Modelling Buildings and their Use as Systems of Agents

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This research investigates the development of a new modelling and simulation approach for building design - defined as Agent-Based Building Modelling - that moves from the current object-oriented representation (such as in BIM) to an agent-based one. In the proposed approach, the representation domain is extended in order to include users and hosted activities, and the static modelling of the building is integrated with the dynamic simulation of its functioning. For this purpose, this paper presents a general template of the agent that ensures homogeneity of formalisation of the different typologies of entities (building components, spaces, V-Users, activities) and support the virtual simulation of the use process.

Keywords: Agent-Based Modelling and Simulation, Behavioural Simulation, BIM, Game engine, Agent-Based Building Modelling

RATIONALE
In AEC design processes, modelling and simulation have been generally considered as two distinct, sequential activities aimed at defining the different key aspects of configuration - both formal and technological - and performance of the design. The sequencing of these two actions, although recursive in the analysis-synthesis-evaluation cycle of an architectural design process, relies on the concept that the output of the modelling is the input (or at least a part of the input) of the simulation (Koutamanis, 1996). This sequence inevitably generates delays and many resources are wasted in modelling the different versions of the building, as it usually happens in trial and error design processes. The advent of Building Information Modelling has even bolded these criticalities: the forced accuracy and coherence of a building information model, as well as the tendency to over-detailing the design for documentation purpose, has pushed - at least conceptually - simulation later in the process. Even when a direct link between the modelling environment and the simulation one has been conceived, there is still the necessity of a well-detailed design in order to successfully perform simulation activities. The introduction of parametric design - in particular in its declination towards the performance-based design - has partially overcome this issue, conceptually and technologically fusing modelling and simulation actions to generate, control and optimise shapes and configurations for specific phenomena such as shading, visibility, energy consumption etc., although in a very qualitative way. More recently, Agent-Based Modelling and Simulation approaches have progressively introduced in the AEC field as a way to represent and control complex systems that can be decomposed into a set of
autonomous, interacting entities (for instance people egress during a fire), in order to predict possible emerging phenomena and explore the effects of design variations (Gerber, 2017). As previously proposed by Smith (2003), a shift is possible in virtual architectures modelling by moving from an object-oriented approach to an agent-based one, overcoming the definition of static places that do not respond to the intended use. In particular, while some effort have been made in the integration of modelling and simulation actions regarding some specific aspects such as daylighting and shading, energy balancing or structural behaviour, few works has tried to enlarge the representation domain in order to include operations, use processes and users’ requirements (Wurzer, 2010; Simeone and Kalay, 2012, Simeone 2015). In fact, while in literature buildings have been often compared to the concept of living systems, even from a computational perspective (such as in the “patterns” proposed by C. Alexander in 1977), current modelling systems are only centered on the virtualization of design and do not consider users and their activities as “part of the model”.

THEORETICAL FRAMEWORK

The integrated definition of the building and of its performances (in particular its use by its inhabitants) has been a hot topic since the introduction of digital technologies to the CAAD field. With the progressive increase of computational power, as well as the development of new paradigms, different approaches have been presented to the CAAD scientific community and some of them are now used in the architectural practice to evaluate specific aspects of human behaviour in buildings such as fire egress or pedestrian movement. From a brief study of the state of the art in this particular sector of CAAD, we can recognise three different main approaches oriented to the simulation of people movement and behaviours in the building:

1. Cellar automata systems;
2. Agent-based systems;
3. Activities-based systems (sometimes known also as Process-driven or Narrative-based).

The first difference between these approaches is the allocation of Artificial Intelligence among the different entities representing the building and its users. The cellar automata approach, that is maybe the older among them, principally rely on the modelling of the built environment as sets of active entities (defined cellar automata) provided with simple algorithms to control specific variables. For instance, in a simulation of people’s movement in a building, the users’ entities are actually passive and their passage from one cell to the other is actually controlled by the cells themselves. Specific variable -such as occupancy or movement speed- are stored both in the cells and in the users and support this computation that is, in fact, distributed. Among the others, cellar automata experimentations in the CAAD field embrace different applications as generative design tools (Herr, 2016) or simulative tool to predict and visualise pedestrian activities (Dijkstra, 2001). The introduction of Agent-Based Modelling in the simulation of people’s behaviour in the building has actually inverted the AI distribution perspective of Cellular Automata. In fact, the core of this approach is the autonomy of the agent, provided with a set of behavioural rules able to interrogate the surrounding environment, make decisions and performs actions that change its status as well as the built environment in a continuous perception-decision-action cycle. In this approach, the built environment is mainly passive and the use phenomenon emerges from the combination, iteration and interference of the behaviours of the n agents.

