Holonic Multilevel Simulation of Complex Systems

Application to real-time pedestrians simulation in virtual urban environment

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Abstract

Simulation, which creates abstractions of the system is an appropriate approach for studying complex systems that are inaccessible through direct observation and measurement. The problem with simulation of great numbers of interacting entities is that it is difficult to create a reliable and tractable abstraction of the real system. Indeed, simulating large numbers of entities requires great computing resources. A solution to avoid this problem is to use macroscopic models. However, this type of model may be unavailable or not reliable for the problem at hand and it doesn't allow the observation of individual behaviours. In this paper a multi-level simulation model is proposed to allowing the use of both microscopic and macroscopic techniques. This model is based upon Holonic Multi-Agent Systems which offer a promising approach for developing applications in complex domains characterised by a hierarchical structure. The proposed approach provides a generic scheduling model for multilevel simulations: dynamically adapting the level of simulated behaviours while being as faithful as possible to the simulated model. It does not only manage the level of entities' behaviour but also of behaviours classically assigned to the environmental part of a simulation. A set of physics-based indicators is also introduced to dynamically determine the most suitable level for each entity and to maintain the best tradeoff between simulation accuracy and constraints.

Key words: Multi-Agent Based Simulation, Multilevel modeling, Holonic multi-agent systems, Holonic multi-agent multilevel simulation

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1 Introduction

A complex system can be defined as a system featuring a large number of interacting components whose aggregate activity is not derivable from the summations of the activity of individual components (non-linear) and typically exhibits hierarchical self-organisation under selective constraints. Often, at different levels, collective phenomena give rise to emergent properties [20]. Simulation, which creates abstractions of the system, is an appropriate approach for studying systems that are inaccessible through direct observation and measurement, either because they cannot be reproduced or because they cannot be directly experimented with [15]. Multi-Agent Based Simulation (MABS) offers the possibility to create an artificial universe in which experiments can be conducted by representing the individuals, their behaviours and their interactions. It thus provides a way to analyse a phenomenon as the outcome of the interactions of autonomous entities. As MABS and other *microscopic* simulation techniques explicitly attempt to model behaviours of individuals, they may be contrasted to *macroscopic* simulation techniques where the characteristics of a whole population are averaged and the model attempts to simulate changes in these average characteristics [18, 31]. Multiagent-based simulation aims at realistically modeling and simulating adaptive behaviours of individuals. But accurately simulate in real-time [1] complex systems, where a great numbers of entities interact, requires extensive computational resources and often distribution of the simulation over various computers. A possible solution to this issue is multilevel simulation. The objective of this type of simulation consists in dynamically adapting the level of the entity behaviours (from microscopic to macroscopic) while being as faithful as possible to the simulated model.

In this paper, a holonic organisational multilevel model for real-time simulation of complex systems is proposed. It aims at exploiting the hierarchical and distributed properties of the holarchies to model and simulate complex systems at multiple levels of abstraction. To fully exploit this model, the deviation of simulation accuracy between two adjacent levels is estimated through physics-based indicators. These indicators are then used to dynamically determine the most appropriate level for each entity of the application to maintain the best compromise between simulation accuracy and execution constraints such as available resources. The holonic paradigm [34] and its applications to multiagent systems have proven to be an effective solution to model complex systems at various levels of abstraction [51, 55]. In Multiagent Systems, the notion of holons is much closer to the one that MAS researchers have about *Recursive* or *Composed* agents. A holon constitutes a way

[1] The term is used to describe a number of different computer features. In this paper "real-time" refers to events simulated by a computer at the same speed that they would occur in real life. In graphics animation, for example, a real-time program would display objects moving across the screen at the same speed that they would actually move (source: Webopedia dictionary).

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to gather local and global, individual and collective points of view. It is thus a self-similar structure composed of holons as sub-structures. The hierarchical structure composed of holons is called a *holarchy*. A holon can be seen, depending on the level of observation, either as an autonomous entity or as a group of holons (this is often called the *Janus effect* [34]).

Michel [39] describes the four fundamental aspects of a MABS namely Agent Behaviours, Environment, Scheduling and Interaction. Our objective aims at allowing multilevel mechanism for the entire simulation (for agent behaviours and environment) while remaining generic. As agents' behaviours and interactions are strongly dependent on the application, our approach focuses on the scheduling aspect to remain generic. If a generic multilevel scheduling model may be obtained, the agent behaviours and interaction can be dynamically adapted according to execution constraints. In order to allow an equivalent approach for the simulated environment, the proposed approach considers the environment as a holonic multiagent system. Giving this model, this paper shows how to use a multilevel mechanism to dynamically adapt environment-related behaviours. With such an approach, the multilevel mechanism covers the entire simulation and allows dynamical adaptation of behavioural complexity in all aspect of a MABS.

Urban systems are typical examples of complex systems. Structurally, an urban system can be hierarchically decomposed in form of streets, buildings, neighborhoods, districts, etc [46]. Economically and socially, it can be seen as a structure consisting of individuals, families, shops, companies, etc. The complexity of urban environments can be addressed according to many points of view [2]. However, two main points of view can be adopted. The first concerns the evolution of the urban structure (formation of cities, morphology and expansion, etc). And the second deals with social activities, including traffic patterns and movement of crowds [32]. The multiagent simulation is a tool particularly well suited to the simulation of urban dynamics. MAS are more flexible than macroscopic models based on differential equations to simulate spatial and scalable phenomena [8]. In this article, the proposed multiagent-based multilevel simulation approach is applied to simulate pedestrians dynamics in a virtual urban environment.

This paper is organised as follows. Section 2 describes related works in the field of the multilevel simulation. Section 3 gives an overview of the proposed approach and briefly describes its application to the simulation of pedestrians in virtual urban environment. After a short introduction on holonic multiagent systems and the associated organisational metamodel (section 3.3), a generic multilevel scheduling model is introduced in section 3.4. In section 4, this model is then applied to the simulation of pedestrians in virtual urban environment. Section 5 then introduces a set of physics-based indicators conceived to determine the deviation of simulation accuracy between two adjacent simulation levels. Finally section 6 presents and discusses some experimental results.

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2 Related Works on Multilevel Simulation

Computer simulation is the discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output [22]. The multilevel simulation may be defined as a specific type of simulation where the proposed system model incorporates different levels of abstraction (at least two) and where the tools managing its execution allow to combine these different levels of abstraction within the same execution. These tools enable dynamic transitions between levels according to defined constraints, dependent on the model or the experimental context [23].

A large number of works dedicated to multilevel simulation have already been proposed in various domains: social simulation [54], virtual urban simulation [19], robotics [45], real-time multilevel simulation platforms [33]. However, multilevel modeling works are mainly oriented to Computer-Aided Design (CAD) optimisations [49]. Besides, the major part of existing multilevel models proposes a fixed number of levels, usually two: microscopic and macroscopic. Moreover, the level at which an entity is simulated is usually fixed, determined a priori by the designer according to his experience and experimental results from previous simulations. In other approaches, the simulated system is split into multiple zones and the simulation levels of these zones are usually a priori fixed for the entire simulation. Transitions between simulation levels are thus done at determined connexion points. Multilevel simulation often lacks of dynamics in the management of the transitions between simulation levels. This point of view is shared by Ghosh [26] who proposes the first dynamical multilevel simulation. Its scope is the simulation of electronic components. It proposes a model based on the hierarchical decomposition of components, in which the level of decomposition can be dynamically changed. But the level is not automatically determined according to the constraints of the simulation or conditions of applicability of the simulation level. It is the user who chooses the level of decomposition.

The field of the simulation in virtual environments provides more dynamical models. In [42], the concept of a *level of autonomy* for the simulation of virtual characters and crowds is proposed. Three levels of autonomy are distinguished by the authors where the behaviour of a simulated entity is either fixed or autonomous (close to the notion of simple reactive agents in MAS), or directly controlled by the user. Another contribution of this work concerns the modeling of the structure of a crowd which is split in the form of hierarchical groups. The objective of this work is to ensure the highest level of visual realism to the simulation, while maintaining real-time performances. However, the level of accuracy of the behaviours of the simulated entities is relatively weak in face to those achievable using multiagent systems. Anyway, the principle of the approach remains one of our inspirations. In the same perspective, Brogan et al. [9] have adapted the concept of *level of detail*, originally used to modulate the complexity of the geometric representation

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of a virtual environment, to model the behaviours of the entities operating in that environment. Also in the field of simulation in virtual environments, the works of [13, 14] also aim at providing a maximal level of realism in a simulation while maintaining optimal performances. The concept of *proxy simulation* is introduced to simulate the entities outside the field of vision of the user at a low level of detail, using event-based simulation. The dynamic transitions are managed in order to regenerate in a coherent state entities which will appear in the field of vision of the user.

In the area of the simulation of transportation networks, the works presented in [36] on hybrid micro-macro approaches and those in [12] or [61] for micro-meso hybrids can be highlighted. By the same, Gloor et al. [28] propose a hybrid model for the simulation of pedestrians in large environments.

