Ann Ist Super Sanità 2016 | Vol. 52, No. 1: 24-32
DOI: 10.4415/ANN_16_01_07

MONOGRAPHIC SECTION

A study of human behavior simulation in architectural design for healthcare facilities

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Abstract
Introduction. Current tools and methods in architectural design do not allow predicting and evaluating how people will use designed environments before their actual realization.
Objective. To investigate how computational simulation can help in evaluating design proposals as far as their use by people is concerned.
Methods. Simulation of a medicine distribution procedure in a general hospital facility, while accounting for serendipitous social interactions made possible by the presence of different users in the same space, at the same time.
Discussion. The simulation shows how use patterns are influenced by the social and physical context in which actors are situated, and demonstrates the significance of the proposed method of evaluating hospital designs before construction. The system allows simulating use patterns with different degrees of complexity, and enables architects to ask new types of questions related to the interactions between people and physical settings.

Key words
- human behavior simulation
- architectural design
- multi-agent systems
- hospital facility

INTRODUCTION

One of the main challenges that architects face during the design process is to assess how well a proposed design will meet the needs of its intended users. Due to their size, cost, and complexity of construction, the systematic evaluation of buildings as far as human behavior is concerned is currently made possible only after they are built and used. This is a risky bet, especially for complex, expensive projects like hospitals or other healthcare facilities.

At present, hospital environments are conceived as holistic human-centered settings designed to heal patients in most efficient ways. A wide array of technologies is put into use, and procedures are devised to maximize the number of patients cured while minimizing costs. In addition, the hospital environment must meet the often-conflicting needs of patients, visitors and staff members. For these reasons, hospitals can be considered as one of the most complex contemporary building types characterized by wide varieties of users and functions that are carried out in the same location, at the same time [1].

Despite the fact that architects and their clients have at their disposal various tools that can help them predict and evaluate a plethora of building performance characteristics like cost, energy consumption, and structural stability, they have no means to predict how well the proposed building will perform from a users' perspective before it has been constructed and occupied. During the design process, in fact, considerations about human behavior are often based on partial, or even speculative information. A gap therefore exists between the expected and the actual users' behavior, which leads to unforeseen consequences in terms of building inefficiency and users' dissatisfaction [2].

While the need to predict and assess human behavior in yet un-built environments has been recognized, few methods exist for conducting this evaluation during the design process itself, because understanding how people act socially, psychologically, and cognitively in their physical environment is relational, and dynamic [3].

Simulation methods have been proposed to address dynamic aspects of human behavior in healthcare environments to allow designers and healthcare givers to simulate "what if" scenarios, and visualize how a proposed design will perform before it is constructed and used.

Current simulation methods rely on two main models: Agent-based, and Process-based (also defined Discrete Event). Agent-based models represent human behavior as an emergent phenomenon that originates from situated interactions between goal-oriented

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agents with their physical surroundings [4]. Process-based models, instead, represent human behavior by means of a structured sequence of activity patterns [5]. While the first approach fails in providing a representation of complex activity patterns, the latter ignores the impact of the social and physical environment on the individual agents and their accumulated impact on the overall system behavior.

Relying on different conceptual assumptions, modeling approaches, and abstraction levels, both paradigms are currently incompatible for integration into more complex simulation scenarios, which can account for contingent and spatially situated behaviors in response to social and environmental conditions.

To address the limitations of current approaches, an Event-based model for simulating user behavior in a hospital environment is proposed in this paper. This model combines aspects of Agent-based and Process-based models. It also accommodates the consequences of unscheduled events, which might occur due to the co-occurrence of scheduled events in the same setting.

This paper presents the simulation of a medicine distribution procedure and investigates the potential of the proposed simulation system to represent the impact of social and physical factors on the performance of such procedures. The implications of such tools for the architectural design process are discussed, and future directions for research are outlined.

OBJECTIVES

The objective of this paper is to examine how human behavior simulation can be used to evaluate design proposals. By human behavior, we mean the modalities through which people use spaces to accomplish a task. The causal relationship between the design of the space and its use allows iterative evaluation of design alternatives. Furthermore, the description of human behavior patterns at increasing levels of complexity enables evaluating different kind of metrics.

