Toward a Temporal Environment for Multi-Agent Simulation

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Abstract — The environment plays an important role in multi-agent systems (MASs). Especially in situated MASs, it is used as a shared memory for agents and as a medium for indirect coordination. There are different types of environment, with different metric and containing different types of information. The more choices for environment structures, the broader its application in the field of MASs. The information space has different dimensions, and the temporal dimension is an important one. Especially in a situated MASs, the agents can be situated in space and time. However, in MASs, this temporal dimension is often neglected or plays a subordinate role. This paper shares the idea of exploiting the potential of this long-neglected temporal dimension by introducing the notion of temporal environment. This consists of using the time axis not only for the simulation scheduling, but as an environment where the agents could interact. The temporal environment presented in this paper is based on a particular time scheduling approach called the Temporality Model and on the influence/reaction principle.

Index Terms—Multi-agent simulation, environment, time axis, scheduler, temporal environment, temporality model, infuence/reaction

I. INTRODUCTION

Multi-agent research community agreed about the importance of the environment for Multi-agent Systems (MASs) [1]. Especially in situated MASs, the environment can work as a robust, self-revising, shared memory for agents and a medium for indirect coordination [2]. This can offload the agent from continuously keeping track of their knowledge about the system. The environment in MASs can also be defined as a "space" with a metric [3]. Thus, there are different types of environments that contain specific types of information, using different metrics. Example: a physical environment, can be modelled as a continuous space, a grid or a GIS and contains information about the coordinate location of an agent. Its metric is the space. A communication environment can be modelled as a graph and can contain information about the link between agents. The more choices for environment structures, the broader its application in the field of multi-agent simulation systems [4] and the more information they contain can be of different types.

Time is an important dimension of the information [5]. However, in agent-based simulation, the temporal dimension is often neglected or plays a subordinate role. Indeed, there are still few works about spatio-temporal environment that really takes into account time as well as space [6]. To address that, this paper introduces the notion of temporal environment, defined as an environment which metric is time. The objective is to raise awareness of the benefits brought by taking into account the temporal dimension.

This document is structured as follows, section II gives an overview of the environment, its role and its relation with the agents, especially the influence/reaction principle. Then, it speaks about the use of the environment as a scheduler of the simulation before ending with a comparison between the most commonly used time scheduling as stated in the literature. Section III introduces the basic notion of temporal environment before ending with the conclusion and further works in section IV.

II. RELATED WORK

A. The Environment in MASs

According to J. Odell & al. [2], an environment provides the conditions under which an entity (agent or object) exists. In a situated MASs, the environment is considered as an active entity with its own processes that can change its own state, independently of the activity of the embedded agents [1]. Intuitively, the environment can be seen as a place for agent's interaction with objects, resources, and with other agents. Therefore, a majority of researchers from the multi-agent systems research community consider the environment as a means for agent communication and as an agent container [7].

There are different types of environments in the literature. The most common are the physical environment and the communication environment [2]. The physical environment provides rules and constraints that govern and support the physical existence of agents and objects. Example: it defines the law, according to which two agents are not allowed to occupy the same place at the same time. The communication environment provides the principles and processes that govern and support the exchange of ideas, knowledge, information,

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the functions and structures that are commonly used to exchange communication. Examples are roles, groups, and the interaction protocols between roles and groups. There is also a social environment that is a particular case of communication environment. It is defined as a “place” in which the agents interact in a coordinated manner. It consists of the social units in which the agent participates, the roles that are used for social interaction and all the other members who play roles in these social units or groups. A group can exist even if it is empty, i.e. no agent participates in the group. It can also contain a single participant or multiple agents. The identity of groups is unique in the overall system. A role is defined as an abstract representation of an agent’s function, service or identification within a group. According to Odell et al., roles determine the patterns of dependencies and interactions among agents.

