Adding users' dimension to BIM

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Abstract In the last few years, several researches have added new dimensions to the usual 3D BIM approach, progressively including information about construction time (BIM 4D), costs estimation (BIM 5D) and life-cycle management (BIM 6D). Nevertheless, a key factor such as the building's interaction with its intended use and users is still under-represented by current BIM and IFC models: many users-related decisions are based on a set of average users requirements and on the assumption that, in this way, the future building will fulfil the needs of the majority of users. In this paper, we propose to include use' and users' semantics in current BIM representation, and to integrate it with the virtual simulation of the building use phenomenon. Its main objective is to provide a visualization of how the future building will actually be used and experienced, before stepping into its construction. This allows designers to test and evaluate the impact of their decisions on future users' life and activities in the proposed built environment during the design phases, when it is still possible to intervene and improve the quality of the final product by solving critical issues and reducing time and costs.

Fig. 1 The use process of a hospital ward simulated in the virtual environment

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Rationale

In the last few years, Building Information Modeling approach has been progressively extended from the exclusive representation of geometrical and physical features of buildings and their components (BIM 3D) to the inclusion and representation of knowledge related to construction time and scheduling (usually known as 4D BIM or simulation-based modeling), costs and expenditure estimation (5D BIM), and different aspects of life-cycle facility management (6D BIM). Nevertheless, current BIM and IFC (Industry foundation Classes) models are mostly focused on the representation of the building and of its components as a product (embedding data related to geometry, functioning, costs, manufacturer, etc.), while other knowledge areas (i.e. context, procedures, use process), although crucial in the design process, are still underrepresented. Among them, the knowledge domain related to future users, their activities and their relations and interactions with the building is maybe the most relevant to assess the quality of a proposed design and its performances (Maggi, 2009).

Even though architects and their clients have at their disposal several computational tools that can help them in predicting and evaluating many aspects of building performance (such as cost, energy consumption, and structural integrity), they have no means to predict and evaluate how well the proposed design will perform from the users' point of view. Since knowledge about users and their activities is not represented in current BIM models, arguably the most important characteristic of a building—how well it will match the functional, psychological, social, and cultural needs of its future users— is still left to architects' expertise and imagination.

As result, at present many users-related decisions are just based on a set of average users requirements and on the assumption that, in this way, the future building will fulfil the requirements of the majority of users (Zimmerman, 2003).

State of the art

Before the development of BIM approach, some attempts have been made in CAD environments to introduce knowledge about users and their activities in AEC models (Eastman & Siabiris, 1995; Ekholm & Fridqvist, 2000, Carrara et al. 1994), implicitly in terms of their spatial features. In the last decade, research attention has moved from a "space-oriented" representation of users' activities, to a "process-oriented" representation, where activities are represented as specific modelling entities on their own, clearly distinct from spaces, but connected with them (Tabak, 2008; Wurzer, 2010).

Since the advent of BIM, activities and users have been left apart from the BIM modelling environment; hence, evaluating the building's *suitability* to support the evolving practices and changing human use patterns is left un-aided by modern representational means, and relies instead on architects past experiences, which are context and time-specific and only partially translatable to the current project. Although the emergence of Building Information Modelling paradigm has allowed to add semantics and non-graphical data to the formerly mostly geometric representation provided by previous CAD systems, BIM has ignored *Use* and *Users* so far. In addition, current BIM models are static, and this feature is ill- suited to the dynamic phenomenon generated by users' behavior and activities in a built environment, that is usually different from one building to another, from one context to another, and from one specific time to another.

Lawson's statement, which affirms that "*the best test of most designs is to wait and see how well they work in practice*" (1997), describes the motivation of progressive introduction of simulative approaches to represent the interaction between people and environment. Usually, simulation is considered to be the most valid method for evaluating the performance of designed artefacts when the relationships among the decision variables are too difficult to be established analytically, because they interact in complex ways or there are too many of them (Kalay, 2004).

With the exponential increase in computing power and the availability of new simulation approaches and paradigms, human-built environment interactions have begun to be introduced into building performance evaluations.

The introduction of simulative approaches has shown different ways this issue can be addressed, at least regarding some specific aspects of human behavior in built environment (Yan & Kalay, 2004; Tabak, 2008; Simeone & Kalay, 2012). Such approaches, though, focus in developing stand-alone platforms, which do not take into consideration common building representation and modeling tools that populate architectural practices' environments, such as BIM. So, we chose to provide two new elements to the Building Information Modeling representation template:

- A more comprehensive formalization of knowledge about use processes and building occupants, and able to embed it in building elements to augment the amount of information they carry;
- A dynamic simulation method (similar to the ones developed for 4D, 5D, 6D BIM models to predict and estimate building construction and maintenance processes) able to predict users' behavior, activities and interaction with the building.