The paper also argues about the importance of simulating human behavior especially in the context of hospital facilities' design, and discusses the potential of such method to be considered as a new medium in design theory and practice.

RELEVANT STUDIES

Current approaches to predicting and evaluating human behavior in healthcare environments

Prediction is a crucial step in architectural design. It consists in foreseeing the implications of design decisions to analyze and evaluate their feasibility before execution. Evaluation criteria then allow comparing the expected performance against a set of objectives imposed by technological, environmental, social, and economic considerations, to determine the extent to which they will be met [6].

In the design of hospital environments, multi-criteria evaluation methods need to be applied to identify a satisfying overall solution, according to multiple, and often conflicting objectives defined by the different stakeholders, namely the client, hospital managers, medical staff and patients [7].

While common quantitative evaluation criteria, such as cost, energy, and structural performances can be calculated through mathematical models, more qualitative aspects, such as human satisfaction, staff productivity, or patients' comfort and well being are usually left to the designers' intuition, imagination, previous knowledge, and professional experience. Yet, even though human performance is difficult to predict and evaluate, it cannot be disregarded since built environments need to support the living and working habits of their occupants.

At present, architects mostly extrapolate from past experiences to predict and assess human behavior in future projects. Post Occupancy Evaluation (POE) and Evidence Based Design (EBD) methods allow improving the performance of existing buildings, for instance to promote patients' well-being and to reduce medical staff errors [8]. The knowledge gleaned from such case studies is therefore implemented elsewhere in the form of norms and regulations. However, because of the context-dependent and culture-specific nature of human behavior, the findings can hardly apply contexts that differ from the original one. Hence, such normative approaches only provide a static and rigid representation of average human behavior [9].

Representational methods such as drawings and models, physical or digital, are used to conceive and evaluate a building before it is realized. However, current CAD (Computer-Aided Design) and BIM (Building Information Model) systems provide only a static representation of the building itself, ignoring the dynamic representation of how buildings are used by their occupants.

Generalized representations of users' activities in relation to spaces have been proposed by Eastman and Siabris [10], Ekholm [11], and Wurzer [12]. Mathematically-inclined methods that analyze the impact of the built environment on users' perceptual and cognitive abilities were proposed by Hillier and Hanson [13], and by Hölscher [14], and can be used to test if the proposed design solution supports visual connectivity and way-finding capabilities.

Pre-occupancy direct-experience behavior observations, such as full-scale mock-ups and immersive virtual environments, attempt to provide a real-life experience of environments that do not yet physically exist.

Full-scale mock-ups have proven to be a valuable means to test specific room design in hospitals, where the level of interaction between the end-users, the space and the equipment cannot be anticipated by drawings or other means [15]. While they are common in most other engineering disciplines, constructing realistic mockups of whole buildings is prohibitively expensive. Furthermore, such mockups rely on the experience of a limited number of users who must be available to conduct the experiment.

A different method to dynamically address human behavior aspects involves simulation – a technique that allows abstracting the complexity of a real system into a model, and conducting experiments with it to test the behavior of the system as a whole under predefined circumstances, especially when many variables interact in complex and unpredictable ways [16, 17]. Simulations allow the iterative testing of "what-if" scenarios to explore the effects of possible design solutions, and to define tradeoffs to find an overall satisfactory solution.

Simulating human behavior in healthcare environments

Different models have been proposed to simulate human behavior at different levels of abstraction and with different degrees of complexity, namely [5]: *System-based* (also known as System Dynamics), *Process-based* (also known as Discrete Event), and *Agent-based.*

System-based models define the behavior of large real-world systems (such as populations) over times through mathematical equations [18]. These models are particularly used in healthcare environments since they allow the representation of aggregate flow of people and resources, such as services or money [19]. For instance, they are used to describe social care systems [20], management of a hospital for short-term psychiatric patients [21] and hospital waiting list [22]. Due to the high level of abstraction required to describe the aggregation of multiple variables into an overall system, system-based approaches disregard explicit information about individual persons and physical settings.

