdapt*) is the mean of the values of the above metrics. The adaptability of the MAS environment is the mean of the adaptability values of the single agents.

3.6 Interpreting the Values of the Metrics

The proposed metric plan indicates the methods for measuring the complexity of the environment and the characteristics of the MAS, but does not enable assessment of its adequacy to the environment where it operates. It is necessary to compare the evaluation of the environment with that of the MAS. For the sake of simplicity, the complexity of the environment has been evaluated as low, medium or high. These values depend on different combinations of the seven metrics characterizing the environment. To make an accurate evaluation of the metric plan all the possible combinations need to be considered. For the sake of brevity only cases of low and high complexity are described, because they are those best suited to general considerations. An exhaustive analysis of the metric plan will be presented in a later publication. If the environment complexity is high this means that the agents have poor perception of the environment and difficulty in accessing the available resources; the environment evolves rapidly and there are complex models of interaction among the agents. For a MAS to act adequately within a complex environment it needs to have a good level of rationality (0.6 to 1) so that the agents' ability to plan, learn and consider the actions and intentions of the other agents can contend with the poor accessibility and observability of the environment. Moreover, a complex environment evolves very rapidly and so the MAS agents need to be proactive and able to negotiate tasks and resources so as to face continually new situations (level of autonomy from 0.5 to 1). Considering that the faster the agents' response the lower their rationailty, in complex environments it is preferable to have a reactivity level that is just sufficient to gain a meaningful perception of the environment (from 0 to 0.3). Otherwise, the agents' adaptability needs to be high (from 0.6 to 1) to be able to manage the different situations that may present, bearing in mind the dynamicity and poor observability of the environment. If the environment has low complexity it is enough to have a rationality level ranging between 0.2 and 0.3, because in this case the ability to maximize the success is more important rather than that of carrying out complex reasoning. If the rationality is low the reactivity level must be high, as otherwise the MAS will waste computational resources. The level of autonomy can be low, provided that is combined with an ability to diagnose errors and problems (from 0 to 0.2). Finally, it is sufficient for the MAS agents to be equipped with the ability to share tasks and resources, so a level of adaptability ranging between 0.2 is enough.

4 An Application of the Evaluation Method

The evaluation method presented was used to estimate the MAS integrated in GeCo_Automotive [12], an ICT system designed to promote knowledge management and capitalization in small-medium-sized companies in the automobile sector. Application of the described evaluation method allowed us to assess the adequacy of this MAS to the environment for recommending teaching and documentary resources, and to observe specific weaknesses of the single agents in the sense of poor rationality, autonomy, reactivity and adaptability to the environment. The results of our evaluation may provide a useful basis for reflections on the possible solutions to be adopted to improve the multi-agent system, whose performance has a strong influence on the overall performance of the ICT system. The MAS of GeCo_Automotive consists of two static agents that classify and retrieve teaching and documentary resources. With these, the MAS is able to suggest the resources best suited to the user's specific needs. The classifying agent catalogs resources on the basis of their descriptions and of previously defined taxonomies. The search agent selects from the set of available resources those best suited to the user's specific needs. To do this, it refers to its knowledge of the user, of the organization of the resources, and its perception of the user's query, by processing its syntax. The following section reports the results of application of the evaluation methods.

4.1 Environment Complexity

The environment where the MAS operates consists of the ICT system it is integrated in and the set of company employees that use it. The inobservability of the environment is defined as the agents' inability to have complete access at any instant to the system components and the knowledge possessed by the company employees. The inaccessibility of the resources was assessed in terms of the incompleteness of the metadata describing them. The time was continuous and the environment dynamic because users can continuously modify their knowledge independently of their use of the system. The effects of the agents' actions can be multiple, because, according to the user profile, the search agent selects different types of resources. Overall, there is a high level of instability. Moreover, the two agents collaborate throughout their life cycle and do not employ trust and reputation models. The environment complexity is low, therefore: the environment lacks complete observability and evolves very rapidly, but its resources are easily accessible.

4.2 Evaluation of the Characteristics of the MAS Agents

Application of the metric plan showed a minimal level of rationality for both the classifier agent and the search agent. Both agents have simple reflexes, do not build plans of actions to reach their goals, are unable to learn and do not possess an internal model of the actions and intentions of the other agent. The ability to maximize the expected result was measured for the classifier agent as the percentage of correctly classified resources in the time interval considered, and for the search agent as the percentage of proposed resources that satisfy the user's needs. The MAS agents show the same level of autonomy. They are not able to learn, nor to make diagnosis of errors or problems occurring during the performance of their tasks, nor can they autonomously undertake or maintain any communication. They have fixed roles in the MAS, defined a priori by the designer, and no ability to negotiate. The only values in favour of autonomy are those relative to their non subordinate position in the MAS structure and lack of sharing of tasks or resources. The evaluation of the MAS reactivity demonstrated a very high reactivity level. The two agents do not perform any processing of the perceptions, carry out actions defined during the design phase, do not have an internal model of the environment and play a single role in the MAS. In addition, they do not communicate between themselves while carrying out their activities. This results in maximum rapidity of the reactions. The MAS cataloguing and search agents of the GeCo_Automotive system present poor adaptability to the environment. For both agents the only value in favour of adaptability is that of the management of exceptions.

4.3 Interpreting the Values of the Metrics in GeCo_Automotive

Evaluation of the MAS using the defined metric plan has highlighted the fact that the considered environment has a low level of complexity. The rationality level of the MAS is appropriate because it depends on its ability to maximize its success. The agent autonomy, instead, is not adequate to the environment because it is related to the agent's independence during the execution of its tasks and does not depend on its ability to diagnose errors or problems. The reactivity level and the environment adaptability are acceptable. The estimated value of the adaptability to the environment is higher than the expected value, this is important in order to face the rapid evolution of the environment. Thus, the MAS considered is adequate to its environment, even if the agent autonomy level needs to be improved by increasing the proactivity.

5 Conclusion

The paper proposes a method for evaluating MASs, based on the GQM approach.

Unlike other evaluation approaches presented in the literature, the paper proposes, first of all, the use of high level metrics that highlight characteristics like autonomy, reactivity, environment adaptability, that thus allow the agents to be distinguished from the objects (of the O.O. paradigm). Moreover, it merges the evaluation of inter-agent and intra-agent characteristics, supplying a ready-to-use GQM. Considering the high level of abstraction of the approach, it is necessary to contextualize the metrics according to the specific MAS to be evaluated. In addition, the work presents a first application of the metric plan to the GeCo_Automotive system that suggests learning activities and best practices to employees of companies in the automotive sector. This application has allowed us to draw some observations about the agents' suitability to the environment complexity.

At present, we are designing an experimentation in order to test and evaluate the metric plan. One of the main future developments of this work will be the definition of guidelines in order to design effective MASs for the environment where they work.

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