In the multiagent domain, works dealing with multilevel problems mainly focus on the study of emergent phenomena with various approaches: mathematical [1], biological [56] or a purely multiagent way [41]. MAS models for emergence usually deal with *multilevel emergent structures* (also called multiple emergence) [30] and focus on the detection and the recognition of behavioural patterns [6]. Multiagent-based simulations (MABS) often lead to the emergence of local groups of entities [50], but provide no means of manipulating them. Giving a full sense to multiagent simulations would certainly imply the dynamic creation of agents groups, but also their agentification to deal with specific behaviours at each level. Van Aeken [57] introduces the notion of *minimal multiagent system* to study the dynamics of multiagent systems. This approach is based on the creation of a composed agent for each couple of atomic agents that could be merged. Even if his model remains almost abstract and difficult to apply to real applications, it is an equivalent approach to HMAS. The modularity and the reusability of the holonic organisational model allow to overcome Van Aeken's model drawbacks. Our approach consists in dynamically grouping agents and creating new levels, and also determining the deviation of simulation accuracy between adjacent levels through physics-inspired indicators, the aim of these latter is to dynamically detect when switching between simulation levels is required.

3 Multilevel Multiagent-based Simulation

3.1 Overview of the Approach

To fully understand the dynamic of a complex system, it is necessary to combine multiple points of view on the studied application at different levels of abstraction. The multilevel simulation is one possible solution to this type of problem allowing to dynamically adapt the complexity of a simulation according to specific

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constraints such as available computational ressources. Our approach to modulate the complexity of a simulation consists in dynamically adapt the complexity of the behaviours of the simulated entities. The tools and models presented in this article are the result of an experiment conducted in the development of a multi-level simulation of pedestrians in virtual environment. Without being exhaustive, this article presents the results of our experience that is being extensible and generalisable to conceive a multi-level simulation tool. To precisely simulate interacting entities, multiagent based models have been selected. Multiagent based simulation refers to individual-centric models and provides a tool to model and simulate the dynamics of populations composed of interacting individuals. This type of simulation assimilates the individual to an agent. To conceive a MABS, we follow the multi-view approach proposed by Michel [39], that distinguishes four main aspects in a MABS : (i) *Agent Behaviours* deals with the modeling of the deliberative process agents (their minds). (ii) *Environment* defines the different physical objects in the simulated world (the situated environment and the physical body of the agents) and the endogenous dynamics of the environment. (iii) *Scheduling* deals with the modeling of the passage of time and the definition of scheduling policies used to run the behaviours of agents. (iv) *Interaction* focuses on the modeling of the result of the actions and interactions between agents at a given moment. Our approach extends these different perspectives to integrate the multilevel-related aspects.

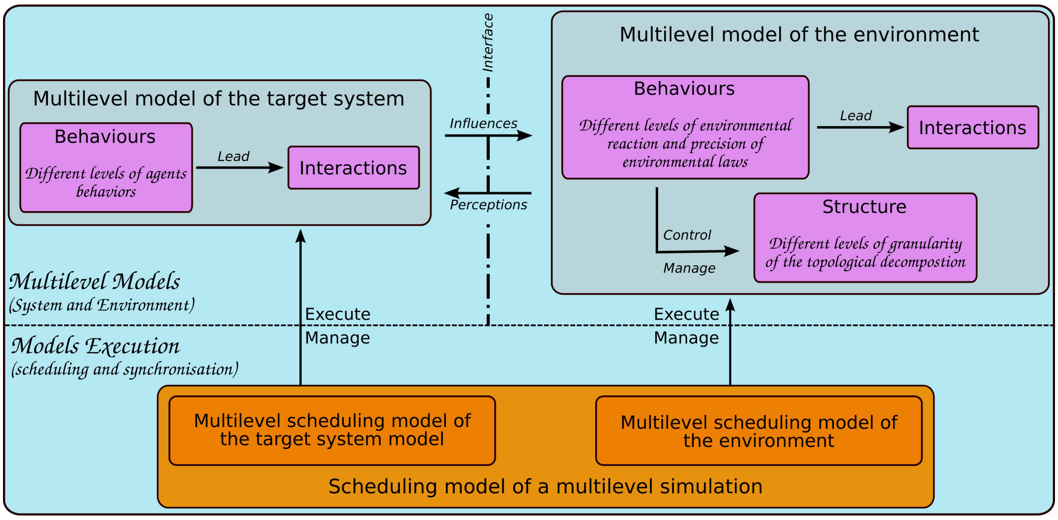

Fig. 1. The different aspects of a multilevel simulation

In order to clearly separate the models from their implementations, and the system from its environment, a multi-level simulation requires the creation of four multi-level models: the first for the environment of the system, the second for the target system and their both associated scheduling models. These different models and their relations are described in figure 1. The fact that the environment is clearly separated from the system enables to independently adjust its complexity. From the viewpoint of multi-level mechanisms' management, system and environment models are therefore independent. The multi-level scheduling mechanisms can be activated or deactivated for one in a transparent manner for the other.

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Each of these models (system and environment) is represented by an organisational hierarchy. These hierarchies will be instancied, together with their respective scheduling model, so as to create at least two holarchies: one for the execution of the system and a second for the environment. The exploitation of the properties of these holarchies allows to dynamically manage the complexity of a given simulation. The holarchy is used to hierarchically organise system and environment components as well as their different levels of abstraction. Each level of the holarchy corresponds to a level of abstraction of the associated model (target or environmental models). The level of the holarchy that is executed determines the simulation level (microscopic, mesoscopic, macroscopic, etc). The design of multi-level models is based on a combination of the organisational and holonic approaches. This aspect is detailed in the sections 3.3 and 4.2. In this paper the environment of a simulation is considered as a multi-agent system with specific missions. The environment is structurally decomposed in a hierarchy, and the behaviours associated to each level are specified. These aspects are detailed in section 4.1.

3.2 Application to Real-time Pedestrians Simulation in Virtual Urban Environment

3D multiagent-based simulation of pedestrians (human crowds) implies to simulate the motion of a large number of people while maintaining a reasonable frame rate for the 3D GUI. Multiagent systems are a convenient way to simulate such behaviours at the finest level but it often requires a lot of computational resources. It is thus often difficult to maintain acceptable performances for the 3D visualisation without increasing the computation capacities. Human crowd simulation is a typical application where the complexity and the realism of the simulated behaviours have to be adapted according to the simulation constraints (here available computational resources). Our holonic multilevel model is adapted to this case study to solve this problem.

This article presents a multi-level model to simulate pedestrians dynamics in a virtual urban environment. To design this simulation, the modeling of the dynamics of pedestrians must be clearly distinguished from that of the structure of the urban environment. Indeed, the structural modeling of the city relates to the environmental aspect of the simulation, while the model of the dynamics of pedestrians is related to the model of the system. In this article, a multi-level model for the urban environment is proposed and especially for pedestrian simulation. The urban environments naturally exhibit a hierarchical spatial structure [46]. The multilevel model of the system reflects the different levels of abstraction of a pedestrians population (individual, group, crowd, etc.) and must integrate the data available at the individual level (eg. from the households polls and surveys) with the statistics observations aggregated from a population as a whole. These different models (environment and system) are then combined with the management of the multi-level simulation.

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These tools enable dynamic transitions between different levels of abstraction in the behaviour of pedestrians, and the automatic adjustment of the level of decomposition of the urban environment.

3.3 How to Conceive Multilevel Models using a Holonic Perspective

Holonic Systems have been applied to a wide range of applications such as Manufacturing systems [38], Health organisations [55], Transportation [11], Adaptive Mesh Problem [48], etc. Thus it is not surprising that a number of models and frameworks have been proposed for these systems, for example PROSA [10], MetaMorph [38]. However, most of them are strongly dependent of their application domain and use specific agent architectures. In order to allow a modular and reusable modeling phase that minimises the impact on the underlying architecture, a meta-model based on an organisational approach is proposed [17]. Figure 2 describes a part of it using an UML class diagram.

