Modelling and Simulating Use Processes in Buildings

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Abstract. *In this paper, we propose a new approach to simulating users' behavior in yet un-built buildings. For this purpose, we have developed a model that connects two different representations: a formal representation of the building use, by means of a method borrowed from Business Process Modeling and Notation (BPMN) approach; and a game-engine based 3D virtual environment, where this process is effectively simulated and integrated with some autonomous behaviour of users/agents. The model has been applied to two test cases, where the activities of doctors, nurses, patients, and visitors in different hospitals were tracked, simulated, and reviewed by medical professionals for validation.*
Keywords. *Building use simulation; human behaviour modelling; BPMN; activity-based modelling; building performances prediction.*

INTRODUCTION/RATIONALE

During the design process, architects are asked to predict and evaluate future building performances related to a large number of functional, typology-based and organization-based requirements. To support their design decisions, architects usually rely on functional programs which are interpretations of the requirements of the organization that will occupy and use the building, namely: the main activities of future building's occupants.

In the past, this interpretation process has been mainly supported by normative methods, regulations and general design rules. Nevertheless, the domination of normative approaches has shown its limits in light of increasing complexity of building design and typology, and the intrinsic complexity of human - building interaction (Koutamanis and Mitossi, 1996). As matter of fact, its high level of abstraction is not well-suited to the intrinsic uniqueness and context-dependence of an architectural product. Specifically, basing design decisions on a set of averaged parameters, in the assumption that the building will satisfy future users' needs (Zimmerman, 2003) much like "similar" buildings have done so in the past, often fails when real users, who may differ from the "average" user in many ways, finally meet the building.

Architects' ability to predict in which manner their design will be used, and whether it will match the activities of its intended users, is currently only supported by the architects' own expertise and imagination. Sadly, the consequences are clearly recognizable in reality: too often buildings do not perform as expected after their construction, and sometimes they completely fail to support the activities of the organizations that will occupy them.

The observation and analysis of human behavior in built environments is usually considered the best way to understand and evaluate how a building fits the needs and the activities of its intended users. On this basis, the Post Occupancy Evaluation (POE) paradigm has proposed several approaches and techniques to assess if the project brief has been met (Preiser, 1988). POE approaches have, of course, one major limitation: they can be applied only after the building has been realized and occupied, and at that point it is usually too late or too costly to intervene in order to solve errors, critical failures, and inconsistencies with the needs of users.

In order to overcome this deficiency in the design process, we chose to investigate how to use "virtuality" to actually integrate building occupancy evaluation into the design process, allowing designers to test their decisions before actually entering into the construction phase. In particular, the proposed model focuses on simulation of activities in the built environment, in order to predict how the building will match the functional needs of the organization that will occupy it.

RELATED WORK

Since the inception of Computer Aided Architectural Design, several attempts have been made to introduce the expected users' activities in building representation models (Eastman and Siabiris, 1995; Carrara, Kalay and Novembri 1986; Ekholm and Fridqvist 1996). In such models, however, activities have been explicitly represented in terms of their spatial features - usually relying on the concept of "functional unit" - or implicitly inferred by using sets of functional requirements as criteria for the evaluation of the capabilities of a space (Archer, 1966).

Gradually, research attention in this field has turned from a "space-based" representation of users' activities to a "process-based" representation, considering activities as entities on their own that are clearly distinct from (but connected with) spatial entities (Wurzer, 2010). This new approaches is based on the idea of modelling processes depending on the operational workflows of the organization - or of an organization typology if the specific data are not available - that will occupy the building, and then simulate their execution in the building model (Tabak et al., 2008; Goldstein et al., 2011). This approach has been worthily tested in buildings such as hospitals, offices and airports, where the organizational workflows and the related interactions with the built environment actually drive and heavily influence users' behavior.

Still, some criticisms has been raised of this approach in terms of its ability to realistically predict human behavior in architectural design, since it relies on a rigid, 'functionalistic' representation of operational processes of the organization, usually completely computed before the actual simulation and not adaptable to single users' behaviors and to the overall status of the built environment (what we call 'serendipitous' or 'emergent' activities). This distortion inevitably reduces the ability of these simulative approaches to predict building response to users' needs and activities, and rely instead on architects' imagination and expertise to actually guess in what ways their design will perform after the building will have been occupied.

