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Multiscale agent-based simulation in large city areas: emergency evacuation use case

Vladislav Karbovskii[1*], Daniil Voloshin[1], Andrey Karsakov[1],
Alexey Bezgodov[1] and Aleksandr Zagarskikh[1]
[1]*ITMO University, Saint Petersburg, Russia*
vladislav.k.work@gmail.com

Abstract
Complex phenomena are increasingly attracting the interest of researchers from various branches of computational science. So far, this interest has conditioned the demand not only for more sophisticated autonomous models, but also for mechanisms that would bring them together. This paper presents a multiscale agent-based modeling and simulation technique based on the incorporation of multiple modules. Two key principles are presented as guiding such an integration: common abstract space as a space, where entities of different models interact, and commonly controlled agents – abstract actors operating in a common space, which can be handled by different agent-based models. The proposed approach is evaluated through a series of experiments simulating the emergency evacuation from a cinema building to the city streets, where building and street levels are reproduced in heterogeneous models.

Keywords: Multiscale modeling, model integration, agent-based modeling, emergency evacuation, urgent computing

1 Introduction & related works

Computer modeling and simulation as a branch of computational science has become an essential part of today's research and analysis methodologies. Models describe real systems and processes and thus can vary from simple projections to exposing high levels of complexity. A large variety of tasks (e.g. simulation of emergency situations and crisis events in order to inform decision-making and planning) requires the modeling of the second type, where a number of processes and factor are being taken into account. At the same time, a great number of models reconstructing the constituent parts of the model and their software implementations have already been developed.

Though the use of the multilevel agent-based models is by no means limited to the domains of computational social science, evacuation behavior simulation, urban planning and pedestrian

[*] Corresponding author.

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modeling, the outlook of the present paper is focused primarily on the models, frameworks and environments that address the issues topical for these spheres of scientific investigation. For the analytical survey of existing approaches, typical issues and theoretical basics of the multi-level simulation in a broader sense, one might refer to Morvan [1], Gil-Quijano [2], N. Gilbert and K. Troitzsch [3]. Multi-level (as well as multiscale and multi-model) simulations has already received significant interest from researchers in different fields [2]. However, the understanding of the very terms multi-model or multi-level simulation is rather ambiguous as comprehensive conceptual papers remain few and the choice of terminology is commonly left to the discretion of the researcher. The state-of-the-art in multi-level modeling can be characterized as lacking ready-to-use solutions and languages and tending toward context- or domain- specific systems [4]. More specifically, as [5] claims, currently-utilized models do not exhibit the potential of simultaneous representation of agents and the interactions between the agents do not receive proper articulation, which are the points being partially addressed in the present paper.

The most widely-accepted approach in the emergency evacuation research simulations is the coupling of the human behavior-related models with the ones that represent the physical properties of the hazard. For instance, Jalali et al [6] propose reflective middleware (or a meta-model) that would link and synchronize the existing heterogeneous models through loose coupling in such a way that could help overcome the limitations of the existing approaches to model integration (represented by the standards that allow the coupling of the freshly-developed simulators). As a result, they obtain a multi-level emergency simulator capable of reproducing the interaction of such factors as the spread of fire (and its by-products), evacuation behavior and the dynamics of communication systems. B. Camus et al [7] also propose to integrate models into common systems through the use of a meta-model but the domain for its implementation is specific – they aim at reproducing the behavior of evacuees in the case of a tsunami-triggered evacuation. It is worth mentioning that the absence of post-productive integration of models is widely discussed in the domain of multi-level and multi-model simulations since the previously-presented approaches are built around highly abstract languages (for instance, MIMOSE and SmallTalk [8]) and do not provide such a capability which might strongly affect the effectiveness of the developmental process in a negative way. T. Korhonen et al [9] look into a problem analogous to the one described in [6] yet they consider only two components to be integrated into the simulator – the already-existing fire dynamics simulator is extended with the evacuation behavior module. Filippoupolitis et al [10] go even further in their attempt to specify the approach for integration of the models representing the physical space of a tall building, fire hazard dynamics and the complex evacuation behavior of intelligent agents and propose an augmented reality-based solution that allows the processing of real-world sensor data. It may be claimed that the ambition of creating complex multi-level models for single-hazard or single-case use nowadays coexists with attempts to produce complex interactive "serious game" architectures and training environments that consider a large variety of scenarios, levels and scales aimed to meet the demands formulated by the military and civic authorities [11].