Process-based models describe a system through activity sequences that require a set of resources (*e.g.* people, equipment, and spaces) and take a certain (usually stochastic) amount of time [5]. These models have a long tradition of use in engineering and workflow management to optimize the resource flow of existing systems (*e.g.* queuing behaviors), especially in buildings where users' behavior is driven by specific set of procedures, such as hospitals [23]. In hospitals, for instance, two main concerns involve capacity management and resource flow optimization, such as moving patients through the facility to reduce queue lengths and making beds available so others can be treated. Physicians, nurses, and other staff are considered as resources that must be moved around the facility to service the patients subject to a variety of constraints including space and time issues, and equipment and supplies availability.

Despite their wide use and applications, Process-based models cannot account for the human factor such as people's physical, psychological and social traits (*e.g.*, doctors' individual experience and personality, or patients' well-being) as well as their situated perceptual and cognitive abilities in relation to their dynamic surrounding environment. In Process-based models, in fact, people are not situated in a spatial context at all: spatial features are abstracted in terms of time required for people to move within a space. However, spatial features do have a significant effect on human activities, beyond the time required to traverse them. They might foster social encounters, which will prolong walking times, or might hinder them making the walking experience shorter, but less pleasant; they may create crowding situations that lead to fighting or other undesirable behavior, which in turn will further affect the process as a whole.

In *Agent-based* models, instead, the behavior of a system emerges from situated interactions between goal-oriented agents with their physical surroundings. In Agent-based models, autonomous agents inhabit dynamic spatial environments, and sense, plan and act autonomously in these environments to achieve a specific goal [4, 24]. Different from process-based models, agents' behavior is triggered by their local condition (both spatial and social) rather than global information, and affects and is affected by the behavior of other agents in a reactive fashion: each agent pursues its individual goal (*e.g.*, exit the building, in case of a fire egress simulation), while reacting to the environment they perceive, as well as to the actions and behaviors of other agents. Complex behaviors therefore emerge from the unfolding of low-level behaviors and interactions among agents [25].

Few relevant applications of Agent-based models have been applied to healthcare environments [26, 27], despite the fact that the importance of Agent-based modeling for healthcare has been recognized compared to existing Discrete Event approaches [28].

Relying on the Agent-based paradigm, Steinfeld [29] and later Kalay & Irazabal [30] and Yan & Kalay [31] developed a general method for human behavior simulation by means of Virtual Users – anthropomorphic goal-oriented agents that mimic human behavior in virtual settings to investigate the macro-scale impact of physical and social aspects of a built environment on the behavior of multiple agents to support the architectural design process.

Despite the advantages of using Agent-based models over Process-based simulations in simulating agents' response to their physical and social environments, the high computational burden placed on the agents prevents current approaches from representing holistic behaviors that occur in physical settings, and in particular, the dynamic, collaborative, and goal-oriented behaviors among multiple agents.

Modeling and simulating Event-based narratives

Expanding on the notion of Virtual Users, Simeone *et al*. [32] and Schaumann *et al*. [33] proposed a method to simulate both scheduled (also defined as "planned") sequence of activities imposed for instance by hospital medical procedures, and unscheduled (also defined as "unplanned") activities that emerge as a reaction to agents' situated perception and cognition of their social and physical surrounding environment (*e.g.* serendipitous social interactions).

The proposed model relies on the notion of *Event*, a computational entity that combines information concerning *people* (who?), the *activity* they perform (what?) and the *spaces* they inhabit (where?).

While in the physical world events can be considered as mundane, temporal, goal-oriented routine activities organized in taxonomic hierarchical structures [34], in a virtual world Events are designed to coordinate temporal, goal-oriented routine activities performed by Virtual Users. Rather than describing collaborative behaviors from the point of view of each actor, Events allow describing behavior from the point of view of the procedures that need to be performed to achieve a task.

Such procedures can involve one or multiple actors indistinctively.