Following the same logic, a temporal environment can be defined as a particular type of environment that provides a structure, rules, constraints, principle and processes, allowing agents not only to evolve following a virtual time but also to share and perceives temporal information. Thus, the temporal environment allows agents to express the dynamic of their temporal activation. Otherwise, the environment in MASs can also be defined as a “space” with a metric. Most of the time, this metric is spatial. However, an agent can be situated in space and in time. Thus, in the temporal environment, the metric is the time.

B. Role of the Environment

Weyns and his collegues [7] defines 6 roles of the environment:

- Structuring by acting as a shared common “space” for the agents, which structures the whole system. Such a structuring can be spacial or organizational. Specific different properties can be defined separately for each space, such as positions, locality, groups or roles.
- Managing resources and services by working as a container for resources and services to be accessed.
- Enabling communication by definition of concrete means for agents to communicate.
- Ruling the multiagent system by defining different types of rules or laws on all the entities that it contains.
- Providing observability by allowing the agent to have (limited) access to its resources, services or action of other agents.
- Maintaining environmental processes by assigning particular activities to resources in addition to the agent activity.

This paper proposes a uniform management of the environment, whether spatial or temporal. Thus, the temporal environment plays the same role as a spatial one, but focused on more time-specific properties. For example, it imposes a temporal structure for the whole system with time-specific properties such as location in time (date, hour, etc.).

C. Relation between the Agents and the Environment

The agents perceive their environment and act upon it. In situated MASs, the result of agents’actions and interactions are usually modelled as a transformation of a global state. This can be illustrated as shown in 0

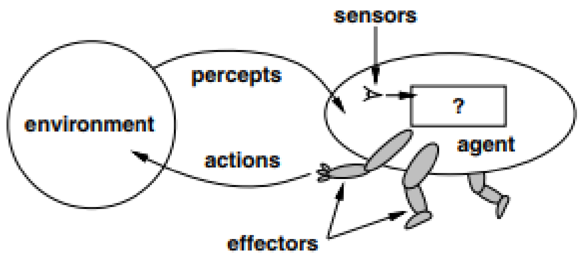

Fig. 1. Agent interaction with the environment [11, p. 4].

However, studies demonstrated that such an action modelling raises a number of problems at both the modelling and implementation levels [8], [9]. As a solution, Ferber and Müller [9] propose the influence/reaction principle which separates what agents do with how the environment reacts upon this. The influence/Reaction principle relies on two notions: influences and reaction to influences.

An influence is different from an action as it does not directly modify the environment. Indeed, from the point of view of the agent, the result of an influence cannot be guaranteed. In other words, there is a clear distinction between the individual gestures at the agent level and what actually happens considering the other gestures, i.e. the environment reaction to all the influences at the multi-agent level. Consequently, the reaction cannot be computed without knowing all the influences produced at the same time.

The implementation of this principle requires a two phase mechanism:

- The influence phase: for collecting influences;
- The reaction phase: for computing their combination results.

The notion of the temporal environment shared in this paper uses the same principle. As the metric used in a temporal environment is the time, the idea consists in sharing temporal information in an environment that the agents could influence and which can react following the influence/reaction principle.

D. The Environment as a Global Scheduler of the Simulation

In MASs, the scheduler is responsible for the virtual time management. It defines how the agents are activated in a simulation cycle and how the simulation time and the internal time of the agents evolve. In their approach called Environment as Active Support for Simulation (EASS) model, Badeig & al. [10] proposes another way of agents activating in multi-agent simulations. They use the environment as a scheduler of the simulation. In their approach, the environment is in charge of managing the agent activation process in addition to the services and roles it already plays. Therefore, the environment becomes the global scheduler of the simulation. It defines the link between the treatment of the simulation time, the triggering and the action of the agents.

Based on that, the approach described in this paper proposes the use of the temporal environment as scheduler of the simulation. Thus, the temporal environment allows the agents to express the dynamic of their activations, to share it and to make it perceptible by other agents. The idea consists in the use of the environment not only as a shared memory for agents and as a medium for an indirect coordination, but also using the information that the agents can be perceived in the temporal environment for time scheduling.