To position the present paper in the multi-level discourse, a comparison with a few conceptual elaborations of the approach in the field is presented. For instance, Gilbert et al [3] characterizes multi-level models as being able to reproduce more than two levels of abstraction with each of them inhabited by complex, but not necessarily numerous, communicating agents. The model described herein may be considered as partially complying with this description, since the number of simulated agents is significant and the communication between the agents of different levels might be described as replication of agents leaving one level of the model for the another one. As Morvan claims in his extensive research on state-of-the art multi-level simulations [1], there are three predominating problems that multi-level simulation seeks to address: (a) modeling of the cross-level interactions, (b) heterogeneous models coupling, (c) contextual adaptation of different levels of detail (for instance, in order to optimize the computational resources). Nevertheless, the question of defining multi-level modeling and conceptualizing the corresponding approaches is still open, and as Gil-Quijano [2] claims, many of the self-proclaimed multi-level models are in fact focused on the reproduction of a predefined single level, whereas other perspectives emerge in the observers' view (which may be as well interpreted as a criterion). Moreover, he insists that the so-called "emergentist" approach is not reasonable on a large scale. Contrary to this statement, it is assumed in the present paper that there are cases that require and allow detailed simulations of different levels that consider agents (as opposed to flows and aggregated groups) as the primary simulated entities. Considering the distinction between the weak and strong integrated simulators, proposed in [1], it might be mentioned herein that the environment proposed in the present paper does not strictly belong to any of them as the levels of the model do share agents as entities but the only environmental properties that match in both levels are the portals between the levels.

2 Problem Statement & Theoretical Backgrounds

To solve the problem of modeling and simulation of the complex interplay of the persistent and emerging processes taking place within modern urbanized areas, we propose to use an integrated conglomerate of agent-based models where different levels are represented by a single model or a combination of multiple models. Such techniques as (a) common space and (b) commonly controlled agents have been proposed so far to facilitate the integration of these models into an organized system.

Quite often models utilize different formats of data representation while pursuing the same purposes. For example, one model uses latitude and longitude to formalize spatial coordinates, while another one operates within the Cartesian coordinate system. Thus, the major issues of integrating different models are the following: (a) ensuring the interaction between the common space (or the basic model as it is) and the complementary models (if necessary and possible, in both directions); (b) compatibility of different implementation technologies of the models; and (c) ensuring a unified representation of data and common space. In an attempt to address these issues (and to ensure the simultaneous performance and interaction of the entities of the different models) a somewhat abstract shared virtual simulation environment with a unified data representation has been defined as an advantageous solution. The use of such a common virtual simulation space (referred to as "common space"), represented in the basic model is proposed herein. Following this approach, it is necessary to "teach" the basic model to use the data from the complementary models mapped on its space. As a basic model, we use the pedestrian virtual society simulator extended with support of the plug-in mechanism. The plug-in determines the interaction of basic model entities with the ones of the complementary model. Integration preprocessing is performed through a sequence of steps: (a) acquisition of the required metadata from the models of interest, and (b) definition of the rules of data exchange and interaction between the models. A reservation needs to be made here about the flexibility of the common space approach: it is assumed that it may be both fully and partially mapped on the model chosen as the basic one and implemented on the outside.