Different from current models, decision-making is placed in Events rather than in agents. The advantage is that Events could describe not only how a nurse and a doctor approach a patient's bed to perform a clinical procedure, but also what should happen if one of them is delayed or called away to attend another duty: it could instruct the remaining actor to wait, or abort the entire event, since the conditions required for the Event to occur are not satisfied.

A framework to identify and analyze events that occur in the real world has been proposed by the environmental psychologist Roger Barker, who developed the concept of *behavior settings* to describe the interplay between people, event patterns, and the surrounding environment [35]. A *behavior setting*, according to Barker, provides the context in which standing patterns of behavior are performed, which do not depend on the individual decision-making processes of agents, but rather depend on the (social) "program" of the setting, and are adjusted according to changes in the composition (and number) of participants or in the physical setting.

Hospitals can be defined as behavior settings since, despite the apparent complexity of human behavior, users' activities are mainly driven by a pre-defined set of rules and procedures related to the type of medical procedures performed in relation to the latest technology developments. This formalization of procedures in hospitals provides a comprehensive and agreed-upon set of behavior patterns on which to build the model.

METHODS

To investigate the potential of the proposed system in supporting the analysis and evaluation of buildings from a human behavior perspective, the paper presents two Event-based simulations of a medicine distribution scenario in a general hospital facility. A first simulation involves the performing of the medicine distribution activity in a designed hospital facility. A more complex scenario is then simulated in the same setting, in which the medicine distribution procedure is performed concurrently to another procedure involving a random number of visitors visiting family members. Unscheduled events emerge from the interaction among scheduled procedures. For instance, social interactions occur when nurse and visitors are at close distance.

Design of the study

Hospitals are complex environments. To simulate a medicine distribution scenario in a virtual setting, a hospital layout, users, and activities need to be abstracted and represented in a computational fashion. Hospital procedures are translated in terms of Events, and are simulated in the abstracted representation of a hospital environment.

Two simulations are designed to demonstrate the proposed simulative approach. The first simulation involves only a medicine distribution procedure: two nurses preparing and distributing medicines to twelve patients located in six rooms. The second simulation represents a more complex scenario in which the medicine distribution procedure is simulated with two more events beside. The first involves a random number of visitors that go to visit their family members. The second originates from social interactions among nurses and visitors as a consequence of visitors asking information about their family member conditions. While the medicine distribution and the visitors' visits can be considered as scheduled events that are initiated when the simulation starts, the social interactions event emerges in an unscheduled fashion as a consequence of the actors' situated location in a spatial setting.

The choice of simulating such events originated from existing issues in hospital environments that regards staff mistakes caused by unintended task interruptions. While social interactions are desirable in many occasions, they are considered disruptive to the nurses' work during medicine distribution, leading to mistakes that affects patients' health [36-38].

Current methods to improve medicine distribution systems only consider the distances that nurses walk between the medicine room and the patient room (*e.g.* [8]). However, as proved by Seo [38], reducing the distance that nurses walk do not necessarily guarantee an improved service, since interruptions may occur.

Three main phases have been defined to develop the simulations presented in this study. In the first phases, data has been gathered in existing hospitals by means of direct-experience observations and interviews to the medical and administrative staff, to understand current issues in designing healthcare facilities. A special focus has been given to medicine distribution procedures and task interruptions. In the second phase, spaces, actors, activities and events have been modeled in a computational environment. In the third phase two simulations of the medicine distribution procedure with two different degrees of complexity have been generated to show the impact of other procedures that might occur in the same ward on task performance.

Data collection

A data collection phase helped identifying current issues and challenges in hospital design. A visit of five major Israeli hospital facilities was conducted together with interviews of the hospital architects, managers, doctors and nurses. From the data gathered, the medicine distribution procedure emerged as one of the key issues to be addressed when designing a medical ward; specifically, the location of the medicine room within the hospital ward, and the impact that interruptions produce on the medicine distribution procedure.

Despite the fact that many solutions have been proposed to address this issue, none of them have been tested in a simulation environment accounting for interruptions generated by social interactions.