The proposed model: methodology

The objective of the research described in this paper is to develop a model able to represent in a coherent system the building and its intended use and users, in order to support designers while making decisions that could impact the life of the future users of the building. On these basis, we chose to extend current Building Information Modeling domain in order to include knowledge about users and their activities, and to integrate it with a virtual simulation environment in order to visualize the building "in use," rather than only its built shell. The first novelty of the proposed model lies on the fact that the representation system is not anymore exclusively focused on the building product and its parts (spaces, building components, furniture, etc.), but it also includes its intended users and their activities, all of them represented in a coherent and homogeneous model. In addition, the introduction of a simulative approach allows designers to virtually test and evaluate the building in terms of its impact of future users' life without wait for its construction, when it is usually too late or too costly to intervene to correct design errors and critical points.

As stated earlier, current building modeling systems are data-rich and appropriate for representing physical properties of buildings. However, they are still not suitable for representing the semantics related to users and their activities. In order to provide to current Building Information Model system this missing semantics, we chose to connect it with an ontology-based[1] representation system, where entities (building-related or use process- related) are formalized in terms of their attributes and relations. Semantics will provide a unified way to express knowledge in order to be computed, exchanged, interpreted and understood by all participants in the design process. Such knowledge should be the base which designers rely on to synthesize their desired design solutions, and it encompasses regulations, field expertise, as well as empirically validated experiences and practices of the discipline.

The homogeneity of the representation of this extended system is one of the main features of the proposed model: Building-related entities (spaces, building components, etc.), and process-related entities (actors, activities, etc.) are formalized in the same way in terms and connected in a single representation model. This approach, partially derived by the ontology-based representation model developed by this research group (Carrara et al., 2009), offers the possibility to formalize in a single model - and in a single representation way - knowledge provided by different areas. This is particularly relevant for our purposes, since knowledge related to human spatial behavior is not already organized in a single system, but it is spread in several domains,

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[1] In the context of ICT, an ontology defines a set of representational primitives with which to model a domain of knowledge. An ontology is a representation vocabulary, a conceptualization structure and, an ontology system is a semantic structure which encodes the implicit rule constraining the structure of a piece of reality; the aim of ontologies is to define which primitives, provided with their associated semantics, are necessary for knowledge representation in a given context.

each of them with its own set of approaches and methodologies. An ontology-based system provides a unified formalization of such knowledge, and to take advantage of the features of the well know object-oriented approach, such as the possibility to store the knowledge only once in a "master" object, than instantiate it whenever needed, and to create a library of entities (including building objects, activities and users), which may be used and shared by different professionals involved in the design process. Considering the highly dynamic essence of knowledge, which unfolds during the design process, the system in which semantics are codified will allow for a quick and easy expansion and modification, offering a reliable, specific and up-to-date knowledge about the considered domain.

To implement the knowledge about the building use process, we add to the existing BIM model new classes of entities representing the building's intended occupants (including their profile and attributes such as physical properties, role, tasks, schedules etc.), and the system of activities that they have to perform in the building (sequence of actions, necessary amount of space, necessary tools and furniture, users' profiles involved, etc.). We also extended building components' representation in order to provide semantics about their use and their interaction with users during the building functioning. In this way, the proposed ontology-based system provides a semantic network, accessible both by designers and computational softwares, where all the entities necessary to describe the building product and its functioning are integrated and connected each other. It allows to add semantics to BIM representation approach, currently able to mainly store and formalize data about geometry and materials of building components[2].

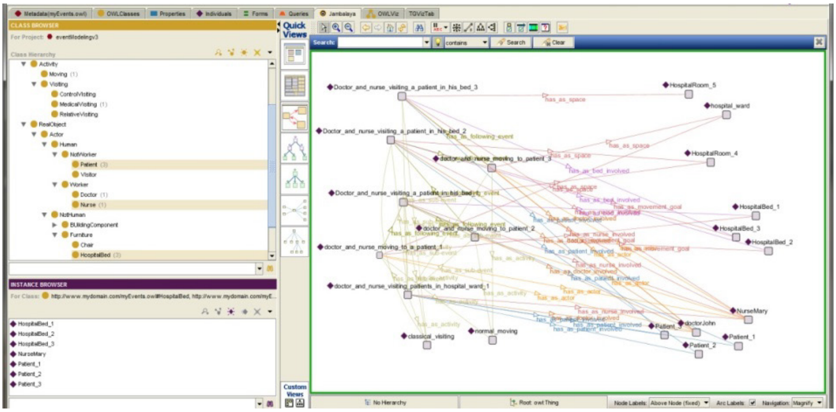

Fig. 2 Activities, users and spaces formalized in the ontology-based representation system

The simulative approach

The process of use of a building is a complex, dynamic and extremely variable phenomenon; the uniqueness and the context-dependence of human interaction with built environment are some of the main obstacles to a static way of representation. To circumvent them, we chose to integrate the proposed ontology-based representation model with a simulation environment to predict (within a certain range), visualize and evaluate the building occupancy and users' spatial behavior. In our model, the simulation environment has been developed by applying methods and technologies dedicated to simulate human behavior in videogames[3].