Sometimes there is a need for expansion of the initial functionality of the model. For example, when a researcher possesses a default pedestrian model, and has an ambition to simulate not only pedestrian agent flows, but also their subsequent vehicular relocations. Here he/she faces two options: (a) implement the required logic in the basic pedestrian model, (b) take an already-existing vehicle transportation model and integrate it with the primary one.

To support the exchange of data between models in real time execution (important for time-stepped models, such as agent-based models), it is necessary to implement additional mechanisms of interaction. For these purposes, the concept of the abstract commonly controlled agent (fig. 1) was introduced for the research in question. Its key feature is the possibility of agent representation in an independent model space (common space), and the ability to manage this agent by a number of models.

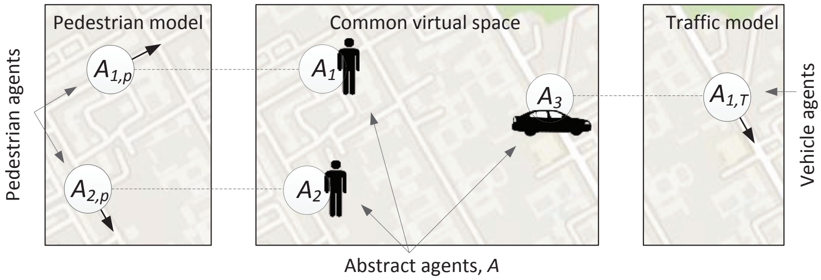

Figure 1: Spatial integration by agents

The abstract commonly controlled agents $A = \{A_1, A_2, \dots A_n\}$ are the agents operating in the common space, and R – the rules of abstract agents. For example, $M \subset R$ – movement, is the rule that the agent finds the path and tries to move from the starting point to the destination.

Referring to the case observed herein, the commonly controlled agent can be handled by the pedestrian model (walk) on the first iteration, but after a few iterations the relocations of the same agent can be administered by the traffic model (implying its "in vehicle" status). The synchronization of agents can be described by simple algorithm (table 1).

```
Foreach A in AbstractAgents:
        If (IsTimeToChangeModel)
                A.ChangeControlModel(requiredModel)

        A.step()
```

Table 1: Integration by agents, control loop

The synchronization by time is described by a simple algorithm (table 2). Different models have their own internal representation of time. The time representation can be absolute or relative, time steps can be regular (time-stepped models) or irregular (models, providing the set of events). If necessary, it is possible to use the offset or multiplier of time. All these factors contribute to the variable `isTimeForStep` for each model at each step. The step `M.step()` includes receiving data from the model, sending new data to the model and the actual execution of the step.

```
Foreach M in Models:
        If (isTimeForStep)
                M.step()
```

Table 2: Integration by time, control loop

3 Models

Two agent-based models have been used for prototyping the multi-level environment incorporating multi-agent simulators for investigation of the evacuation use case. The building-scale model was built "from the ground up" and the district-scale one is a result of modifying the model from the authors' previous work [1]. The purpose of the building-scale model is to simulate the residential dynamics in buildings (and other closed spaces) of various purpose while the district-scale model aims at a higher level of representation. These models are both multi-agent, utilize the activity approach to path planning and common mechanisms of representing the heterogeneity of physical profiles of agents. Despite that, there are differences between the models that are related to the variance in scales of representation of the corresponding simulated environments (i.e. the district-scale model does not presuppose the level of detailization of agents' pedestrian behavior that cannot be neglected in the building evacuation model). The coupling of the models in question has been performed with the use of PULSE - the multi-model integration framework. The following subsections are dedicated to the description of the models that have been used for the simulation of the case investigated in the present paper and the tool that has been used for their interaction and integration.