After identifying this subject as a test bed for the proposed simulation system, further interviews were performed with the medical staff at the Sammy Ofer Heart Building in the Tel Aviv Sorasky Medical Center to gain knowledge about current ways to perform the medicine distribution procedure, and the modalities through which interruptions occur because of social interactions among staff members, or with visitors.

Modeling

A modeling phase involved generating a computational representation of Space, Users, Activities, and Events.

Space consists in an abstracted version of a hospital ward, which includes six double-patient rooms, a medicine room, and a nurse station. The different rooms are connected through a corridor in which the nurse station is located. The nurse station is adjacent to a central medicine room where medicines can be prepared before their distribution to patients. Different from Process-based simulation in which space is considered only in terms of distances among resources (*e.g.* both rooms, people, or equipment), in this model a geometrical layout in defined in which Actors can move and perform a set of activities. The Space representation also includes furniture, and equipment.

The Space is subdivided in zones, portions of space that include semantic information in relation to possible use patterns, which depend on the people present in the room and their activities [39]. Actors detect the spatial semantics, and respond to them. Visitors, for instance, detect the presence of a nurse station in the corridor and avoid passing through it, in conformity to social and cultural norms.

The spatial setting is populated by *Actors*, anthropomorphic goal-oriented Virtual Users that mimic end-user behavior. In the presented study, Actors are of three types: Patients, Nurses and Visitors. They contain properties that define their role in the hospital organization (*e.g.* whether they are nurses, patients or visitors), their current status (*e.g.* the activity they are currently engaged in), and the relation with other Actors (*e.g.* nurses are associated to patients to medicate, and visitors are associated to a patient to visit). Furthermore, every Actor has some basic capabilities of navigation through the space, and perception abilities that allow detecting the presence of other agents if they are in the same zone, and within a certain distance.

Actors are associated with a set of *Activities* to perform in relation to their role in the organization. Activities provide a set of actions that direct agents toward the accomplishment of determined goals.

Events combine one or more Actors, an Activity, and a Space to generate an individual or collaborative behavior aimed at achieving a specific goal. To do so, every event has *pre-conditions* that specify the requirements for their activation, *performing rules* to guide their execution, and *post-conditions* to update the status of the Actors and Spaces involved in their performing.

The main type of Event that the study aims at simulating is the medicine preparation and distribution. The first task is to assign patients to each nurse. In this case study, one nurse is responsible for six patients. The event procedure instructs the nurses to move to the central medicine room and prepare the medicine. After this, they distribute the medicine to each patient. After arriving at the patient, in some instances, which are initialized randomly, the nurse returns to the medicine room to prepare additional medication or equipment. After doing this, the nurse returns to the patient. This completes the medicine distribution procedure.

A second event consists of visitors meeting patients. A randomly determined number of visitors enter the hospital ward. Every visitor is associated with a patient. Each visitor walks to their patient and talks to them for a fixed amount of time. After this, visitors exit the ward from the entrance they came in. This completes the visitor event.

These two events are triggered from the beginning of the simulation. They may be considered to be "scheduled" events. In scheduled events, the sequence of activities, the involvement of actors and the location of the actions are known in advance. However, it is likely that the visitors visiting patients would run into a nurse in the hallway. This type of encounter is managed by an "unscheduled" event, which is triggered when specific spatial and social conditions (such as, whether or not the actors involved know each other) are satisfied. In this case study, one such unscheduled event has been considered: is such event, visitors interrupt nurses who are conducting their scheduled duties in order to inquire about their patients.

The existence of scheduled and unscheduled events can produce conflicts, which can lead to the disruption of the organization of scheduled events. To manage this disruption, the Event Manager has been conceived. The function of the Event Manager in the simulation is to manage conflicts about resources and priorities between Events (scheduled and unscheduled).

Simulation

A simulation engine activates Actors, Spaces, Activities, and Events to generate a dynamic time-based representation of the building use phenomenon. Two different simulation scenarios are presented.