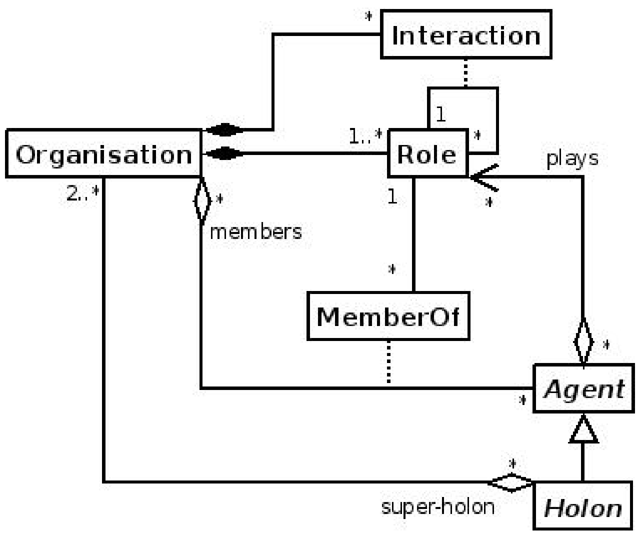

Fig. 2. The UML diagram of our holonic organisational meta-model

This meta-model is based on four main concepts : organisation, role, interaction and holon. An *Organisation* is defined by a set of *Roles*, their *Interactions* and a common context. This context is defined according to an ontology. The aim of an organisation is to fulfill one or more requirements. An *Interaction* is composed of the event produced by a first role, perceived by a second one, and the reaction(s) produced by the second role. The sequence of events from one to the other can be iterated several times and includes a not a priori specified number of events (and participants). The interacting roles must be defined in the same organisation. A *Role* is the abstraction of a behaviour in a certain context — defined by the organisation — and confers a status within it. The status is defined as a set of rights and obligations provided to the role, and also defines the way the entity playing the role is perceived by other entities playing another roles in the same organisation.

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Another important aspect is that the role — and not the individual, like an agent or a holon, who plays the role — belongs to the organisation. This means that the same individual may participate to an organisation by playing one or more roles that are perceived as different (and not necessarily related) by the organisation. Besides, the same individual can play several roles in other organisations.

An *Agent* is an entity which can play a set of roles defined within various organisations; these roles interact with each other in the specific context provided by the agent itself. These roles, in turn, belong to different organisations, each one defining its own context. An agent in our approach defines a particular context of interaction between roles belonging to different organisations.

A *Holon* may be considered as a specialisation of *Agent*. However two overlapping aspects have to be distinguished in this notion: (i) The first deals with the holon structure and management. This aspect is directly related to the holonic nature of the entity and deals with the government and the administration of a super-holon. It is common to every holon and thus called the *holonic* aspect; it describes the decision making process and how members organise and manage the super-holon. (ii) The second is related to the problem to solve and the work to be done (goal dependent interactions). It depends on the application or application domain; it is therefore called the *production* aspect. It describes action coordination mechanisms and interactions between members to achieve the objectives of the super-holon, the tasks to fulfill, or the decisions to make. A *Holon* may thus play a set of roles that can be defined on various organisations interacting in the specific context provided by the holon itself. A holon can play several roles in different organisations and can be composed of other holons. A composed holon (called *super-holon*) contains at least a single instance of an *holonic organisation* to precise how members organise and manage the super-holon and a set (at least one) of *production organisations* describing how members interact and coordinate their actions to fulfill the super-holon tasks and objectives. An atomic (non-composed) holon can be considered as a classical *Agent*. The *Holonic organisation* describes the government of a holon and its structure in terms of authority, power repartition. It represents a *moderated group* (see [25]) in terms of roles and their interactions.

Depending on the level of abstraction, a super-holon can be seen as an atomic entity (at level n) or as an organisation of holons (at level n-1). By the same manner, several different holons could be seen as interacting individuals, parts of some organisation or as parts of a super-holon. A holon may contain several instances of the same organisation. Further details on this meta-model and especially a formal specification of holonic roles described above can be found in [17, 48]. The HMAS structure can be seen as a set of hierarchical levels. This hierarchical structure is called a holarchy. For clarity reasons, at a given level, the higher-level entity composed by its members or *sub-holons* is a *super-holon*.

A holon joins a HMAS organisation, if it wants to collaborate with other holons.

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It may remain alone, and in this state its decisions are not attached to any restriction but its own goals and objectives. It will remain in this state as long as it is satisfied. According to its needs, a holon may want to join an existing super-holon and request to the holon *representative* its admission as a member. If accepted, the holon is becoming a member of that holon. From that moment on, until it is leaving the holon, either by selfdecision or command of the holon's *head*, it can directly interact with the members of the holon.

3.4 How to Execute Multilevel Models

This section details how to adapt the previous holonic meta-model to build a multilevel scheduling model for multiagent based simulation. This model is directly applied to dynamically adapt the behavioural level of simulated entities.

Section 3 has described the four fundamental aspects of a MABS namely Agent Behaviours, Environment, Scheduling and Interaction. As Agents' behaviours and interactions are strongly dependent on the application, our approach focuses on the scheduling aspect to remain generic. Scheduling mechanisms play an important role in MABS [3], especially because the output results given by a single MAS model can be very different considering the way it has been computed [35]. However as pointed out by [40], the *scheduling problem does not have almost any methodological support whereas paradoxically this is a mandatory stage when computing a MAS simulation*. Within this context, our holonic organisational meta-model is applied to MAS scheduling issues. Hierarchical structure and scalable properties of the holarchies are exploited to ensure a dynamical scheduling of the behaviours (roles) at various simulation levels. The main hypothesis considered in this paper is that any MAS simulator can itself be expressed as a MAS (even HMAS). The scheduling system thus becomes an organisational sub-structure in a MABS.

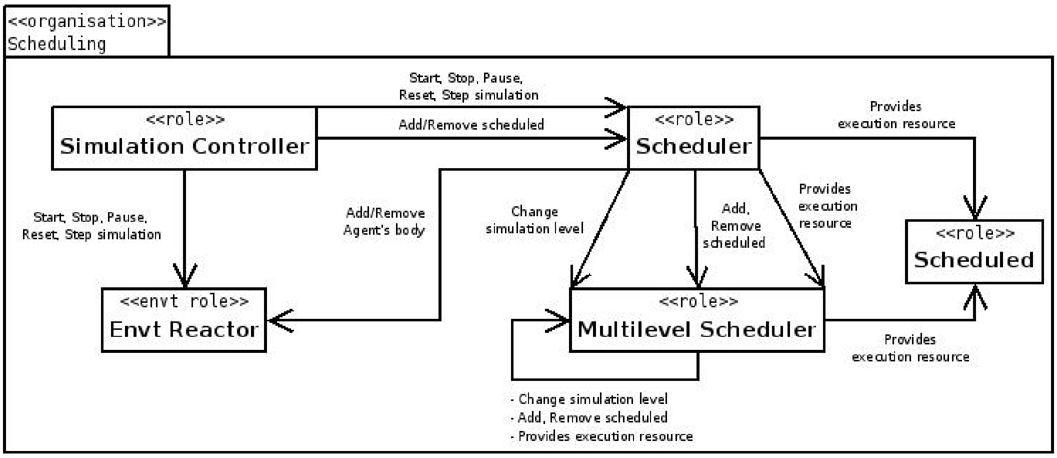

Fig. 3. The UML diagram of the *Multilevel Scheduling* organisation

Considering a MAS simulator as an organisational HMAS, the behaviours related

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to the scheduling mechanisms are depicted in the UML diagram shown in figure 3. Roles are presented using stereotyped classes, and interactions using associations. This *Scheduling* organisation defines five roles: The *Scheduler* role has to be played by a holon having and controlling its own computational resources (i.e. thread, computer . . .). This role provides its player with the right to schedule [2] holons that play the role *Multilevel Scheduler* or *Scheduled*. The *Scheduled* role provides the right to schedule/execute its roles. The *Multilevel Scheduler* role has absolutely to be played by a super-holon (composed). It represents a fusion of the two previous roles allowing its player to schedule its role and its members. It also provides all required tools to dynamically determine if it is necessary to schedule its members or its application roles (cf. the section 5 for more details). *Environmental Reactor* represents the environment and allows other roles to add or remove a holon body from the environment. *Simulation's Controller* is dedicated to the controls of the simulation and their graphical user interfaces if any.

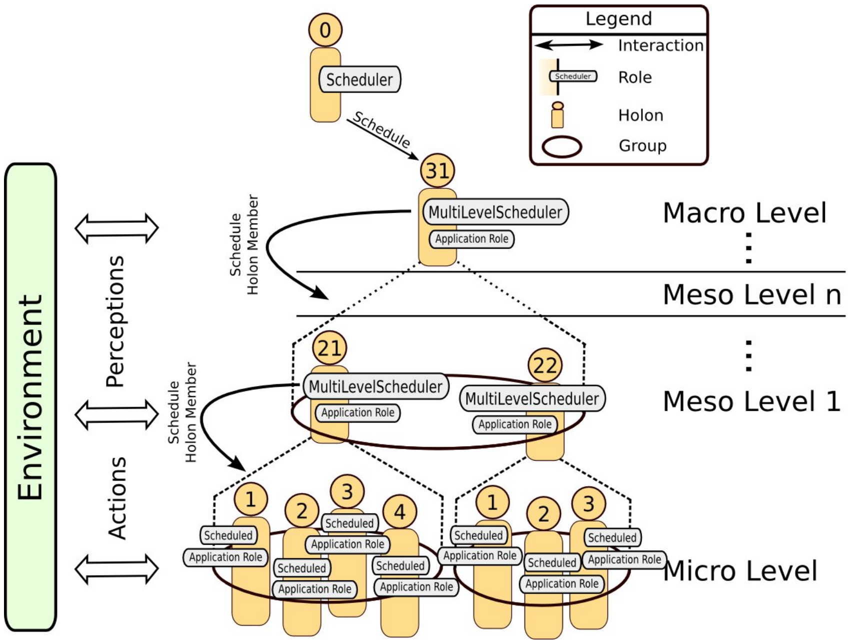

Fig. 4. The structure of the scheduling holarchy

Let's now consider how to combine this organisational approach of scheduling with the holonic perspective and application-dependent organisation. Each individual (of the application) is associated to an atomic holon. These holons are grouped into super-holons according to their affinities. Then super-holons are grouped in their turn, and so on, to obtain a single and complete holarchy. The affinity measures, according to the application objectives and simulation constraints, the compatibility of two holons to work together to fulfill a shared objective [48]. In this context, the concept of affinity is exploited to dynamically aggregate holons and

2 As an organisational approach is used, executing a holon is modeled using an interaction between *Scheduler* and *Scheduled* where the first provides the computational resource for the second.