3.1 Building Model

Model environment E is presented as a pseudo-3D continuous space, i.e. a set of interconnected two-dimensional levels. It is composed from the following elements: (a) points of interest, (b) navigation route graph that links the points of interest, (c) impenetrable obstacles and (d) so-called portals (uni- and bidirectional). Points of interest are the objects that attract agents and imply potential interaction (for instance, seats, bar counters, tables at the waiting area or ticket office in the cinema case described herein) that can take various amounts of time. The route graph facilitates the connection of the points of interest that reflect the most common relocation patterns and sequences. Obstacles are solid objects such as walls through which agents cannot pass through. Portals, allow agents to move between the two-dimensional levels (using the stairs and elevators), around the same level or out of the building.

The model utilized the following types of input data:

1. The building floorplans (composition of levels in a building). Each floorplan includes information on the walls, obstacles, points of interest and waypoint-based route graph.
2. Cinema movie sessions schedule.
3. The description of the agent role structure (cinema activities for visitors and staff).
4. The description of physical classes of agents represented in the simulation (which lays the foundations for the estimation of the max speed and other movement attributes).
5. Data on amounts and characteristics of agents entering the building.

It is worth mentioning that datasets, matching the types of data 1-4, are static and thus configured as separate files, whereas data on agents entering the building can be both static and dynamic. In the latter case, the generation of agents on a particular level is dependent on the input from another model (for instance, an agent leaving the district-scale modeled space through the portal that marks the entrance to the cinema is transferred to the cinema-scale model). The example of the cinema building floorplan is presented in figure 2. The following are the key objects that it is composed of: 1 – main entrance, 2 – ticket offices, 3 – waiting area, 4 – bar, 6 – cloakroom, 5 – service entrance, 7 – toilets, 8 – seat places, 9 – staff rooms, 10 – second floor stairs (staff only), 11 – emergency exits, 12 – screen.