The first involves the simulation of the medicine distribution event. *Figure 1* shows the end state of the simulation, after all patients have been checked. The lines define the paths along which the nurses moved through the ward. Quantitative measurements can be extracted from the simulation, such as nurses' walking distances, the time required to distribute medicines to all patients, and the maximum time that a patient waited to receive medical care.

The second simulation scenario adds complexity to the first. A random number of visitors enter the ward to visit their family members. If a visitor on the way to a patient encounters a nurse on the way, the conditions to perform an unscheduled event will therefore manifest. A conflict between current scheduled performed by the visitor and nurses is resolved by the Event Manager that evaluates the status of the Actors, Space, and Activities, and deliberates whether actors should perform the unscheduled Event or not. In this study, a stochastic probability is assigned to determine the outcomes of such decision.

Figure 2 shows an interaction between a nurse (N1) and a visitor (V5) that occurs in the corridor, triggered by the spatial proximity between a nurse and a visitor. While such interaction can be considered beneficial for the visitor, it potentially interrupts the task that the nurse was performing, eventually leading to medical mistakes. While the simulation runs, or after its termination, a set of measurements can be extracted in rela-

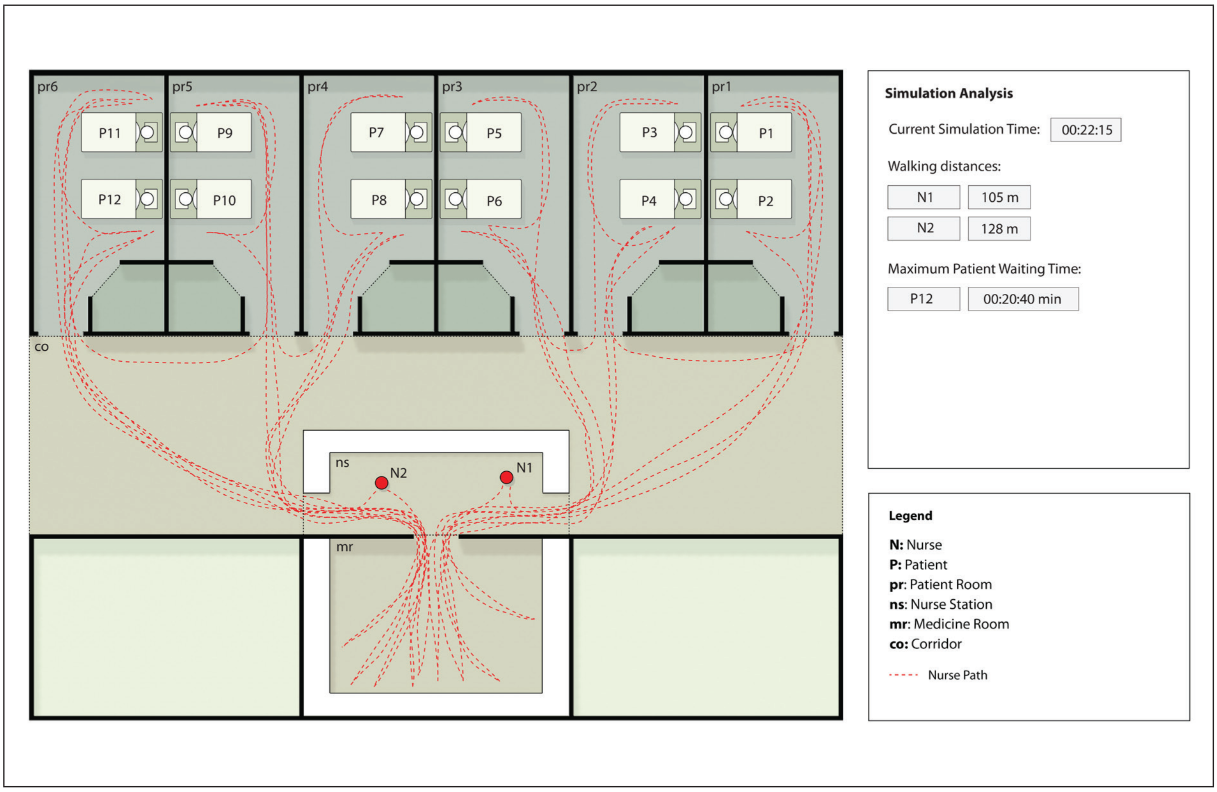

Figure 1
Simulation 1: medicine preparation and distribution.