E. Time Scheduling Approaches in MASs

As said in subsection D, a simulation platform makes a simulation model evolve following a virtual time. This is done by an entity called the scheduler, using different time scheduling approaches. Most classical ones are the time-stepped, the event-driven and the mixed approaches [12].

According to subsection the previous sections, the time scheduling approach used for the temporal environment should meet the following criteria:

- Allow the structuring of temporal information that agents can share and perceive using influence/reaction principle.
- Allow the agents to express the dynamic of their activations, to share it and to make it perceptible by other agents.

In addition, since many agent simulations run on personal computers, with limited computing power, it is important that the proposed solution minimizes the impacts in terms of performance (scalability while maintaining acceptable performance).

This subsection briefly describes the different time scheduling approaches that are commonly used and discusses about the advantages and the limits of each of them based on these criteria.

1) The time-stepped approach

The time-stepped approach is the most used approach in multi-agent systems. It divides the simulation time into regular intervals called time steps and updates all the agents synchronously at every time step [12]. The time axis can be illustrated as shown in 0

The biggest advantage of this approach is its ease of implementation with regard to the simulation infrastructure. Moreover, its modelling of the agents' behaviour is simple since all actions implicitly obtain a duration. Thus, this approach is suitable in the case where the simulated model is composed of homogeneous agents, i.e. agents that have the same activation frequency. Moreover, in this approach the dynamic of the agents' activation is expressed as it is defined by the time step.

However, the author of [13] showed that using of a regular discretization of time is not appropriate when the simulated model is composed of heterogeneous agents. Indeed, in that case, because of their different nature, the agents may have different needs in terms of activation frequency. Consequently, imposing the same time-step on all the agents is inappropriate.

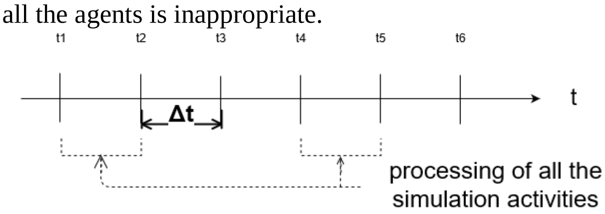

Fig. 2. The time axis for the time-stepped approach [14].

2) The event-driven approach

In this approach, the time axis of the simulation is continuous, but the state of the system is discrete. It changes at precise time called events. An event can be defined as the description of the agents' behaviour activation condition at a specific time [12]. Thus, the simulation consists in executing an orderly list of events (See Fig. 3). It combines irregular time intervals with an asynchronous update of the agents. The activation dynamics of the agents is therefore difficult to predict and therefore complicated to express. This constitutes a first limit with respect to its possible use in the context of the temporal environment.

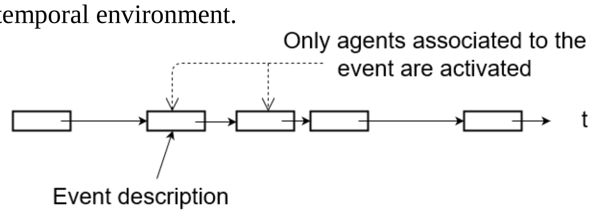

Fig. 3. Time axis for the event-driven approach [14].

This approach is more efficient than the time-stepped approach since it is focused only on points in time when changes actually occur and skips inactive phases of the system. In addition, only entities affected by the current event have to be updated. Moreover, it is more accurate as it allows events to occur at the correct time. This addresses the limitation of the time-stepped approach and fits in a case of a simulation that is composed of highly heterogeneous agents.

However, in terms of performance, this approach was criticized because of the simulated time forms that could become very complex [15] and that can lead to substantial calculations [16].