In the last few years, Agent-Based Modeling approaches have been introduced in this research field, aiming at simulating users' behavior in built environments by developing a series of autonomous entities - the agents - each of whom interacting in an autonomous way with the other users and with the environment surrounding it (Macal and North, 2007). Although Agent-Based Modeling has been successfully applied to simulation of some behavioral phenomena generated by individual actors/agents (such fire-egress and pedestrian movement), it has shown its limitations in simulating agents' cooperation and collaborative activities performing.

AIM OF THE PROJECT

The work presented in this paper aims at developing a different model to simulate users' behavior in buildings, in which the building use representation is still based on a process-driven system, but it is more adaptable both in terms of its activities structure and of users' individual decisions and actions. In order to provide these capabilities, we intervene at two different levels of the model: in the formalization of the building use process, which we define as use scenario, and in the simulation system of the users' behaviour derived by the scenario.

A building use process has a direct correspondence to the way the occupant organization works in terms of operational workflows, procedures and systems of activities (Ekholm, 2001). Based on this assumption, we chose to rely on a modeling approach -the Building Process Modeling and Notation- already developed to represent how an organization operates and to extend it to representing the use process of a building.

The BPMN level, where the use process is formalized, is connected to a 3D simulation environment (a game engine in our case), where the same process is effectively computed, simulated and visualized at the same time. In this environment, Users/Agents are provided with the abilities to autonomously adapt their behavior within a predefined range, depending on the status of the environment model and on the reference process model. In turn, the simulated users' serendipitous actions are fed back into the process model, and can influence it. For example, in the case of a hospital, when a doctor and a nurse are scheduled to check on a patient, but the patient has chosen this particular moment to visit the bathroom, the absences of the patient is fedback to the process model, which defines a different flow of activities for the doctor and the nurse. Likewise, if the paths taken by two agents brings them into geometric proximity, due to the geometry of the building, they may choose to stop and chat, or ignore each other and continue on their predefined missions.

The novelty of this approach lies in making the process execution more flexible and partially adaptable to serendipitous "emergent" activities in real time during the simulation, while in current approaches the activities flow is usually compiled and fixed before stepping into the effective simulation (Tabak 2008). In addition, the proposed model can represent and simulate collaborative, planned activities, such as cooperation among various users when performing their tasks. In terms of usability by architects, planners and clients, the outcome is a simulation/visualization in a 3D virtual environment of how the use process is actually carried out by the building users in the building spaces prefigured by the architect. In this way, it is possible to predict and evaluate the correspondence and the mutual influence between the building and its intended users, and rapidly compare the simulation outcomes of different design solutions and spatial configurations. To test and calibrate the model, it has been implemented to simulate the functioning of two different hospital wards, comparing its output with the real users' behavior.

REPRESENTING BUILDING USE PROCESSES BY MEANS OF BPMN

As asserted by Ekholm (2001), we can look at an organization as a system with relations among its parts whose functioning is actually a process (a sequence of events) derived from performing a series of activities. In accordance with the purpose of our research, we chose to extend the concept of 'system' from the simple organization to the sum of building spaces, activities and actors. The *Business Process Modeling and Notation* (BPMN) approach allows representation of operational processes of an organization in order to orchestrate the activities and the decisions of the different actors involved (White, 2006; Lam, 2012). It provides a representational system that, different from previous approaches, provides at the same time a formalization schema for processes and explicit semantics for its execution/simulation. In particular, it is able to describe different aspects of actors' interaction in an operational process (orchestration, collaboration, choreography, decision points), a feature we consider relevant for the purpose of our research, since it allows formalization of cooperation among different building users during the performing of an activity.