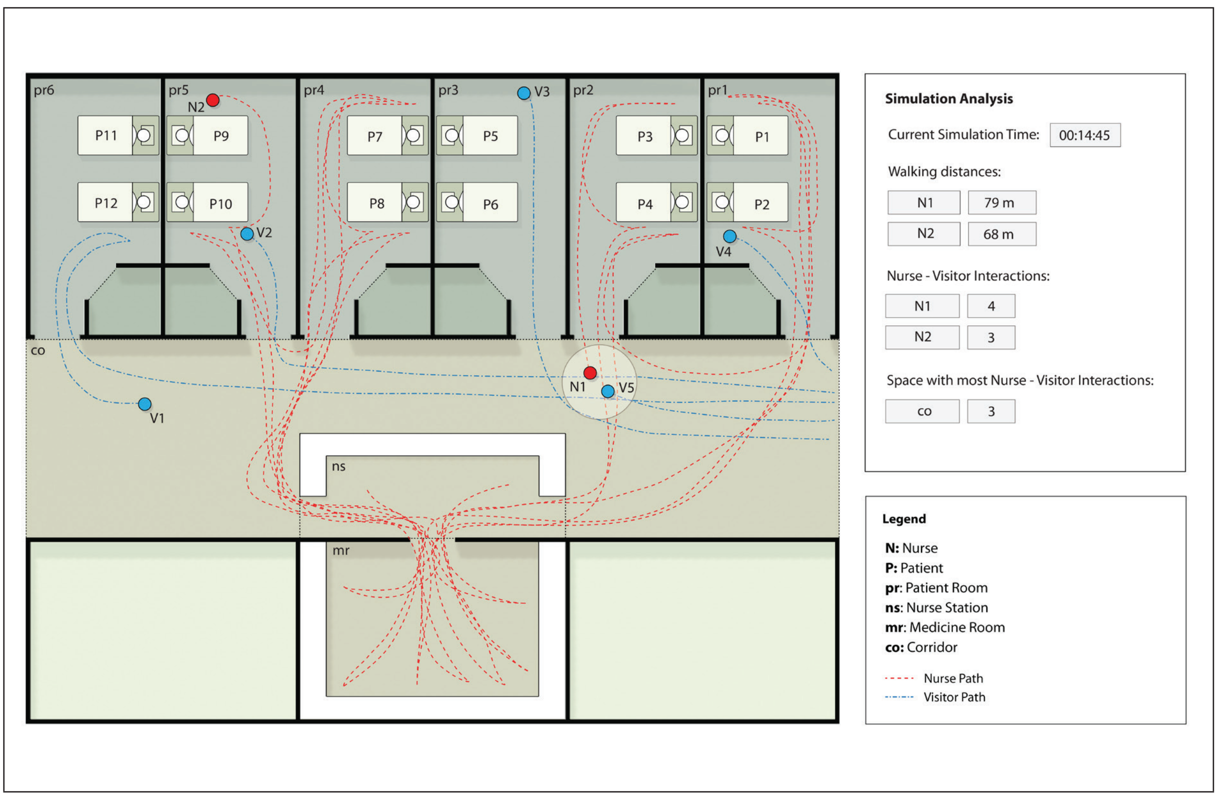

Figure 2
Simulation 2: the visitors visiting patients interfere with the medicine distribution process enabling a social interaction event to take place.

tion to social interactions between nurses and visitors, and the location where most interactions occurred.

This simulation was facilitated by a host of computational tools: Autodesk AutoCad allowed the physical setting's geometrical modeling; Unity 3D – a video game engine tool – provided a simulation environment with dynamic visualization capabilities. Spatial semantics, Actors' profiles, Activities, and Events were also scripted in Unity by means of C#, a common object-oriented scripting language.