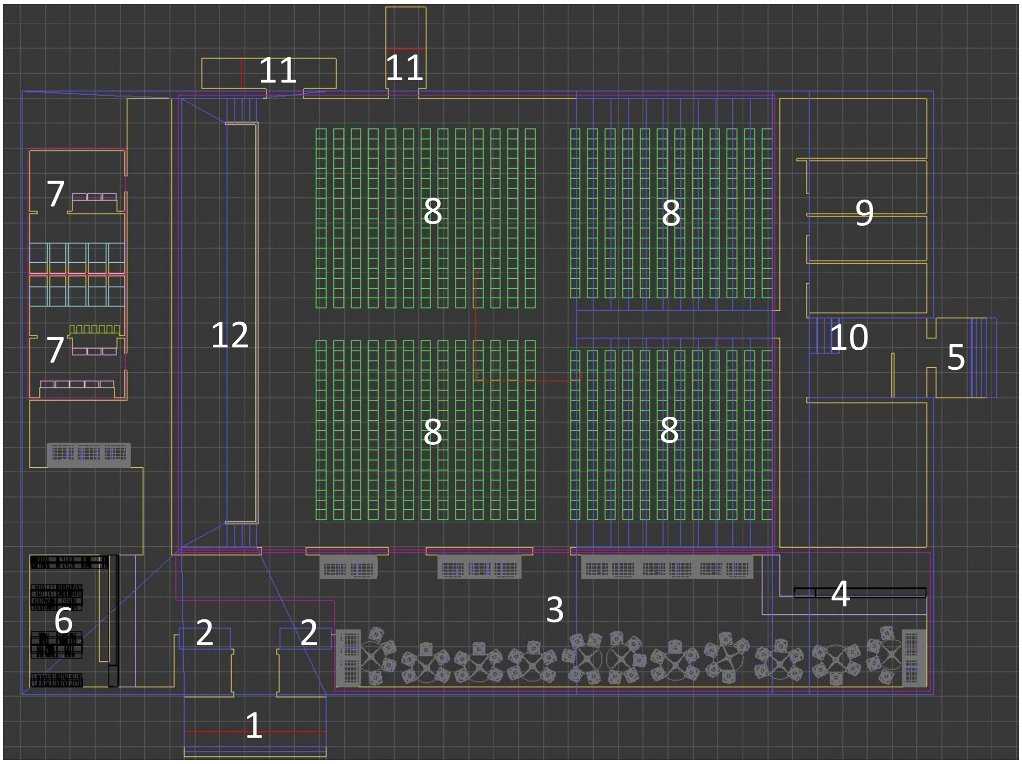

Figure 2: Cinema plan

Agents operating within the environment of the building scale model are virtual "staff" and "visitors" of the physical space that is being modeled: $A_b = \{A_{1,b}, A_{2,b}, \dots A_{n,b}\} \subseteq A$. Each agent is described through a combination of internal features (its current position, the nearest desired position or point of interest, present speed, maximum speed, performed and scheduled activities) and behavioral rules. The latter are linked to the functional roles (representing the generalized "purposes" of agents' presence and aims of the corresponding relocations within the modeled environment) allocated to the agents' population. Each agent is allocated strictly to a single role at a time. For the cinema case a function-based composition of the population of agents has been developed with two major classes (visitors and cinema staff members) defining the attributed mandatory primary points that set the basic route (for a cinema visitor these points are the entrance, seat place and an entrance or exit portals). Complementary to them, a number of subdivisions (based on gender, intention to visit the bar, the necessity and purpose of visiting the toilets, type of ticket, etc.) has been elaborated to demarcate the probabilistic alternatives for secondary activities (after the movie is over, an agent may either visit the toilet and the cloakroom or proceed straight to the exit).

In order to bind the behavioral patterns of the simulated agents to the physical environment that they are operating in, a set of navigational and path-planning mechanisms has been composed based upon the adaptation of the solutions presented in [2]. The resulting multilayer navigation approach is built from the activity scheduling, path planning and micro-level components. Since each agent has a functional role and an appropriate schedule, his path is merged from the sequences of primary and secondary activity points that are thus linked by the operational waypoints of the navigation graph. Because two waypoints can communicate in a number of ways, in order to facilitate optimal relocations, agents' travel along the graph vertices is informed by the A* algorithm. Potential collisions with stationary objects and other agents are solved with the use of the modified Social Force approach first presented by Helbing in [3]. All the interactions between the atomized agents and the environmental objects are regulated by the dynamic interplay of the multiplicity of forces.

R_b – Building scale model rules:

$W_b \subset R_b$ – In-building warning behavior rules - the rules whose execution is triggered as soon as an agent receives the warning message urging it to leave the building immediately.

$C_b \subset R_b$ – In-cinema general behavior rules. The execution of this set of rules flows from the very moment an agent enters the cinema building. Each visiting agent is obliged to buy a ticket (or to collect a pre-booked one) and proceed to the designated seat place. With a certain probability that is imposed imperatively, an agent can use the cloakroom, go to the bar, waiting area or the toilet.

$L_b \subset R_b$ – Leaving-the-cinema rules. The rule in-question is brought into execution with the agent leaving the building. Further regulations of the agent as well as his coordinates are delegated to the district model.

3.2 District Model

The district/city scale model is an elaborated version of the multi-agent model described in [12]. In its current state, the model has not only received a significant degree of autonomy but has served as the cornerstone for the integration of other models within the PULSE environment.

The inputs for model are:

1. The city infrastructure data. Includes information on the walls, obstacles, buildings, points of interest and road graph.
2. Cinema movie sessions schedule.
3. The description of the agent role structure (activity chains for social-economy classes).
4. The description of physical classes of agents represented in the simulation.
5. The initial distribution of agents in the modeled area.

$A_d = \{A_{1,d}, A_{2,d}, \dots A_{n,d}\} \subseteq A$ – District scale model agents, R_d – district scale model rules:

$D_b \subset R_d$ – Daily behavior rules. Following these rules agents visit only those points of activity that correlate with their socio-economic status (for instance, office buildings, universities, specific shops, leisure facilities etc.)