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to obtain a scheduling holarchy that is coherent with the application objectives. A non-composed holon can thus be changed into a super-holon during the simulation if its goals evolve and thus impact its affinity with other members. Affinity provides an easy mean to integrate application constraints in our model. Each holon of this holarchy plays at least one role in the scheduling organisation, one role corresponding to the behaviour related to the application. An example of a possible structure of the resulting scheduling holarchy is described in figure 4. If two or more independent application behaviours/roles must be scheduled at various levels, one holarchy exists per role. The application holon is thus a multi-part of two super-holons, of two different scheduling holarchies. When a holon integrates a super-holon in the scheduling holarchy, the application role associated to the current holarchy is specified. The *Scheduled* role, when it is activated, has thus the means to know which application roles have to be scheduled. The lowest level of the holarchy represents the most accurate simulation level where each individual is modeled using an atomic holon. This level is commonly described as the microscopic level. Then the more you rise in the holarchy the more the application behaviours are aggregated. The height of the holarchy depends on the affinity function that defines how holons are grouped. This holarchy is built from a dynamic bottom-up approach. Each new super-holon is associated with a behaviour of an upper aggregated level than its members. This mechanism allows to simulate behaviours at several granularity levels.

4 Application to pedestrian simulation in virtual urban environment

4.1 Multilevel Modeling and Execution of Virtual Urban Environments

The environment is commonly considered as one of the most important parts of a MABS [39, 43, 60]. However different perspectives exist about the roles played by the environment in agent systems and about its definition. This section focuses on the modeling of environments dedicated to the simulation and is clearly distinct from the communication layer: the situated environments for multiagent based simulation. Situated environments refer to the class of systems where agents, as well as objects, have an explicit position in the environment and perform situated actions [21].

MAS literature gives several definitions of the environment. The one from [59] is retained: "*The environment is a first-class abstraction that provides the surrounding conditions for agents to exist and that mediates both the interaction among agents and the access to resources*".

In this context and considering the environment as an explicit part of the MABS that must be carefully designed, a set of building abstractions are provided. This model

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is based on the previous holonic concepts. It is exploited in a multilevel simulation to dynamically adapt environment-related complexity.

4.1.1 Global Architecture of the Urban Environment

The model of virtual urban environment has been designed to be associated with a wide variety of system models to simulate various dynamics of a virtual city: pedestrians simulation, simulation of transportation networks (buses, cars or bicycles). This section presents this general model and its relations with the various tools necessary for the implementation of the final application: graphics engine, virtual reality platform, multi-agent platform, etc. To ensure the connection between the environment and these various tools, a set of environmental interfaces have been developed. Each one corresponding to a particular point of view on the overall environment of the simulation. An environmental interface acts as a filter to focus on a specific aspect of the environment, bringing together the elements required for the application. These interfaces notably include tools to manage the connection between a MAS and the virtual urban environment, and the mechanisms of perception and action available to the agents. In figure 5 the three low layers describe the overall architecture of the offered urban environment model. The heart of the

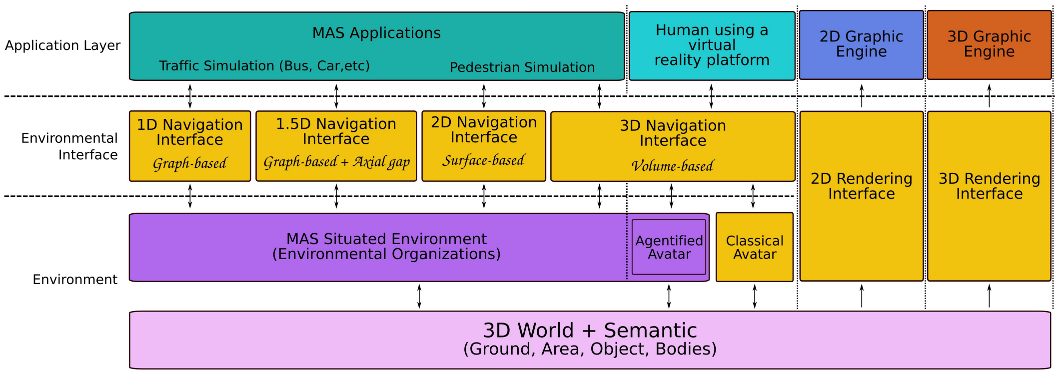

Fig. 5. An Architecture of a 3D Situated Urban Environment

simulation environment is represented by the structure and the hierarchical decomposition of the virtual environment (called 3D World in the figure). This part of the environment is stored in a dedicated database directly constructed from the GIS data and digital models of the considered virtual spaces. It must integrate spatial and graphics (images, textures, etc.) informations and static information such as geometrics, topologies and semantics of the urban environment. This type of database is generally called Urban Information System (UIS). The heart of the environment can then be manipulated by environmental agents, but also by other applications, including those dedicated to the display, and virtual reality modules allowing a user to move in the virtual world and interact with him. The way to model and decompose the urban environment as part of a multi-agent simulation is described in the next section.

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4.1.2 *Structure of the Urban Environment*

In the reviewed application, the urban environment is managed by a HMAS in charge of carrying out the different missions traditionally assigned to the environment in a multi-agent based simulation. Four main missions are classically assigned to the environment in a MABS:

Sharing informations The environment is a shared structure for agents, where each of them perceives and acts. This shared structure can also be the support of indirect communication (i.e. stigmergy).

Managing agent's actions and interactions The action model in situtated MAS from Ferber [21] is adopted. It is based on the distinction between influences and reactions to these influences. Influences are produced by agents and represent their desires to modify the environment. Agents do not directly modify the state of the environment. Reactions, which result in state changes, are produced by the environment by combining influences of all agents, the current environment's state and the set of laws governing it. This distinction between the results of agents behaviours and the reactions of the environment provides a good mean to handle simultaneous actions and *easily* solve conflicts. The influence/reaction concepts also provide a good mean to verify if environmental laws are not broken by agents before impacting environmental states. Adopting such an approach also imposes to distinguish the agent itself from its body. An agent is situated in its environment and is able to perform actions through its body. This body also corresponds to the way of existence, the appearance or the representation of this agent in the environment. In our approach the body of an application is part of the environment, and the agent cannot directly manage its body. This aspect will be detailed later.

Managing perception and observation The environment must be locally and partially observable. Thus agents can also manage the access to environmental informations and thus guarantee the partialness and localness of perceptions.

Maintaining internal dynamics The environment is an active entity; it can have its own processes, independently of the ones of the agents. A typical example is the evaporation of artificial pheromones in ant colony based algorithms.

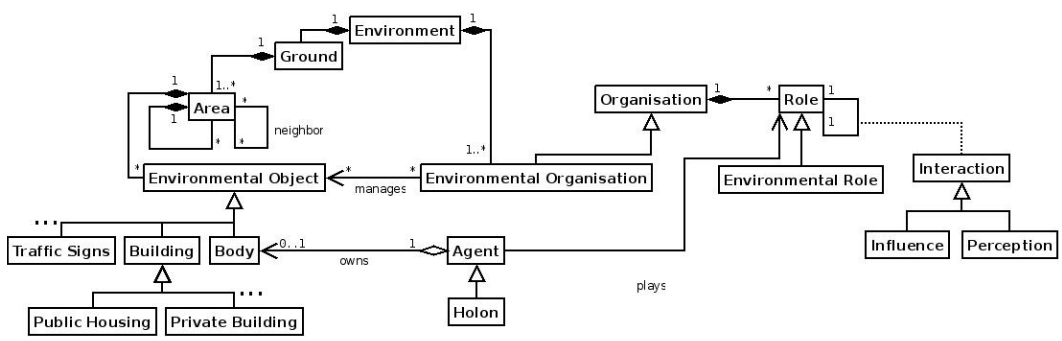

Fig. 6. Overload and extension of the holonic meta-model to environmental issues

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To deal with the specific missions assigned to the environment in a situated MABS, the holonic meta-model presented in section 3.3 has been extended. These extensions are described in the UML diagram presented in figure 6. This model introduces the concept of *Environment* and its different components. Thus the environment is defined as a *Ground* and a set of specific organisations. The *Ground* refers to the environment as a shared structure between agents. It contains the structure of the environment, and it can be hierarchically decomposed into *Areas*, sub-Areas and so on. Each *Area* is associated with the set of *Environmental Objects* locating on it. Even *Bodies* are considered as *Environmental Object*, because a body is not directly managed by the holon who owns it. Indeed when a holon wants to move, it emits an influence of movement. All influences are gathered by the environment. Then the body of an application holon [3] is effectively moved if the requested movement respects all environmental laws (i.e. does not cross a wall). The body of an agent (or a holon) represents the agent's location and thus constrains the way it perceives and acts within its environment (in the Ground). Let's consider the example of a pedestrian urban simulation. The human body of a pedestrian, its 3D representation, corresponds to its localisation in the city. It can perceive locally its environment using its eyes (3D perception) and acts in the limits defined by its physical conditions.