The BPMN formalization is based on a set of elementary entities that can be used to decompose and represent an operational process, the main ones are:

- **Activities**: representation of tasks, works, or operations that have to be carried out or ex-

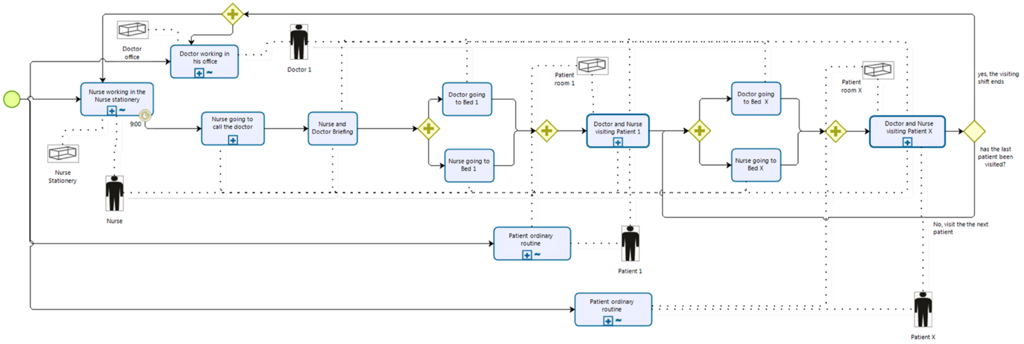

Figure 1
A building use process (in this case a visiting routine in a hospital ward) represented by means of BPMN approach. Actors and spaces entities are connected to the activities sequence, providing a formalization of What (which activity) is performed, Where and by Whom.

ecuted during the process;

- **Connectors**: links to connect an activity to another activity in order to define an operational sequence flow. Other classes of connectors allow to associate other kinds of entities to activities;
- **Events**: occurrences that "happen" during the process, starting, delaying, interrupting or ending a flow of activities;
- **Gateways**: modeling elements that control the pathways of the process, its diversions and its convergences, allowing parallel or exclusive paths.

For the purpose of our research, these classes of entities (with their subclasses) are relevant, but not sufficient. So, in order to make the BPMN system able to represent building use processes, we chose to rely on the ability to extend the BPMN representational approach by creating two new classes of artifacts:

- **Actors**: entities representing each actor involved in the building use process, in order to connect it to the performing of the activities he/she has to carry out;
- **Spaces**: entities representing the spaces of the built environment, and necessary in the BPMN environment in order to effectively connect the use process to the building, and allow its simulation in the 3D environment.

We consider the addition of spaces and actors entities to the process representation a key point of our modeling approach. The formalization of spaces effectively provides the conceptual connection between the building use process based on the organization's operational dynamics, and the building design solution provided by the architect. In this way, the activities, considered elementary units of the organization's operational workflow, are not abstract anymore, but explicitly represented in the building model, providing a representation of what is going to happen, where, and by whom. Although the BPMN representation already takes into account actors' declaration by means of "swimlanes" (White, 2006), we chose to develop a specific artifact for the actors, since in a building use process formalization each actor has to be associated to several activities and this is hard to represent with the swimlanes system (Figure1).

The BPMN approach allows us to represent not only complex sequences of activities, but also their articulation in (and relation to) time: specific time-triggers or event-triggers can represent conditions for an activity to be activated, interrupted or deactivated, influencing the performing of the building use scenario. Gateways are used to formalize and control parallel or exclusive executions of multiple activities; they can be considered decision points in the flow of activities, since they allow testing the model status for specific conditions and choosing which sequence of activities to perform. For instance, if we imagine a scenario where a doctor is visiting a series of patients (as the one shown

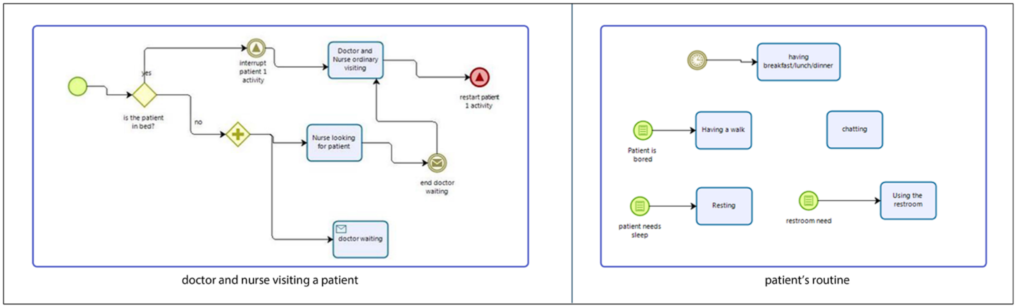

Figure 2
An encapsulated set of activities (on the left) and an ad-hoc process (on the right) used in the building use process representation. Their role is to make more manageable the representation of complex processes and not-structured activities.