$C_d \subset R_d$ – Entering-building rules. The described type of rules serves as the basis for the regulation of the behavior of agents entering the cinema building. Having entered the building, agents' properties (such as coordinates) migrate to the building-scale model.

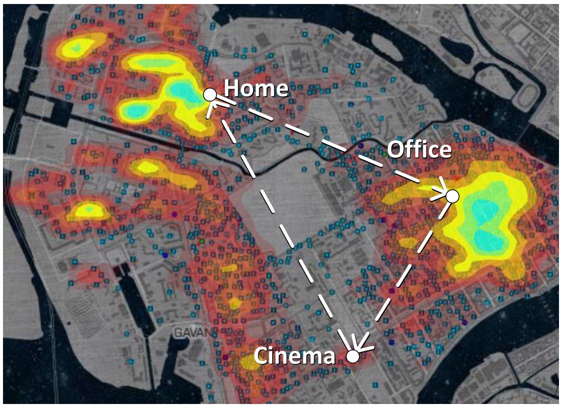

Figure 3: Example of agent's daily schedule

3.3 Software

To resolve the model integration problem, PULSE (recursive acronym, Pulse – urban life simulation environment) was used. PULSE is our research and it is under development, however it has already reached a level that allows us to use its features: (a) common space and (b) commonly controlled agents.

In order to satisfy high computational performance and urgent computing [15] requirements that derive from the specificity of the utilized models and the potential users' activity workload, the CLAVIRE cloud platform [16] has been integrated as a computational systems background infrastructure. The CLAVIRE includes a workflow management system module that allows for the representation of the estimated PULSE scenarios in the form of a workflow project.

Dynamic visualization is obtained through the interaction with the project_Fusion framework. The goal of project_Fusion is to provide a framework that facilitates rapid development of visualization. A client-server architecture with asynchronous requests was used to facilitate the interaction between PULSE and the project_Fusion solution.

4 Use case research

The aim of the present section is to illustrate the idea that a wide variety of research can be carried out by using a set of integrated models, where specific scales and levels (as well as points of view) are represented by the designated modules. The district scale model is used as common space, whereas the building scale model serves as a secondary model and the commonly controlled agents technique is applied to ensure the integration of the both models' agents. Moreover, the latter provides the models with a capacity to exchange data in real time. We do not pursue the objective of presenting the original research results on the emergency evacuation dynamics in this paper, however as a use case, the models were extended with a simple model of emergency evacuation.

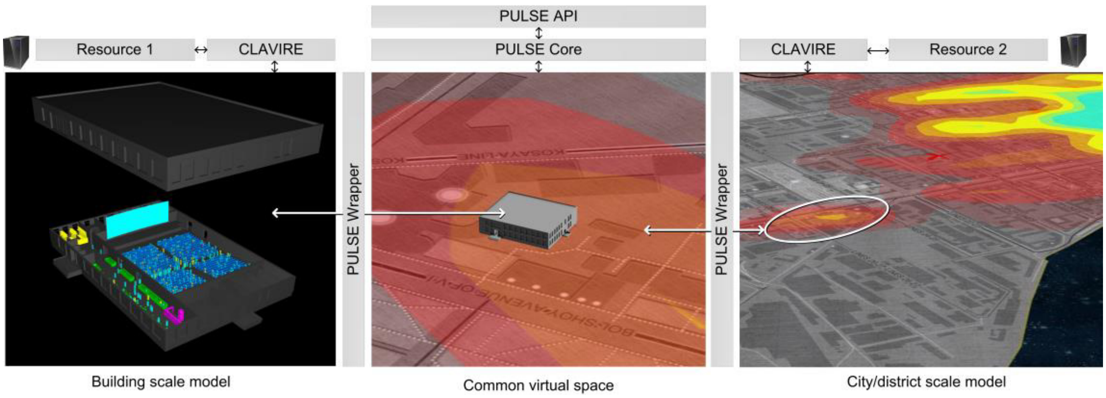

Figure 4: Spatial integration by agents

According to the scenario, the daily population dynamics on Vasilyevsky Island, St. Petersburg were simulated with the district scale model. As a form of social and recreational activity, some agents attend the cinema. In the midst of the session agents receive the warning notification of an immediate evacuation from the building. Agents (both staff and visitors) attempt to follow the warning and leave the building.