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[2] To build the knowledge base and represent these semantics, we have chosen to use the ontology modelling system Protégé, a Java-based open source ontology editor and knowledge-base framework (http://protege.stanford.edu).

[3] To represent and visualize the users and their activities in a 3D simulation environment we chose *Virtools,* a video game engine developed by Dassault Systèmes, integrated with compatible Artificial Intelligence libraries (http://www.3ds.com/products/3dvia/3dvia-virtools/).

On this basis, a game engine has been implemented to support human behavior representation and simulation in a virtual environment.

Game engines are composed of two different parts: a scripting interface, where behaviors of agents and objects are structured and computed, and a 3D environment, where these behaviors are actually visualized. The proposed representation model allows to formalize all the data needed as input for the simulation engine. For instance, this semantics can provide information about the permeability of doors and the solidity of walls, the schedule of an elevator, the usability of furniture, the state of occupancy of a space, knowledge that is absolutely necessary to effectively simulate users' behavior in a building. To represent the users, some specific entities provided with AI (Artificial Intelligence) resources have been implemented in the simulative model. These Virtual Users (VUsers) inherit from the ontology-based system their profiles, their attributes, their tasks, and their behavioral rules; then, in the simulation environment, they perform autonomously the tasks envisioned for the future building occupants, providing both dynamic simulation and 3D visualization of their performance. In this process the AI resources are necessary in order to provide them with the capabilities of observe the environment surrounding them, making decisions and performing actions.

In addition to the building and its users, the proposed system provides in the simulation environment data about the system of activities and their specific performing. This in needed because the objective of the model is to simulate not only some specific aspects (for instance the movement) of users' behavior, but more in general the tasks and activities that users will perform. In particular, when the model is dealing with the testing of a design solution, the system has to get not only general information about the activities but a specific and circumstantiated *use scenario*, in order to provide an effective and evaluable phenomenon as result. A building use scenario describes a real-world example of how an organization (in terms of the people involved) interacts within itself, with the built environment, and with the context in which it operates. In the simulation environment, the building use scenario is represented as a game narrative, a story path where each activity is a milestone of the plot, involving some VUsers and being located in a specific portion of the building environment. The general complexity of a building use scenario, where several activities can be performed simultaneously and affect each other, is reflected by the complexity of its representation; multiple paths of activities to be performed in a temporal sequence, generate an articulated graph, which connects and combines them in an oriented network where the orientation of each branch shows the logical sequence of their performing.

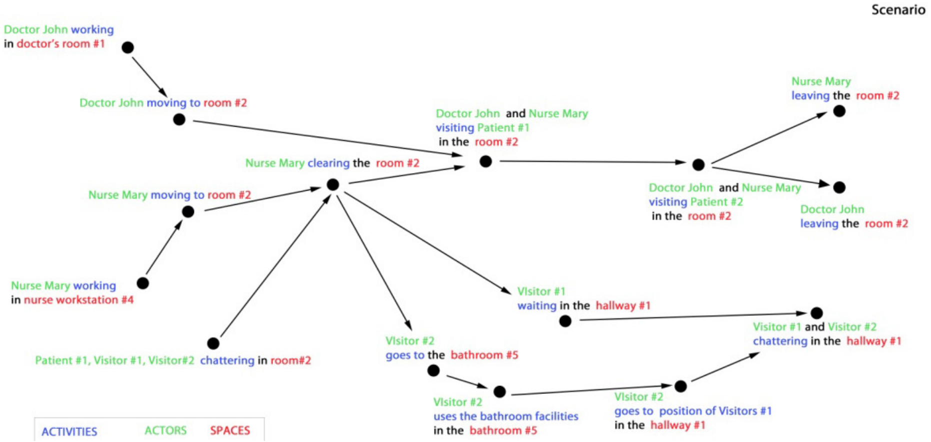

Fig. 3 A part of building use scenario (for a hospital ward) formalized as an oriented-network