4.1.3 Organisations Managing the Environment

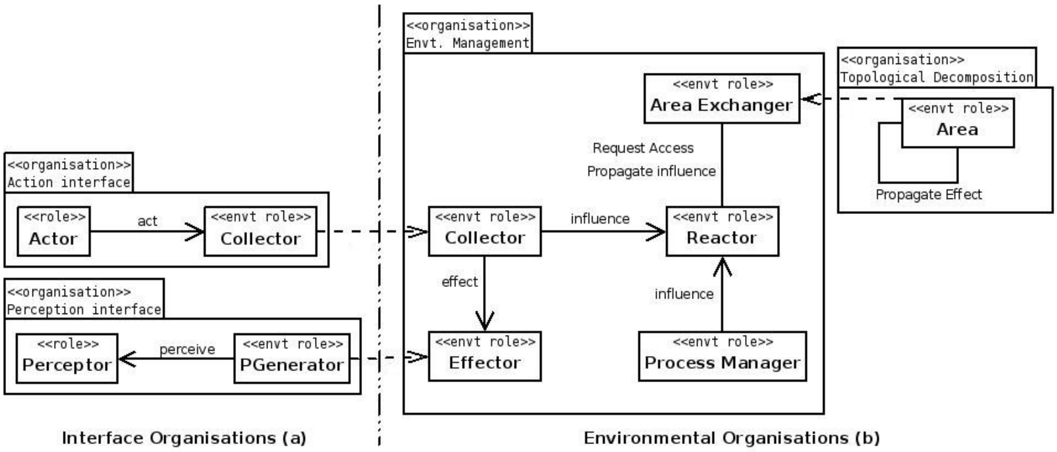

Fig. 7. UML diagram of generic Environmental and Interface organisations

The *Environmental Organisation* is in charge of assuring environmental missions. It defines only *environmental roles*. These roles represent behaviours that fulfill a

[3] In this section a model of situated environment that can be used in various simulations is proposed. Moreover it assumes that the environment of a MABS can be modeled as a HMAS. It is required to distinguish holons and roles involved in the environmental part of the simulation from holons and roles involved in the non-environmental part. To refer to this last category, the term of *application holon* (resp. *application role*) is used, because the non-environmental part is typically specific to each simulation.

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part of pure environmental requirements. Two major environmental organisations have been identified and are depicted in figure 7(b). The *Topological decomposition* organisation corresponds to the organisational model of the *Ground* decomposition. The role *Area* is played by a super-holon in charge of managing a given *Area*. The *Environmental Management* organisation (inspired from [58]) is in charge of carrying out all environmental missions for a specific area of the environment. This organisation is integrated inside a super-holon playing the role *Area*. It defines five environmental roles. The *Collector* gathers all influences emitted by all entities that are located in its associated area. The *Area Exchanger* gathers influences arriving from neighboring areas. It can forward to these neighboring areas influences whose impact exceeds the only range of its current area. The *Process Manager* maintains the environmental dynamics within the current area, and thus produces influences to modify the state of the environmental objects. For example it may ensure the evaporation of a pheromon, perpetuate the movement of a (non-agentified) ball which was pushed in the past, or modifies global environmental variables like temperature, pressure, gravity... All influences are then transfered to the *Reactor* that computes the reaction according to environmental laws, resolves possible conflicts between interfering influences and finally modifies the state of the environment. It then informs the *Effector* that computes agent's perception for the next simulation cycle. The *Effector* finally forwards perceptions to the different *Percept Generators*.

Two organisational patterns have also been identified to deal with agent's action and perception. These organisations are described in figure 7(a) and will be called in the rest of this paper *interface organisations* because: (i) they are composed of environmental roles and application roles as well; (ii) and they are located at the border between the environment and the application. The *Action interface* defines two roles: the *Actor* role is supposed being played by entities defined in the application, and provides it with the means to emit *influence* in the environment, incarnated in this organisation by the role *Collector*. Reciprocally the Perception interface defines also two roles: the *Perceptor* role procures to application entities means to perceive their environment. The environment is embodied in this organisation through the *PGenerator* role. These two environmental roles (*Collector* and *PGenerator*) defined in the environment's interface have to be jointly played with the roles *Collector* and *Effector* of the environment Management organisation. They thus allow to transfer influence (resp. perception) from the application to the environment (resp. from the environment to the application). Each of these interface "patterns" have to be specialised according to the application.

Figure 8(b) describes an example of an environmental holarchy. Figure 8(a) represents the associated hierarchical decomposition of the environment into areas. Two environmental holons H_{21} and H_{22} manage two neighbor areas. These areas are connected by a holon H_{23}, part of the two previous super-holons (*Multi Part*), playing the role *AreaExchanger* and so allowing the transfer of influences between these two neighbor areas.

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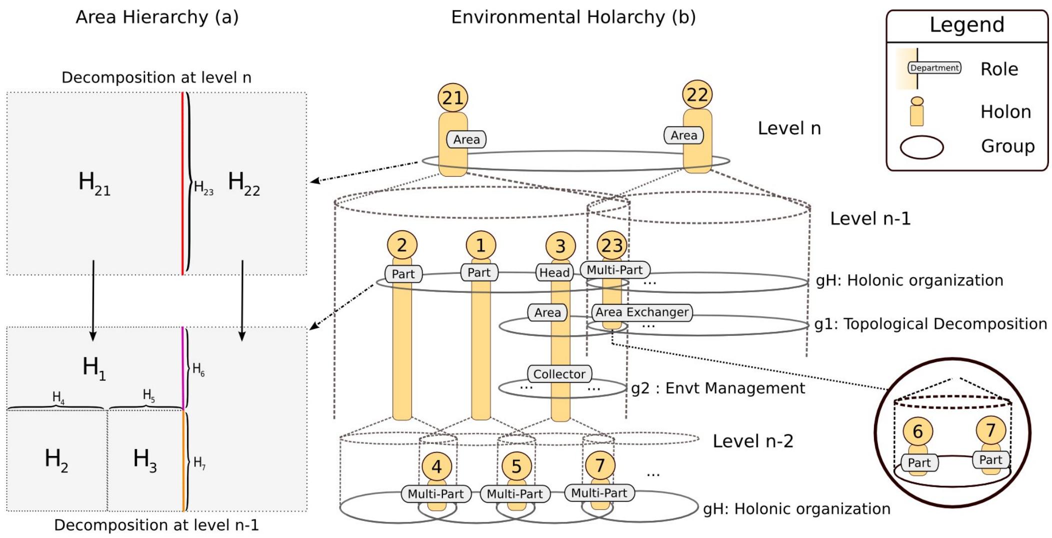

Fig. 8. An example of a possible resulting environmental holarchy

4.1.4 Interfaces between System and Environmental Parts of the Simulation

Figure 5 describes four different specialisations of this interface for a situated urban environment. It details the complete architecture of a 3D situated urban environment. The core of the environment is represented by the 3D world, its various components and its associated semantics. This environment may interact with different applications: a MABS (MAS applications in the figure) , a graphic engine for the visualisation of the simulation and a virtual reality platform to possibly integrate a human inside the simulation. This integration of a human may be done in two different ways: either via a classical 3D avatar/phantom, or via an agentified avatar allowing the human to interact with agents of the simulation. Between the MAS environment and MAS applications (such as a traffic simulation), four different environmental interfaces are identified according to the used types of perception/action mechanisms:

1D: Entities are moving along splines. An entity location is thus represented by a curvilinear abscissa on the spline. The set of splines is integrated into the environment and pre-compiled before the simulation. One spline corresponds to a possible path avoiding static obstacles. Other entities are perceived to their abscissa on the spline. This kinds of interface is particularly well suited for vehicles behaviours.

1.5D: Extension of 1D with a w-coordinate that corresponds to a shift distance from the spline.