in Figure 1), a gateway formalizes the necessity of checking the patient presence and, in case of his/her absence, it adapts the use scenario by directing the doctor to the next patient.

The BPMN ability to encapsulate activities in sub-processes also allows us to manage complex processes and to reuse the same activities structure several times. At the same time, non-structured or intermediate activities (such as "using the restrooms", or "having a walk") (Tabak, 2008), are represented by means of ad-hoc sub-processes that can be invoked during the actual simulation according to probabilistic curves (Figure 2).

In order to make the process representation more flexible and adaptable to different systems (meant as building + activities + users), we also used BPMN messages and signals to stop and restart different sub-processes depending on specific conditions or events. The BPMN system allows us to actually export (via XML) and execute the represented building use process in external simulation environments and to use it as input for such systems. For the development of the building use scenario in the BPMN environment, we chose to use Bizagi, a freeware business process modelling software [1].

SIMULATING BUILDING USE PROCESSES IN 3D VIRTUAL ENVIRONMENT

The BPMN approach is a valid way to represent and simulate processes composed of one or more flows of activities involving some actors. Nevertheless, the BPMN representational system alone is not sufficient to effectively represent a building use process. In fact, it is not able to take into account and consequently simulate how the use process (meant as a set of activities and actors involved) is influenced by the built environment, and how it will be actually be carried out in it. In order to provide architects and clients with a reliable prediction of how the building users carry out the defined activities, we chose to integrate the BPMN representation with a 3D simulation environment, where the formalized use process is effectively simulated within the built environment provided by the architect. In this environment (developed by means of the game engine Virtools [2]), the building use process, previously formalized in an abstract way in the BPMN system, is connected to the virtual model of the built environment where its activities are supposed to be performed.

To compute and simulate the use scenario developed in the BPMN model, a specific script has been developed in the Virtools game engine by means of behavioral blocks -visual programming blocks that correspond to the different activities represented by them. In Virtools' scripting environment, we chose to develop a specific programming level for the formalization and computation of the use scenario; its role being to guide and control the execution of the sequences of activities, adapting their performing to the environment and to the status of the users' involved. It also enables control and simulation of serendipitous events, triggered by the physical (actually, geometrical) proximity and location of the actors within the simulated built environment (Fig-

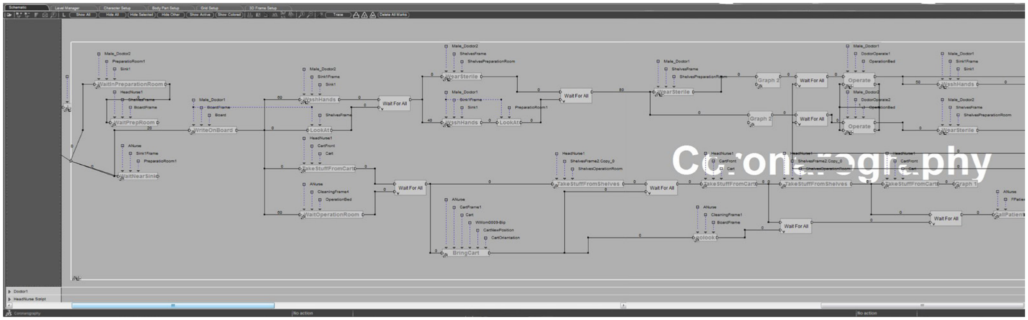

Figure 3
A part of the building use scenario script developed in the Virtools scripting environment.

ures 3 and 4). Such chance encounters may trigger different performance paths. In addition, we chose to equip activity entities with specific scripts to simulate their performing in order to coordinate actors' actions and cooperation. This is a fundamental difference from previous agent-based models, where the activities simulation is generated by the sum of autonomous actions and decisions of the users, with several limits in terms of manageability and coherence of the output.