3) The mixed approach

The mixed approaches (0consist in splitting the simulated model into sub-models. Each sub-model is associated with the most appropriate type of scheduler. The time management system is a combination of the different schedulers chosen. Thus, there is no global time axis. Use cases can be found in [17] and [18].

This lack of global vision makes analysis of the simulation time difficult [16].

Each of the 3 classic approaches has their benefits and their disadvantages. However, Payet et al. [16] proposed an alternative approach called the temporality model as an appropriate approach that addresses these several limits while combining the advantages of these 3 classical approaches. Therefore, this temporality model approach is considered as a potential candidate for the structuring of the temporal environment.

III. The Temporal Environment: Application to MASs Transport Simulation

A human life includes of a succession of activities such as work, leisures, study, etc. These activities are located in the space and the time and are often constrained by space and time. These form the daily schedule which is allowed through travel using means of transportation and communication. This already indicates the important role that time plays as the space in the daily mobility. Therefore, the transport flow simulation seems to be a good example to illustrate the concept of temporal environment. However, in this context, if the importance of the spatial dimension is obvious (insofar as most of MASs naturally integrates a spatial environment), the temporal dimension is less so [6]. Thus, although some works deal with the spatio-temporal environment [6], attention accorded to the time is often limited, even if in some cases, such as in transport flow simulation, the temporal dimension could be as important as the spatial dimension. For that purpose, this paper proposes a uniform management of the environment whether spatial or temporal. The temporal environment described in this paper is based on the same principles as the spatial environment. A temporal environment is defined as a particular type of environment that provides a structure, rules, constraints, principle and processes, allowing agents not only to evolve following a virtual time but also to share and perceives temporal information. In this kind of environment, the metric is time.

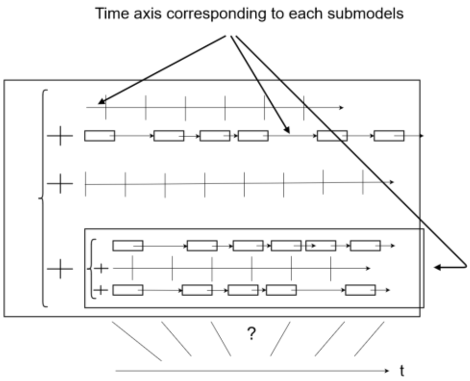

Fig. 4. Time axis for mixed approaches [14]

The idea is based on the use of the environment as:

- A shared memory for agents and a medium for an indirect coordination
- A global scheduler of the simulation

Therefore, the temporal environment can be divided into two parts:

- An independent environment for sharing and perception of temporal information
- A sublayer for global time scheduling.

A. Temporal Environment for Sharing and Perception of Temporal Information

The MASs is defined by:

$$\{ Ag, \Sigma, \Gamma, Op, Exec, React \} \quad [9]$$

where Ag is a set of agents, Σ is a set of the environment's states, Γ is a set of influences, Op is a set of operations, Exec describes the application of an operation and React is the reaction of the environment.

As mentioned earlier, a human life includes a succession of activities, located and constrained by time and space. This forms the daily schedule and is allowed through travel using means of transportation and communication. Inspired from this system, a temporal environment Σ in MASs is defined as an environment composed of **calendar c_i**.

$$\Sigma = \{c_1, c_2, \ldots, c_n\}$$

Each agent of the system is assigned at least a calendar c_i. A calendar c_i is a representation of an agent in the temporal environment. It is a structured representation that allows displaying and sharing information about behaviours that the agent wants to activate based on time. Thus, the agents express their activation dynamics through these calendars.

This environment Σ, composed of calendars, is influenced and perceived by the agents, based on the influence/reaction principle. That requires a two phase mechanism:

- The influence phase: For collecting influences;
- The reaction phase: For computing their combination results.