2D: Entities perceive the 3D world as its projection on the plane (floor) via a 2D frustum. The first version of our 2D visual perception model in a 3D environment was described in [24]. A movement corresponds to the combination of a 2D vector and a 2D rotation.

3D: Entities fully perceived in 3D via a 3D frustum. A movement corresponds to the combination of a 3D vector and a 3D rotation.

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These various kinds of interfaces correspond to increasingly fine levels of realism. It allows to develop in the application different levels of behaviour for each kind of entities. These aspects emphasise another way to manage complexity, by only switching the way of perceiving the environment by simulated entities. It is absolutely not an anecdotal aspect, because perception especially in a 3D vritual simulation often consitutes a significant part of the computational costs of simulation.

4.1.5 Execution of the Environment Model

The previous environment model can describe a situated environment of a MABS as a HMAS (see section 4.1). This section briefly exposes how to merge it with our multilevel scheduling model. The notion of multilevel takes a particular sense in environmental modeling because situated environment is directly related to geographical area and its possible decomposition. Two words with a lot of different meanings are generally used to describe the decomposition of a situated environment: *level* and *scale* (multiscale and multilevel). They reveal two different points of view on a situated environment: a *behavioural* and a *structural* approach. This duality is classic in complex system analysis, and generally designers choose one approach or test both and compare the results. However it is generally difficult to integrate these two points of view into one model. The holonic perspective may offer a good answer. Applying the previous environment model allows to obtain an environmental holarchy as described in figure 8(b) by the same manner that it was previously done with the agents' behaviours and interactions part of a MABS, except in this case that the holarchy already exists. At each level of the holarchy, holon will play a role in the scheduling organisation. The scheduling holarchy is thus mapped with the environmental holarchy.

According to specific runtime constraints (i.e. available computational resources), each super-holon will decide to schedule or not its members. If members are scheduled, the decomposition of the environment is more fine grained (one more level in area hierarchical decomposition) and the environmental reaction and associated laws computed in this area may be more precise. Figure 9(b) describes an example of a multilevel environmental holarchy. This model allows to dynamically choose the granularity of the decomposition of the environment into areas (Structural Aspect) as well as the level of environmental behaviours (Environmental Laws and Reaction).

4.2 Multilevel Modeling and Execution of Pedestrian Dynamics

Simulate crowds of pedestrians in 3D virtual environment means to be able to simulate the movement of a large number of entities, while maintaining a refresh rate

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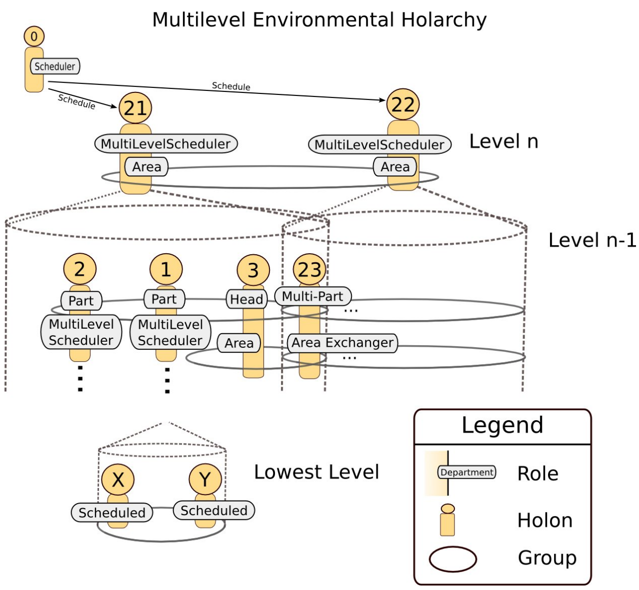

Fig. 9. An example of a possible resulting multilevel environmental holarchy

of the graphical user interface (2D and 3D) near the real-time. MAS are particularly well suited to simulate these types of behaviour at the finest level, where each pedestrian may have its own objectives and characteristics. But MAS quickly require significant computing resources, it is therefore difficult to maintain the performances required by the GUI and the virtual environment. This issue is a typical example where the level of complexity of simulated behaviours must be adapted to the available computational resources.

According to the proposed organisational approach (see section 3.3), the pedestrian behaviours are defined in terms of roles and interactions. The *Pedestrian* organisation, depicted in figure 10, describes the three main roles involved in the simulation of pedestrian motion. *Actor* and *Perceptor* provide means to act (resp. perceive) in the urban environment. These roles are linked with roles of the environmental interface described in section 4.1 (see figure 7). Integration of the perceptions and computation of the motion according to holon objectives and environmental constraints is handled by the *Pedestrian* role. Different levels of abstraction are

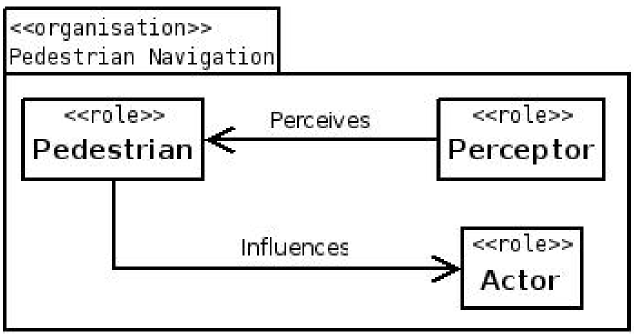

Fig. 10. The structure of the pedestrian's holarchy

considered for the role *Pedestrian*.The most accurate one corresponds to the micro-

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scopic level: a pedestrian moves according to the perceived obstacles and its current goal. Each pedestrian has a starting point in the virtual world (eg. home), and one or more goals (eg. workplace, supermarket, etc.). At this lower level of abstraction a pedestrian is associated with an undecomposable holon. At the higher level, called macroscopic, each super-holon simulates the behaviour of a group of pedestrians. The group behaviour is equivalent to the behaviour of a unique pedestrian, but whose perception is enlarged, and whose goal is an average of the goals of its members. The *Pedestrian* role played by the super-holon remains the same as at the lower level, but the perceptions and actions are aggregated. The body, or the representation of the super-holon in the virtual world is the aggregation of the bodies of its members. When a movement is computed at the macroscopic level, the bodies of the members of the considered super-holon are moved. Self-similarity of holons is directly exploited to reuse the same behaviour at different levels of abstraction. The wide range of possible simulation levels for the pedestrians is depicted in figure 11.

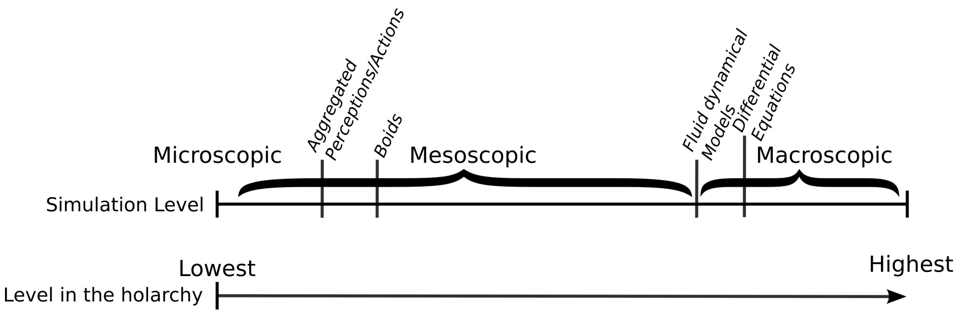

Fig. 11. Simulation and holarchy levels

The behaviour of a pedestrian is inspired by a classical model based on a set of attraction and repulsion forces (social force model, magnetic force model [52]). The behaviours models proposed by [7, 27, 29, 53] may also be used. The behaviour of a pedestrian (respectively of a group of pedestrians) is based on three forces :

- a forward force (equation 1) attracting the holon to its next local goal;
- the force resulting from the repulsions of the other holons (equation 2);
- the force resulting from the repulsions of the environmental obstacles (equation 3).

$$\overrightarrow{F}_{obj} = \beta_{obj}.\overrightarrow{A_i O_{bj}} \tag{1}$$

$$\overrightarrow{F}_{rep_{ij}} = \beta_{ij}.\frac{m_i.m_j}{d_{ij}^2}.\overrightarrow{d_{ij}} \tag{2}$$

$$\overrightarrow{F}_{rep_{obs}} = \beta_{obs}.\frac{m_i}{(d.sin(\alpha))^4}.\overrightarrow{n} \tag{3}$$

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$$\text{with} \begin{cases} A_i \text{ position of the holon i.} \\ O_{bj} \text{ position of the next holon's goal.} \\ O_{bs} \text{ position of a given obstacle.} \\ \overrightarrow{d_{ij}} \text{ vector from agent i to j, and } d_{ij} \text{ the norm of this vector.} \\ m_i \text{ mass of agent } i. \\ d = \|\overrightarrow{A_i O_{bs}}\|\text{, distance between agent i and its next objective.} \\ \alpha = \angle(\overrightarrow{A_i O_{bj}}, \overrightarrow{A_i O_{bs}}) \\ \overrightarrow{n} = \begin{pmatrix} 0 & -sign(\alpha) \\ sign(\alpha) & 0 \end{pmatrix} \cdot \frac{\overrightarrow{A_i O_{bs}}}{\|\overrightarrow{A_i O_{bs}}\|} \\ \beta_{obj}, \beta_{ij}, \beta_{obs} \text{ constants.} \end{cases}$$

Affinity between two pedestrians is defined according to three main functions : the distance between holon objectives, the distance between holon locations, and the energetic affinity (see equation 4).

$$\text{Given two holons i and j, } \operatorname{Aff}(i,j) = \frac{1}{E_i^n - E_j^n} \tag{4}$$

The way to compute the energy E_i^n of a holon i, located at the level n in the holarchy, is problem-dependent and is detailed in section 5.