The introduction of this approach has represented a big shift both in the research field and the professional practice: many of current tools that are currently use to predict people’s movement in specific buildings as stations, airports, shopping malls (such as Mass Motion by Arup and SmartMovement by Buro Happold) (Cenani, 2008; Yan, 2004), as well as simulating evacuation processes (Gwynne, 1999), rely on this approach. More recently, research has proposed a new approach, partially derived from industrial production planning and management, that re-
lies on the “smart” formalisation of use processes in terms of a sequence of activities, organised and scheduled by means of a temporal-logic approach, and their simulation in a 3D virtual environment. This approach, particularly effective in representing more articulated use processes rather than the simple people’s movement, is at the base of different modelling and simulation methodologies such as the USSUU system proposed by Tabak (2010) and the Event-Based Modelling (Simeone and Kalay, 2012, Simeone et al., 2013, Schaumann et al., 2015). In terms of AI distribution, this approach assigns AI resources to a process engine (as in the USSUU system) or to autonomous process entities (the events) able to coordinate and simulate multi-actors activities performing in the built environment.

AGENT-BASED BUILDING MODELLING

In this context, we propose to shift the current BIM methodology towards a new user-centered perspective, in which the building is defined not only in terms of mere constructive components but also in terms of use and performance, including the representation of how it will work and how it will be used and experienced by its inhabitants. The development of an innovative system based on the integration of both modelling and simulation is indeed at the core of this research. In this system, entities are not passive databases for data storage (as in current BIM) but active agents provided with their own “intelligence” and behaviour. This modelling and simulation approach - defined as Agent-Based Building Modelling (ABBM) - differs from current ABM applica-

Figure 1

The BIModel of the case study - a hospital - that shows initial discretization of the building in terms of elements, provided with their own semantics (not yet agents because of the absence of behavioural rules).
tion to the AEC field for the fact artificial intelligence is distributed among V-Users (the virtual computational entities representing the various users of the building), the entities that compose the building (i.e. floors, doors, furniture), spaces, and process entities (activities, organized through temporal logic). To obtain a homogeneous multi-agents system, we conceived a general ontology for the agent, meant as a self-contained AI entity capable of controlling its own decision-making and acting based on its perception of its environment, in pursuit of one or more objective (Wooldridge and Jennings, 1995). In the proposed MAS system, the agent embeds three different components, applicable to all the different entities of the Building + Users + Use model:

- ID;
- Properties-Status;
- Behaviour Engine (meant as a set of decision/action rules).

The role of the first component, the ID, is clear: it supports the identification of any single entity within the model, from its generation to its elimination, and allow the agent to feel and recognise the different entities that surround it. ID are conceived as an alphanumeric code where the first part represents the class of the element and the second part indicates in a unique way the instance number within the model. The second component, the properties/status, represents both configuration and status during the simulation of any entity. While in a BIM system the properties component describes the static features of the building entity (i.e. topology, materials, construction information), in the ABBM system it embeds all those variables that 1) add use semantics and 2) represent the status of the agent/entity during the simulation. In the case of the technological components of the building, as well as of spaces, the properties formalisation is very similar to the usual BIM-oriented one. In fact, in building information models classes already embed some semantics related to specific construction and production aspects. In the proposed model, this semantics is enlarged in order to formalise information related to usability and use,