In the simulation environment, to each activity formalized in the use scenario is associated one or multiple algorithms, which compute and simulate its performing, and the actions/behaviors of the VUsers involved. At the same time, in order to provide a reliable prediction of the users' occupancy and behavior, the scenario has to be able to adapt to the different conditions emerging from the performing of determined activities in a specific building layout. This feature highlights the difference between our approach and the numerous animation tools that populate the architectural representation industry, in which the simulation result is coordinated and scripted in advance; rather than predicting the use phenomenon, they provide a mere visualization of the architect's idea on how the building will be experienced and used. These tools do not provide the possibility to perform a qualitative or quantitative evaluation of the use phenomenon, since they are choreographed by architect's imagination and do not reflect the reality they are keen on simulating. On the contrary, in our proposed model the building use process interacts with and is actually mediated, influenced by the built environment as designed by the architect. To reach this adaptation process, we chose to distribute AI resources at different levels of the model: in the Virtual Users, in the building objects and in the use process controlling system. The AI engine located in the virtual users has the role of controlling individual tasks and behaviors. This method is derived from the Agent-Based Modeling approach[4], where each agent entity has the control (in certain range) of its own behavior (or at least of some aspects of it), making decisions in accordance with its goals and the status of the model. But, since "pure" agent-based systems fail in representing cooperation and collaboration among agents, limiting the reliability of the building use process simulation, we integrated this system with a process controlling AI engine, at level of the scenario. Its task is to control and coordinate the performing of the different activities, solving interferences and conflicts among them and, most generally, guiding the flow of activities in accordance with the information and data formalized by means of ontologies in the knowledge base. In addition, the AI resources distributed in the building components have the task of controlling the simulation of local interaction with the VUsers by taking momentary control of their behavior. For instance, a door can include knowledge about the users already inside the room and decide if the approaching user is allowed to enter or not. In this way, the AI resources are balanced among a large amount of entities rather than just concentrated in the 'brains' of the VUsers, and this makes the simulation process more computationally manageable and its outputs more reliable and realistic.

Fig. 4 The building use scenario scripted and simulated in the 3D environment

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[4] An agent-based model is a system modeled as a collection of autonomous decision-making entities called agents, with a view to assessing their effects on the system as a whole. An agent-based model simulates the simultaneous operations and interactions of multiple agents, aiming to represent the system's dynamics and to predict the appearance of complex phenomena (usually named "emergence"), under different sets of initial or boundary conditions (Macal & North, 2007).

Case study: testing a hospital ward

Operational efficiency in hospitals is heavily influenced by the design of the built environment and by the location of some "problem areas" such as specific patient care spaces, departmental areas (nursing units, diagnostic and treatment units) and public areas (corridors, lobbies, waiting rooms) (Cohen U. et al., 2010). At the same time, although hospitals are relatively complex buildings, as currently conceived and designed they are highly specialized "machines" whose purpose is to "fix" ailing patients. They use a relatively straight-forward, standardized use pattern, which is advantageous for this research since it provides a comprehensive, and agreed-upon, data set against which the model can be tested. Based on these assumptions, we chose to apply the model to the simulation of human behavior and activities in a simple hospital ward. We have developed a double scenario in order to test typical activities within the ward and a special occurrence as an emergency in a random patient's room. In this study case, we have simulated how different spatial configurations affect the same use scenario, improving or hindering operational activities, patients control by nurses, accessibility in case of emergency, etc. Currently, we are applying the same scenarios to an already built hospital, in order to compare the simulated functioning with the real world functioning, and validate the structure and the results of the modeling approach[5].

Conclusions

In this paper, we have described the development of a modeling approach aimed at representing knowledge about users and their activities in current Building Information Modeling. In order to achieve this objective, we chose to integrate BIM with a knowledge base, developed by means of ontologies, able to add semantics and to homogeneously represent not only building components and spaces, but also users, activities and the relations among them. In addition, since the phenomenon of building usage is extremely dynamic and dependent from the environment (without taking into account social and cultural factors), and deeply influenced by design choices, we chose to integrate the proposed model with a simulation environment, where this phenomenon can be virtually simulated and evaluated. In this way, designers could be supported:

1. During the synthesis phase of the design process, having the possibility to access to knowledge and data about users and activities, and use it in order to develop design solutions more accurate in terms of their user-oriented performance;
2. During the evaluation phase of the design process, to virtually test the design solution in use conditions.

A better comprehension of how people will use and interact with the built environment will necessarily impact the design process. Therefore, we believe that the possibility to provide a reliable prediction of how people will behave in a building before its actual construction could allow the designers to evaluate the final quality of an architectural product and, in case of emergent usability problems, critical points, or inconsistencies, to intervene by improving its quality, its livability, and reducing unnecessary costs.

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[5] please visit: http://www.youtube.com/watch?v=3OKgipQ6Pbs&feature=g-all to witness the dynamic behavior of the proposed model.

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