1) *The influence Γ*

The **influence** Γ is obtained by the application of an operator Op on the environment. The application of an operator can be described by a function Exec that takes an operator, a current state and returns an influence:

$$Exec: Op \times \Sigma \rightarrow \Gamma$$

Examples of operators could be: try to write, to remove, or to update an information in a calendar. The resulting influence could respectively be: add, delete, replace the corresponding information in the calendar or do nothing.

Actions can be composed to define an influence resulting from the simultaneity of actions performed in a given state of the world. The simultaneous action combination operator, which is written | that makes the union of the influences of the actions taken separately. The function Exec can then be extended to become a morphism of the action space with the simultaneity operator fir the set of influences:

$$Exec: (Op, \|) \times \Sigma \rightarrow \Gamma$$

2) *The reaction react*

The laws of the universe are described using a React function that specifies how the world is transformed from one state to another, and in particular how it reacts to influences.

$$React: \Sigma \times \Gamma \rightarrow \Sigma$$

3) *The perception percept*

Perception is the quality for an agent of being able to classify and distinguish the states of the world at the same time, according to the salient features of the environment, but also according to the actions that it undertakes. As a result, a perception is considered as a function that associates with all the states of the world Σ a set of values called percepts or stimuli. If we call P_a the set of percepts associated with an agent a, then the perception function of an agent can be defined as:

$$Percept_a : \Sigma \rightarrow P_a$$

The deliberation behaviour of an agent can be given in the form of located actions. These actions are defined as a set of partial functions that associate a particular action with a percept. A located action is represented by a rule: if <percept> then <action> where <percept>

A very simple example:

Rule update-info$_i$-in-c$_1$

if info$_i$ -exists-in-c$_1$

then update-info$_i$

B. A sublayer for Global Time Scheduling

The second part of the temporal environment proposes a scheduling mechanism that uses the data collected from the calendars, for the agent activation. The advantage is that this unloads the agent and the developer of all the complexity of the scheduling mechanism. In addition, the mechanism is completely transparent from the user's point of view. The agents only need to define activities based on time, and the environment takes care of everything: scheduling and conflict management.

The proposed approach consists in setting up another sublayer that evolves depending on the temporal environment and based on the temporality model defined by Payet & al. [16].

The temporality model approach [14] is focused on the activation dynamics which are directly expressed by the agents. These activation dynamics are expressed using a data structure called the "temporality". A temporality t specifies a point on the time axis for which an agent wants to be activated. t can be defined by the tuple:

$$t = \{id, d, f, p, v\} \quad [16]$$

where:

- id is the identifier of the temporality. It is used by agents to associate a specific behaviour with the temporality.
- [d, f] is the time interval during which the temporality can be triggered.
- p is the time period, i.e. the time interval between two executions of a temporality (p=0 if the action is only executed once).
- v is the variability. It defines the accuracy below which the temporal occurrence remains valid.

Thus, a temporality activates the agent's behaviour at each time equal to x=d+p*k, where k is an integer such as $0 \leq k \leq n$ and n is the biggest integer that verifies (d+p*n)=f.

The agents are invited to define their temporalities during the simulation initialization. Afterwards, if they need to adjust their behaviour, they will be able to redefine or create new temporalities at any time. The scheduler immediately processes the creations and the modifications, then updates the time axis (see Fig. 5). Thus, at a given time, the scheduler activates only the agents who need to be activated. This could reduce the computation resources required. Consequently, simulating a large number of heterogeneous agents becomes easier. Another particularity of the temporality model, approach is the ability to add time constraints. This is done by specifying regulation properties:

- The minimum time-step Δt_{min} that indicates that two distinct activation dates should be separated by a duration at least equal to Δt_{min} . If such a situation occurs during the analysis of the temporalities, the scheduler will use the variability parameter v of each of the temporalities to determine if they should be separated from each other or regrouped together on the same date.
- The default time period value that is used for some agents that do not define any temporalities during the initialization of the simulation.