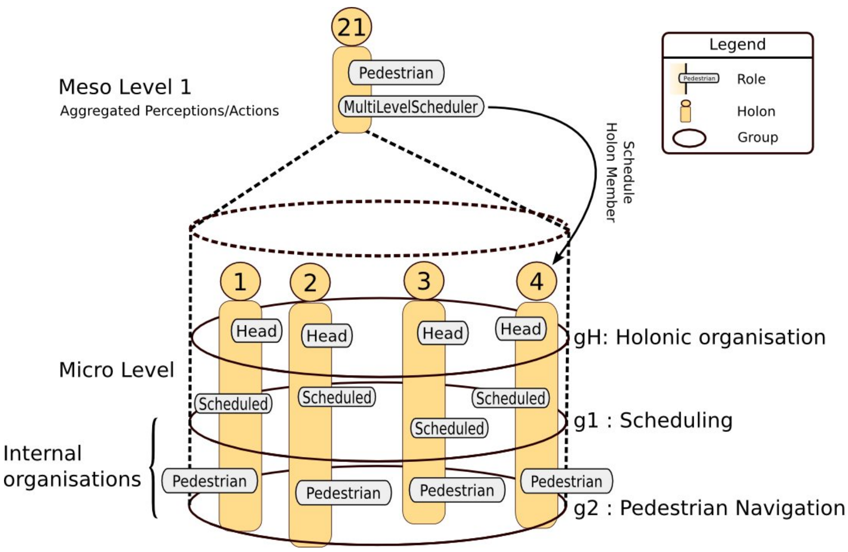

Fig. 12. An example of a possible resulting pedestrian holarchy

The two lowest levels of the resulting scheduling holarchy are shown in figure 12. If enough computational ressources are available, the super-holon schedules its *multilevelScheduler* role and then its members, else it schedules its pedestrian behaviour. All members play the *Head* role in the holonic organisation of the holon 21, because they all have an equivalent part in the decision making process within their super-holon. Super-holon *21* has the similar pedestrian behaviour as its members but its perceptions correspond to an aggregation of its members perceptions.

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Its environmental body corresponds to a group of individual bodies. When a motion is computed, all members bodies are impacted by the same movement. Thus the self-similarity of the holon is exploited to reuse the same behaviour at various levels. In this case a macroscopic holon can be considered as a kind of pedestrian boids [47]. Aggregating perceptions and actions allows a significant reduction of computational costs while maintaining a relatively good simulation accuracy.

5 Using Indicators to Evaluate Simulation Accuracy

Since we consider different levels of abstraction in a single simulation, the issue of transition between these levels becomes crucial. Ensuring the transition between two levels of abstraction requires that the models used for each of them are compatible. This section introduces some tools to facilitate the work of the designer of a simulation and the development of compatible models. These tools also evaluate the appropriate time to make a change in level depending on the constraints imposed by the context of the simulation. We consider that the most accurate which it is possible to simulate a given system is the microscopic level. When levels of abstraction higher than the microscopic level are considered, the accuracy of the simulation decreases. The mesoscopic and macroscopic levels are only an approximation of the behaviour of the system according to a certain point of view. The tools described in this section aim at estimate the level of quality of this approximation.

This problem may be related to a broader problem within the MAS, which is to assess the accuracy/efficiency of the system relatively to the task to perform and to the local mechanisms involved. Various approaches have already been proposed in the literature, some inspired by biology (fitness value, etc), sociology (utility function, satisfaction, etc.), or physics (entropy). Among them, entropy has been widely used in reactive MAS in particular in order to represent disorder/organisation in the system. Various methods have been proposed to compute the entropy of a MAS from the hierarchical social entropy [4] to the dynamic and static entropy [44]. [57] also uses entropy to determine the best compromise between size and the balance of its hierarchical structure in minimal MAS. Even if this measurement can be usefull in many cases, the entropy has two main drawbacks. First, since it depends on the past transformations of the system, entropy cannot be considered as a state function. Indeed two identical systems can be in the same state but with two different entropy values depending on their previous states. Second, entropy is mainly a global measurement that does not take into account local phenomena of the system. In order to overcome these drawbacks, other approaches can be used. One generic solution is the computation of energy as a state function on both agent and system levels [16]. This solution is well adapted to holonic system thanks to the compositional properties of energy. However, energy is not always easily computable and thus has to be restricted to force-based behavioural models. Finally, other interesting methods based on statistical physics/thermodynamics duality seem to be increasingly used

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[37], [5]. These methods are based on the partition function Z from which stem all the state functions (Gibbs function, Free Energy, Enthalpy, Free Enthalpy, etc.) in thermodynamical systems. Z-based methods are able to take into account, statistically, all the behavioural items of system's components in order to compute a global representative value. The main difficulty of Z-based methods is the restrictive conditions of an application (Is the number of agents important enough to be statistically significant?).

In the case study of pedestrian simulation, the proposed approach is based on a physics-based evaluation of simulation accuracy. The basic principle of the proposed approach lies in the computation of the energy of the holons of the simulation. The quality level of approximation realized at a given level in the holarchie is obtained by successively comparing energies of lower levels holons. Three measurements that are inspired by different energy values widely used in physics are designed:

- Kinetic energy E_{c_i}: measurement linked to the dynamics (velocity) of the considered holon i.
- Goal potential energy E_{pg_i}: measurement linked to the individual goal that holon i has to reach.
- Constraints potential energy E_{pc_i}: measurement linked to interactions of holon i with other holons and with obstacles in environment.

These three measurements can be considered as state functions since they only depend on current parameters such as velocity, position relatively to the individual goal, and positions of obstacles/other holons. Moreover, these measurements can be used irrespective of the level of the considered holon in the holarchy (microscopic, mesoscopic, macroscopic).

According to these three energies, the global energy of a holon k can be defined by $E_k = E_{c_k} + E_{pg_k} + E_{pc_k}$. This energy is characteristic of the current state of a holon and thus can be used to determine the deviation of the simulation accuracy between two adjacent levels. In that way, the notion of level similarity s is defined by:

$$s_{n+1} = (\Delta E)_{n+1} = E_j^{n+1} - E_i^n \qquad (5)$$

with E_i^n the energy of holon i of a level n and E_j^{n+1} the energy of its super-holon j (level $n+1$). If the similarity is aiming toward zero, the upper level constitutes a good estimate of the lower level. If the difference is increasing, it can be interpreted as a degradation of the upper level approximation. The similarity can thus be considered as an indicator of the quality of the approximation realised by an upper aggregated behavioural level.

Each pedestrian has at least one objective (local and/or global). To model pedestrian behaviour, a classical force model based on three main forces is used (see section 4.2): a forward force (equation 1) attracting the holon to its goal, and two repulsive

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forces from the other holons (equation 2) and the obstacles (equation 3).