DISCUSSION

This case study describes a medicine distribution scenario at two levels of complexity. In the first, the scheduled medicine distribution event is demonstrated. In the second, more complex simulation, two concurrently scheduled events interact and produce conditions that occasionally trigger an unscheduled event.

The introduction of the concepts of the Event and the Event Manager make it possible for scheduled and unscheduled events to be studied, and their interactions, to be analyzed. For example, in this case, the proposed system makes it possible to evaluate the effects of interruptions by visitors on the medicine distribution process. Is this effect negligible? Is it significant? Can it be mitigated by redesign of the layout? This case study demonstrates the feasibility of systematically considering questions.

Even though this study considers one type of unscheduled event, it is possible to model multiple unscheduled events in this way. The Event Manager and Event hierarchy makes it possible to scale in terms of numbers of events, actors, activities and spaces.

Simulating events in a hospital ward makes many different types of evaluation possible. First, it is possible to systematically evaluate chosen metrics and study how they interact in a given design. In this example, the distance walked is calculated. Apart from such conventional analysis, the spatial-temporal presentation of the simulation enables architects to systematically observe not just how scheduled events cause and interact with unscheduled events in different designs, but also re-evaluate their conceptions of spaces in their designs in the process of doing so. In the example described above, the corridor, which connects the medicine distribution room and the patient rooms, is seen to serve not just as a corridor, but also as an ad-hoc meeting space for visitors and nurses. This provides architects with the design opportunity to re-imagine the corridor and develop a more detailed understanding of the kind of space that they intend it to be.

The simulation does not make these choices for architects, nor will it provide self-evident answers. But it will enable architects to ask new types of questions and systematically examine possibilities in a way which current tools for representing architectural design problems do not allow. Due to its spatial-social nature, the simulation of events in the hospital accounts for more than just processes as a traditional process based simulation might do.

The proposed Event-based simulation model affords the evaluation of complex behavior (such as one might expect in a complex building like a hospital) through a rich description of simple events and management of interactions and conflicts between these events. This will be of use to hospital designers and healthcare givers who will be able to test "what if" scenarios, and visualize how a proposed hospital will perform under different use patterns before it is constructed. They could then adjust the design to allow for more flexibility, or for changing needs, thus potentially saving money and improving the services provided by the facility [40].

FUTURE WORK

The Event-based simulation model proposed in this paper is a work in progress. It holds promise for enabling improved collaboration between hospital managements, architects and other stakeholders in planning new hospital projects, as well as developing scenarios to study how to re-develop existing hospital projects to meet new requirements and to take advantage of new medical technologies and advances in hospital administration techniques. Collaborative architectural design, a process which describes nearly all architectural design, is a complex area of research in its own right, and further study to evaluate the uses of the Event based-model in collaborative design are urgently necessary.

The model itself can be developed further to understand Events' taxonomies, which are applicable to the hospital domain. Developing event taxonomies will require close collaboration which experts in day-to-day hospital management and other domain experts.

Eventually, the Event-based model should be used to simulate longer time spans of a single workday. This feature will enable new types of questions about proposed designs and design changes to be asked and answered (for example, the performance of the hospital from the human behavior standpoint on weekends and weekdays could be simulated).

The event based simulation approach offers a promising avenue for improving architects ability to evaluate multiple complex design proposals from the human-behavior standpoint for new and existing hospitals and has the potential to be a contribution towards planning for future changes.

Acknowledgments

This research is supported by a European Research Council grant (FP-7 ADG 340753). We are grateful to the nurses, doctors and hospital managers of the Sammy Ofer Heart Building in the Tel Aviv Sorasky Medical Center for their availability, and to the following research group members for their useful comments and insights: S.W. Hong, H. Sopher, M. Gath Morad, E. Morad Zinger, M. Brodeschi, A. Nicola, and M. Kislev.

Conflict of interest statement

There are no potential conflicts of interest or any financial or personal relationships with other people or organizations that could inappropriately bias conduct and findings of this study.

Submitted on invitation.
Accepted on 18 December 2015.

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