To improve the adaptation of the scenario simulation to the built environment and its status, we chose to integrate the scenario script with some agent-based components, intended to control some autonomous aspects of virtual users' behavior (for instance, path decision, walking actions, obstacles avoidance, local interactions with other entities, such as doors or other agents). This choice has two main advantages: resemblance to the visual reality of the resulting simulated phenomenon, and improving the manageability of the computation system. The first consists of the possibility to reduce the rigidity of a process-driven simulation by including variations related to single actors' behaviors, actions and decisions. In that way, we can simulate serendipitous events generated by the interactions of

Figure 4
The simulation of the building use process in the 3D visualization environment of Virtools.

the agents with the built environment that are not predictable in the scenario development. The ability to provide actors with some degrees of autonomy allows us to represent some aspects of users' behavior that would be difficult and time-consuming to represent and compute at the process level. For instance, the abilities of a user to compute a path in the built environment and perform the movement actions can be easily developed and controlled directly in the agent entity, while their representation and computation at the process level would be very difficult, and if iterated for each agent and activity would make the process representation too complex and difficult to manage.

A CASE STUDY

Operational efficiency in hospitals is strongly influenced by the physical design of the built environment. Although hospitals are relatively complex buildings, their use-pattern is relatively straight-forward, which is advantageous for our research since it provides a comprehensive and agreed-upon data set against which the model can be tested. For this purpose, as a first implementation of this model, we chose to simulate the functioning of different hospital wards, in routine and in discrete emergency cases. The large quantity of money that is being invested in healthcare facilities suggests that enhancing, even by little, the efficiency of routine procedures might lead to substantial savings in time and costs.

As a first implementation of our approach we chose as target the cardiology department of the Bnei Zion medical center in Haifa, Israel. The size of the department and the complexity of the activities are appropriate to test our simulation model. We chose to observe and simulate both a routine procedure - a coronary catheterization - and a more complicated scenario, such as the intensive care unit, whose emergent phenomena are harder to predict.

Several coronarography events have been observed during a period of a week, after a series of meetings held with the principal physician, who explained to the observer the list of procedures performed during the operation. Reproducing the activities related to this operation in the BPNM environment and simulating it in the virtual environment was not a difficult task, because of the structured nature of the procedures involved in scheduled surgeries. Simulating the activities performed in the intensive care unit required extensive observations, long meetings with the medical staff, and still we were only able to reproduce them computationally within a high degree of abstraction. During the experiment, two different configurations of the physical environment provided by the architect have been tested in relation with the same use scenario, in order to support the design team and the hospital managers in the evaluation of their functional quality (Figure 5).

In order to validate the simulation output, some medical specialists have been interviewed to verify the validity of the formalized use process and the reliability of the simulation results. The use process model proposed in this paper proved to be highly reliable in situations when a clear sequence of observable activities can be recognized by lightly trained observers. When the inherent complexity of the situation produces phenomena hard to decompose in activity chunks, the model shows some limitations.

Future developments will involve exploring different way of decomposing inherently complex situations in sequence of chunks computationally manageable.

CONCLUSIONS

By integrating a building use process formalization with its visual simulation in a virtual environment, the proposed model offers architects and clients the opportunity to test the functionality of a design solution and to foresee its consequence on users' behaviour, before actually being constructed and occupied. The building use process simulation approach allows architects, clients and process planners to easily formalize a use scenario in terms of the activities performed, the actors involved and the spaces where such activities will take place. The visual/geometric simulation provides the necessary connection of the abstract scenario to its perform-

Figure 5
A screenshot from the simulation of one of the proposed configurations for the Cardiology department of the Bnei Zion Medical Center [3].

ing in a defined physical environment, thereby introducing the environmental constraints that affect the process and contribute the important element of serendipity. The 3D visualization of how such use process is effectively performed by future building users, is helpful in making the results accessible to the experts who must judge the outcomes of the simulation.