In order to consider local and/or global characteristics such as individual holon goal, system's goal, and holons and environmental dynamics, energetical paradigm has thus been used to build evaluation functions. Three different energy values have been build in order to evaluate the accuracy of multilevel simulation. According to the previous force model, these energy values can be defined as follows :

- **Kinetic energy** is defined by a standard expression. In the following equation, m_i corresponds to the mass of agent i and $\overrightarrow{V_i}$ to its velocity

$$E_{c_i} = \frac{1}{2}.m_i.\overrightarrow{V_i}.\overrightarrow{V_i} \tag{6}$$

- **Goal potential energy**, E_{pg_i} for agent i, is computed using the general expression of the potential energy considering a conservative force:

$$E_p = -\delta W_{\overrightarrow{F_{obj}}} = -\overrightarrow{F_{obj}}.\overrightarrow{du} \tag{7}$$

  with $\overrightarrow{du}$ a unit vector in the direction of agent speed. Expression of the goal potential energy is given by equation 8.

$$E_{pg_i} = -\frac{\beta_{obj}.\overrightarrow{A_iO_{bj}}.\overrightarrow{V_i}}{\|\overrightarrow{V_i}\|} \tag{8}$$

- **Constraints potential energy**, E_{pc_i} for agent i, is computed with the same principle as previous item:

$$E_{pc_i} = \sum_{o \in \{obstacles\}} \frac{\beta_{obs}\overrightarrow{n_o}.\overrightarrow{V_i}}{\|\overrightarrow{V_i}\|(d_o.sin(\alpha_o))^4} + \sum_{i \neq j} \frac{\beta_{ij}\overrightarrow{d_{ij}}.\overrightarrow{V_i}}{\|\overrightarrow{V_i}\|d_{ij}^2} \tag{9}$$

6 Experimental Results

To validate the coherence of this model, the first element to verify is that an aggregated behavioural level is computationally less expensive than a more fine grained level (especially a microscopic). This is the lifeblood of the multilevel approach. To validate this aspect, computational costs between microscopic and macroscopic simulation levels have been compared. Experimental results are presented in figure 13. These results confirm that macroscopic approximation is effectively less expensive than the microscopic level. These results thus validate that rising in the scheduling holarchy implies a reduction of computational cost. Figure 14 shows the evolution of the energy of an agent following the path described in the left part of the figure. The energy clearly oscillates until the agent reaches its goal. This agent has been simulated at microscopic level. Figure 15 shows the evolution of

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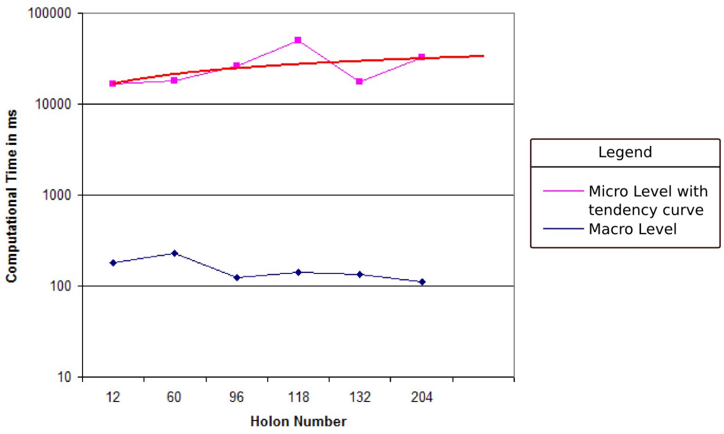

Fig. 13. The evolution of computational cost according the number of simulated individuals

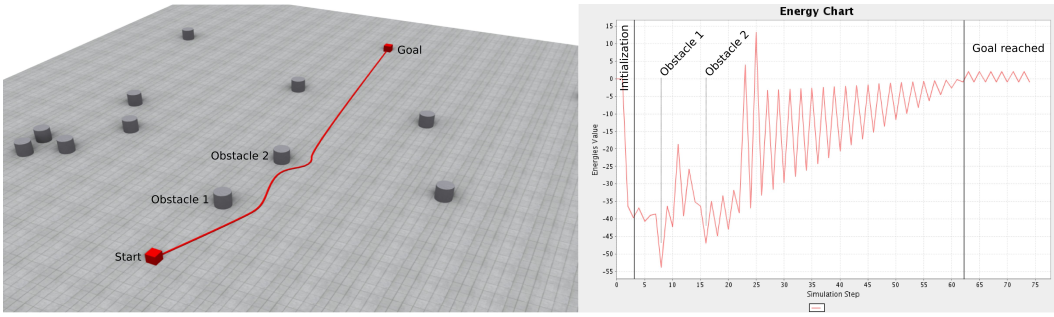

Fig. 14. The evolution of the energy of an agent microscopically simulated following the path described in the left part

the energies of three agents simulated at macroscopic level having a start point and a goal close to the previous one. Their energy curves at a microscopic level have the same look that the one presented in figure 14. At a macroscopic level, a group of pedestrians is considered as one single pedestrian, oscillations are compensated because the super-holon behaviour is based on a mean approximation of its members behaviours. Similarity between microscopic and macroscopic levels remains near zero when the approximation is correct and and can quickly increase when the situation is unfavorable for the goal of one of the members. In this case it signifies: it may imply that the given agents should integrate another group if possible or the user may accept it knowing that its simulation is only an approximation according to the available computational resources.

This multilevel scheduling model is so able to adapt agent behavioural level according to simulation constraints, i.e here computational cost. Consequently the macroscopic level may provide a good approximation of pedestrian behaviour while maintaining a visually realistic pedestrians animation. The simulation was succeeded on a quite performant computer [4] a reasonable number of agents (0–230) with a good behavioural level while maintaining an acceptable 3D visualisa-

[4] Pentium 4 2.40GHz, 512 Mo RAM, GeForce3 Ti 200

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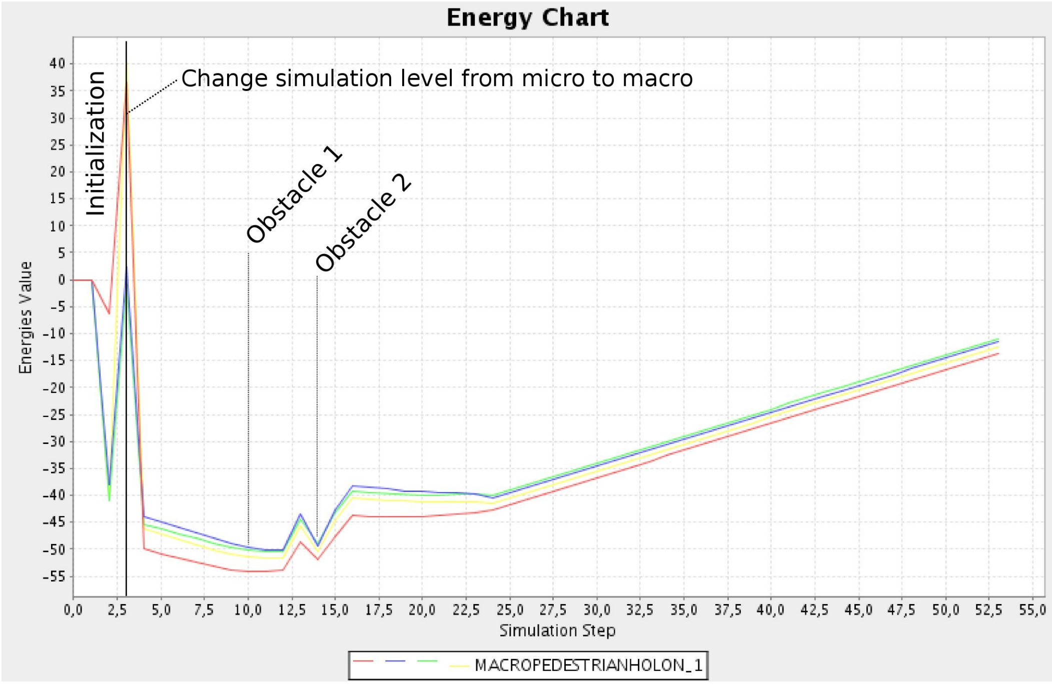

Fig. 15. The evolution of computational of the energy of 3 agents macroscopically simulated

tion: frame rate 18–23. Future works will study the refinement of our physics based indicators, to better evaluate the need of changing level. Especially we will focus on level transitions (micro ↔ meso ↔ macro). Because changing level implies an increase of computational costs to ensure the transition. For a given area, it is thus not interesting to change the level of simulation too often. Further works will so deepen the evaluation of the most appropriate moment to change the simulation level by taking care of this aspect. Based on our physics-based indicators, it will be determined if and when it is really appropriate to change level, by trying to foresee at short terms the next states of a holon and by enriching our collection of indicators.

7 Conclusion

This article focuses on multilevel simulation of complex systems. The adopted approach is based on a holonic organisational meta-model and so encourages a modular and reusable modeling. Then this holonic meta-model is applied for the conception of a complete multilevel MAS simulator. This simulator is based on a generic multilevel scheduling model, adapted to the complexity management of a simulation according to defined constraints. A set of physics-based indicators is provided to estimate the deviation of a multilevel simulation in comparison with the most accurate level: the microscopic level. This model is applied to adapt the behavioural level of simulated entites, but also to tackle specific issues related to

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the simulation of situated environments (i.e. urban environments). The scheduling system and the environment of a simulation are expressed as holonic MAS and considered as an organisational sub-structure of the simulation. The principle of this approach is finally validated on a pedestrian simulation in a 3D urban environment.

This work is part of a larger effort to provide a set of tools to support the analysis, design and implementation of complex simulations. Future works will deepen the meta-model concepts and associate a methodology to guide the developer during his work of modeling and implementing a complex (and possibly holonic) multi-agent system. Various optimisations are currently studied to refine our multilevel simulator. This article also contributes to show the interest of holonic multiagent systems for the modeling and simulation of complex systems. Due to the large range of possible configurations and their intrinsic multilevel and scalable properties, HMAS confirms being a promising paradigm.

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