Figure 2
The Agent-Based Building Model of the hospital case study (in the game engine Unity3D), where any entity - Building elements, V-Users and activities - are agents with their own set of properties and rules.
both to enrich the static model and to support data access, variation and evaluation during the simulation of the building+users+use system functioning. These properties - the static and the dynamic ones - clarifies the twofold feature of the proposed Agent-Based Building Modelling. The static properties, that are defined by the architect, represent invariant features of the elements such as materials, etc.. The dynamic properties, instead, represents the status of the elements during the simulation of the building use and embeds all those features that can actually vary during the process of use of the building. For instance, a door embeds a static property that clarifies which users are allowed to pass or a Boolean property that describes if it is open or closed. In a similar way, space entities can store information regarding the maximum number of users allowed at the same time while a dynamic property (controlled by a measurement algorithm) can store the number of people actually present in the room during the different stages of the simulation. By operating on these primitive properties, other properties (i.e. the temperature related to the room occupancy) can be derived through specific calculation algorithms. The memorization of the variation of this kind of properties is particularly effective during the evaluation of the simulation results since it allows designers to estimate particular phenomena such as overuse or underuse and consequently optimise the design. In a similar way, static and dynamic properties are useful in representing V-Users and their features. Static properties can be used to define the specific profile of the Users in terms of role (i.e. a patient in a hospital), physical features (age, sickness typology etc.), specific abilities and all the other aspects that can be considered and modelled during the design process. Dynamic properties, instead, can be used to represent the status of the V-User during the simulation: a walking_speed property or tiredness_level, for instance, can describe the specific condition of the V-User at a certain time of the simulated use-process. In the case of activities entities, the properties (both static and dynamic) embeds all those information necessary for a correct representation and simulation of its system of actions. Static properties can formalise the kind of V-Users necessary for its performing, while dynamic properties such as performing_time or influence_radius can represent both efficacy and influence of the activity performing within the built environment and in accordance with the use process. During the simulation, the sum of the status of the different entities - representing the building (and its spaces and components), the V-Users and the planned and unplanned activities - as well as its variation, represent the state of the entire system at a certain step of its intended use process, allowing even quantitative estimation of different aspects of the use phenomena. Compared to current BIM representation schema, the proposed model, in its static formalization of entities, represents both an extension and a “deepening”: on one side, in fact, it enlarges the representation domain in order to include Users and Activities; on the other, the classes-subclasses-instances schema allows to build more deep taxonomies if compared to the family-type-instance schema typical of BIM, ensuring a better accuracy in the definition of the entities and of their features. As in usual Agent-Based Modelling and Simulation Systems, phenomena emerge from the interaction of different agents behaviour, as well as their mutual combination and interference. For this purpose, it is necessary to conceive the third component of the agent, defined as the Behavioural Engine, a set of rule that allows the agent to 1) understand the surrounding environment 2) make decisions by comparison of the system status with its objectives 3) perform actions and 4) update the status of the environment (and of the agent itself). In the case of a V-User, the Behavioural Engine controls its actions during the simulation, as well as updates its status for each simulation frame. In a similar way, the behavioural engine of a building component can control some usability aspects and measure particular conditions, in order to provide specific feedbacks to designers. For instance, a door entity will be enriched with semantics about its usability and it will be able to know which people are allowed to open it and
how. The AI-enriched door will check any usability issue during the modelling phase and the door will perform accordingly to these assumptions once the simulation of the building use will be running. Even the process entities - the activities - are provided with a Behaviour Engine: in this way, they can coordinate different V-Users involved in the same activity, in order to manage complex collaboration that would be particularly difficult to manage only with mutual interactions between V-Users agents. Temporal logic relationships among activities, as well as their organisation on different priority levels, also drive the simulation in accordance with the previously defined use scenario. The conception of this abstract schema of the agent, potentially applicable to all the typologies of entities that are part of the Building+Users+Use system, ensures both homogeneity and extendibility of the model. In fact, different classes of agents, belonging to any of the three domains, can be included in the model if they are constructed according to the proposed schema. This is actually an advantage of ABMS systems that could not be reached in simulation systems that rely on a central simulation engine. This model prerogative is also very well suited to a BIM-oriented architectural design process since it integrates the definition of objects - typical of BIM - with the specification of its functioning/behavioural dynamics. From the implementation perspective, we chose to rely on a game engine (Unity 3D) in order to integrate building modelling and use simulation in a single platform. In fact, the game engine allows to conceive and develop smart entities representing the different building components (as in a BIM environment) and provide them with both the properties/status component and the Behavioural Engine. At the same time, in the game engine provides the technology and the Artificial Intelligence resources that are necessary to simulate the building use processes and the behaviour of a large number of agents. In addition, specific third-party applications ensure good interoperability with BIM software such as Autodesk Revit, in order to support
design documentation and additional detailing. Currently, the Agent-Based Building Modelling approach is under application in the field of hospital design, where operations and use processes assume a particular relevance. In particular, current experiments are focused on the functioning of diagnostic and ambulatory units of a newly designed hospital in Rome, as well as the people's behaviour within the public spaces of the hospital (see Figure 1).

Those services, in fact, are the more affected by a number of potential patients, as well as by the kind of services provided and the availability of human resources and machinery (Cohen, 2010) (see Figure 2). In particular, waiting rooms occupancy was measured, as well as medium waiting time for the generic patient. In addition, mobility within the public areas was evaluated, particularly measuring the access to both relax areas or commercial services. To improve users' experience and hospital resources management, different allocations of human resources were tested, considering different time shifting. Although these tests are still under development, the proposed Agent-Based Building Modelling is showing good potentials in giving a new dimension to the hospital design process, integrating the definition of the building in its parts and the configuration of the services that it will provide, and the behaviour of the users it will host (see Figure 3).

CONCLUSIONS
The result of this distributed intelligence approach is a modelling and simulation platform that will support architects, engineers, managers and all the other specialists to conceive the building and its articulation by predicting and understanding how it will interact with its inhabitants and how they will behave in it. While current BIM approaches mainly provide construction and assembly coherence, the Agent-Based Building Modelling will ensure also functionality and use quality, allowing designers to virtually conceive, model, test, and optimise the design without even stepping into the construction process. At the same time, clients will be actively involved in the design process: the simulation platform allows them to understand how their building is going to work and operate after its construction. The anticipation of use evaluation will increase designers' awareness of the impact of their design decisions on the future users of the building, enhancing the overall quality of the building and, consequently, the quality of the life of its inhabitants.

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