Differently from previous activity-based models where the use process is entirely computed before and then merely visualized, in the proposed model the use scenario is computed in real time during the simulation, providing a better adaptation of the sequence of activities to the built environment and its occupants and, consequently, a more coherent and reliable simulation output.

By providing a real time simulation of users' behavior within a defined physical environment, although limited to specific use cases and processes, this simulation model would support:

- Architects and clients in evaluating the functional performances of a design solution before it is actually built, leaving them the possibility to correct errors and solve critical points;
- Process planners, analysts and building managers in testing different workflows and operational procedures, and to test different configuration of human resources such as number of workers, their profile and specialization, their scheduling.

So far, the research shown in this paper has mainly focused on simulation of users' behavior in terms of activities performing and operational management. It would be interesting in follow-up research to introduce social and environmental psychology data in the simulation model, in order to provide a more comprehensive and reliable prediction of users' life and activities in buildings.

REFERENCES

Archer, B 1966, *Activity Data Method: a method for recording user requirements*, Ministry of Public Buildings and Works, London.

Carrara, G, Kalay, YE and Novembri, G 1986, 'KAAD - Knowledge-Based Assistance for Architectural Design' , *Teaching and Research Experience with CAAD - Proceedings of4th eCAADe Conference*, Rome, Italy, pp. 202-212.

Cohen, U, Allison, D, and Witte, J 2010, *Critical Issues in Healthcare Environments*, Research Report for the Center for Heath Design, Concord CA.

Eastman, CM and Siabiris, A 1995, 'A generic building product model incorporating building type information',

Automation in Construction, 4(4), pp. 283–304.
Ekholm, A 2001, 'Modelling of User Activities in Building Design', *Architectural Information Management - 19th eCAADe Conference Proceedings*, Helsinki, Finland, pp. 67-72.
Ekholm, A and Fridqvist, S 1996, 'Modelling of user organizations, buildings and spaces for the design process', *Construction on the information highway. CIB Proceedings Publ. 198*, CIB W78 workshop, Bled, Slovenia.
Goldstein, R, Tessier, A and Khan, A 2011, 'Space Layout in Occupant Behavior Simulation', *Conference Proceedings of the IBPSA-AIRAH Building Simulation Conference*, Sydney, Australia, pp. 1073-1080.
Koutamanis A, Mitossi, V 1996, 'Simulation for Analysis: Requirements from Architectural Design', *Proceedings 6th EFA - European Full-scale modeling Association - Conference*, Vienna, Austria, pp. 96-101.
Lam, VSW 2012, 'A Precise Execution Semantics for BPMN', *IAENG International Journal of Computer Science*, 39(1) pp. 20–33.
Macal, C and North, M 2007, 'Agent-based modelling and simulation: desktop ABMS', *Proceedings of the 2007 winter Simulation Conference*.
Preiser, WFE, Rabinowitz, HZ and White, ET 1988, *Post Occupancy Evaluation*, New York, Van Nostrand Reinhold.
Simeone, D and Kalay, YE 2012, 'An Event-Based Model to simulate human behaviour in built environments', *Digital Physicality: Proceedings of the 30th eCAADe Conference*, Prague, Czech Republic, pp. 525-532.
Tabak, V 2008, *User Simulation of Space Utilisation – System for Office Building Usage Simulation*, PhD Thesis, Eindhoven University of Technology, Eindhoven, Netherlands.
White, SA 2006, *Introduction to BPMN,* IBM Corporation.
Wurzer, G 2010, 'Schematic Systems – Constraining Functions Through Processes (and Vice Versa)', *International Journal of Architectural Computing* 08 (02), pp. 197-214.
Zimmermann, *G* 2003, '*Modeling the building as a system*', *Eighth International IBPSA Conference Proceedings*, Eindhoven, Netherlands, pp. 1483,1490.

[1] http://www.bizagi.com.
[2] http://www.3ds.com/products/3dvia/3dvia-virtools.
[3] http://www.youtube.com/watch?v=3OKgipQ6Pbs.