$A = A_b \cup A_d$, because we used only two models (building and district scale). $A_c \subseteq A$ – cinema visitors agents. In the experiment it is true that each agent $\in A_c$ keeps his affiliation with the set A_c even after leaving the cinema building.

We track the evolution of the agents' states for the presented scenario, the results are shown in figure 5.

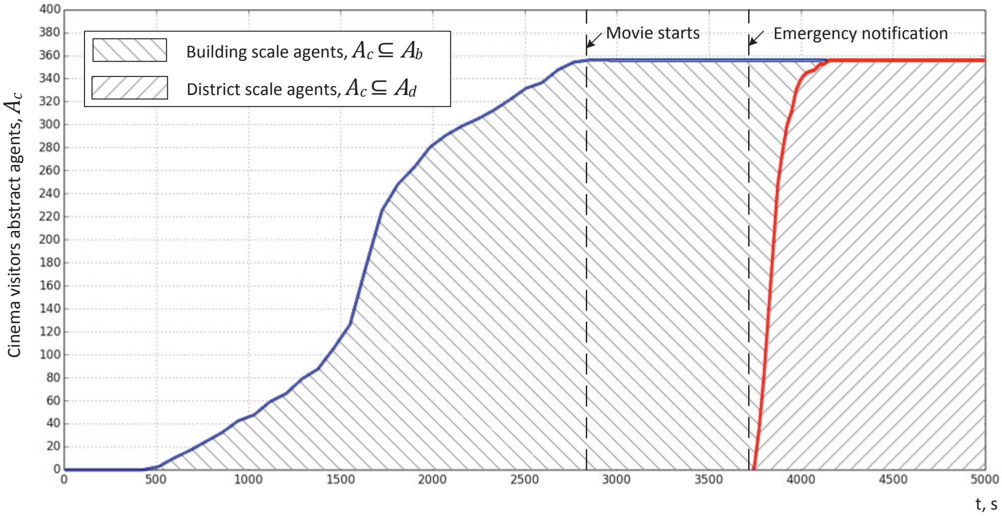

Figure 5: Spatial integration by agents

In terms of Kendall's notation (arrival process/the service time distribution/the number of services) [17] of queueing theory [18] the system can be classified as M/D/1 or similar. The arrival process, presented on the plot, is not random. It is determined by district/city scale model and agents' daily activities and visually it is similar to the Poisson process. The service time is deterministic and the number of services is one (the cinema). After the warning notification is disseminated, all agents quickly leave the building. When an agent leaves the cinema, he loses the connection to the building model, but connects with the city/district scale model.

5 Discussion & conclusion

In this paper we have presented a technique to address multiscale agent-based modeling and simulation of processes. To solve the problem we proposed a method of model integration using common virtual space and abstract common agents. The presented common space and agents help us to achieve a clear interaction between different models and their entities, particularly agents. The described techniques were implemented in the PULSE, by means of which the models have been integrated. Two models were used: (a) the building scale model to simulate the cinema and (b) the city/district scale model to simulate the daily activity at Vasilyevsky Island. The presented study is confirmed by the use case.

In future we plan to make a few important extensions to PULSE and the related models. One of our current works in-progress is the one focused on PULSE, its infrastructure and code base. We plan to improve the agents' navigation system and extend it by introduction of new levels and scales (in addition to planning, pathfinding and collision avoidance). One of the most recent future works is the integration of the district/city model (also known as the virtual society model) and traffic model (the theoretical example from P2).

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