Thus, in the extreme cases, if no agent defines any temporality, we automatically fall back into a time-stepped approach. Otherwise, if all the agents are complex and express a large number of temporalities, we end up with an event-driven type of scheduling. That shows its flexibility.

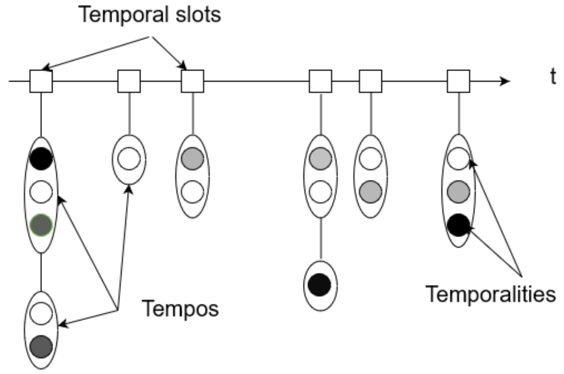

Fig. 5. The Temporality Model Time axis [16].

Therefore, this approach provides a structure of temporal information. In addition, in terms of performance, it tries to combine the advantages found in the three different approaches mentioned in section E :

- The periodicity and reducibility of the execution time that we can have when using the time-stepped approaches;
- The precision of the event-driven approaches;
- The adaptability to complex models of the mixed approaches.

The time axis can be illustrated as shown in 0 The scheduler advances the simulated time from a time slot to another. In this approach, each time slot, the scheduler processes to the activation of the agents' behaviour which will exert their influence on the environment (influence phase) and then processes to the computing of the results of the combination of these influences (reaction phase), before advancing to the next slot.

IV. Conclusion and Further Work

This paper introduces the notion of temporal environment as an environment which metric is time. It proposes a uniform management of the environment, whether spatial or temporal. The objective is to ensure that MASs naturally integrate a temporal environment, as well as a space environment.

To begin with, this paper sheds light on the environment as stated in the literature. It subsequently defines the physical, the communication and the social environment. Based on that, it also defines the temporal environment. A temporal environment plays the same role as spatial environment, but is focused on more time-specific properties. The relation between the agents and the environment is done using the influence/reaction principle. This principle is used for sharing temporal information through an environment that agents could influence. The environment reacts to influences.

However, this temporal environment is not only used as a shared memory for agents and as a medium for indirect coordination, but also as a global scheduler for the simulation. That is done by allowing the agents to express the dynamic of their temporal activation. So, at the end of the related work part, the paper made a comparison between the classical time scheduling approaches that are commonly used in MASs. It concludes that the temporality model approach is a potential candidate for structuring this temporal environment as:

- It combines the advantages of the three commonly used approaches
- It takes into account the influence/reaction principle
- It allows to express the agents activation dynamics using “temporalities”.

The temporal environment described in this paper is based on the same principles as the space environment. Therefore, it includes several principles that are commonly used for modelling the spatial environment such as the influence/reaction principle or the management of conflicts at the environmental level. It is structured in two parts:

- An independent environment for sharing and perception of temporal information
- A sublayer for global time scheduling.

This paper presents a beginning of thinking about the temporal environment in order to raise awareness of the benefits that taking into account the temporal dimension could bring to MASs. In order to confirm that, this type of environment is being implemented in a simulation model running on two different simulation platforms: Repast Simphony [19] and SimSKUAD [20]. The principle is to model a uniform environment, whether spatial or temporal. Thus, the temporal environment in the simulation model built upon Repast Simphony is based on contexts and projections. For that purpose, a custom projection called temporal projection is defined. Similarly, the implementation of the temporal environment in the SimSKUAD model uses the same principles as the space environment, in particular the use of a calendar type of devices. Further work consists in presenting the results of these implementations in order to really prove the effectiveness of the proposed approach. In addition, a formalism for the temporality model should also be defined in order to facilitate comparison with other already formalized approaches. For that purpose, it is possible to draw on existing formalisms such as DTSS or DEVS [21].

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