People flow management in a healthcare facility through crowd simulation and agent-based modeling methods

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People flow management in a healthcare facility through crowd simulation and agent-based modeling methods

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Abstract. The study investigates the optimization of user flow and space management in the Cottolengo Hospital located in Turin by simulating activities and patient flows of the blood drawing center. The simulation aims to verify the maximum number of people allowed to occupy the spaces simultaneously, manage user flows, and verify compliance with COVID-19 pandemic restrictions. Pedestrian Dynamics, supported by Building Information Modeling (BIM) methods, and NetLogo are used to simulate and optimize user flow and space management relying on crowd simulation and Agent-Based Modeling. Patients' movements and hospital activities are modeled to identify bottlenecks, crowded situations, and other issues. The methodology also allows the comparison of the two selected tools via the two simulations that are set with equal parameters. The results of the simulations enabled the analysis of current conditions and the testing of scenarios and hypotheses without inconveniencing users and interrupting hospital activities. Some improvements in space and people flow management could be proposed, e.g., distributing patients' entries over the center opening times via an online booking system and modifying room functions. The proposed improvements support the facility managers to avoid, or at least minimize, crowded situations during which is not possible for patients to comply with COVID-19 pandemic restrictions, while minimizing layout changes and consequently the costs and efforts of implementing the changes. The proposed methodology will enable better management of future emergencies in healthcare facilities. The tool comparison will support future studies on simulation tool selection according to simulation and stakeholder needs.

1. Introduction

Space features and people's behavior inside buildings are among the causes of overcrowding. During emergencies crowding management is even more critical, such as during the recent COVID-19 pandemic due to the need of maintaining minimum safety distances, which in turn affects people's movements and the capacity of spaces and horizontal and vertical connections. This is of utmost importance when considering healthcare facilities. The possible rise of new global pandemics [1] in the future leads to the need of optimizing existing healthcare facilities in view of possible future pandemic-related emergencies. Crowd simulations and Agent-Based Modeling (ABM) can be used to provide insights and produce strategies for reducing the transmission risks of COVID-19 within facilities [2]. In addition, crowd modeling and simulation can be applied to verify safety management strategies and optimize design solutions in large spaces and facilities [3,4]. Crowd and pedestrian dynamics are simulated by modeling user and space features. Building Information Modeling (BIM) methodology allows for the efficient management of complex buildings by providing different building data, e.g.,

geometrical data, building and space functions, and characteristics [5], consequently, BIM models can support crowd simulations [6]. BIM as a relational database repository can serve as a foundation for the simulation and investigation of factors that may impact building performance and safety.
Crowd simulation and ABM [7,8] are applied in this study to the blood drawing center of the Cottolengo Hospital located in Turin, retrieving data from the facility BIM model. The case study application aims to optimize patients' flows by modeling their movements and activities and to verify the presence of overcrowding phenomena and compliance with COVID-19 pandemic regulations. The methodology allows the identification of the less invasive interventions to the people flow and space management to support the optimal use of the spaces by simulating scenarios in a virtual space without inconveniencing users and interrupting hospital activities. Furthermore, the paper compares two tools to identify the main advantages and disadvantages of ABM and crowd simulation, as they are relatively new approaches to modelling complex systems composed of agents whose behavior is described by simple rules [2].

2. Methodology

The methodology uses Pedestrian Dynamics (InControl) and NetLogo to simulate people's movements and activities in healthcare facilities. The aim is to simulate and verify current conditions identifying bottlenecks and crowded situations that could affect the efficiency of hospital activities and compliance with COVID-19 pandemic regulations. Based on the outputs of the simulations, it is possible to propose improvements in space, activity, and people flow management, e.g., changes to the building layout or the implementation of new user flow management strategies. In addition, the methodology allows the comparison of the two selected tools via the two simulations that are set with equal parameters.

2.1. Building Information Modeling and crowd simulation

Pedestrian Dynamics is a crowd simulation tool that uses built-in mathematical models to simulate people's movements and behavior in crowded environments, such as hospitals, shopping malls, and airports, and to predict people's interactions among themselves and with the environment. As a basis to create the simulation model via Pedestrian Dynamics, the BIM model of the facility is created with Autodesk Revit. The BIM model represents in fact a unique database of the following aspects:

- Building and space geometrical data and the location of stairs, elevators, entrances, and exits;
- room functions and other room data, such as the maximum occupancy in standard conditions and according to the COVID-19 pandemic regulations.

Based on the BIM model, the following spaces are modeled in the simulation model, as shown in Figure 1, in which each space is identified with a number as follows:

- on the ground floor: entrance (space #1), reception (space #2), and a corridor connecting with the elevator and stairs (space #3);
- on the first floor: two waiting areas with room codes W1 (space #4) and W2 (space #5), a registration room (space #6), two blood draw rooms (spaces #7 and #9), and an additional waiting area currently under-utilized (space #8).

The simulation is then set defining the following parameters:

- agent profiles: three agent profiles, i.e., able-bodied patients, disabled or pregnant patients, and in-hospital patients, each profile with a specific walking speed and size. In particular, disabled, pregnant, and in-hospital patients have lower walking speeds to consider, for example, the wheelchair for disabled patients. In addition, all agent profiles are set for the agents to respect the interpersonal distance of 1 m according to COVID-19 pandemic requirements.
- activities: entrance, admission, reaching the first floor via elevator or stairs, waiting to register, registration, waiting for the blood test, blood test, and exit.

- activity routes, i.e., the sequences of activities that the agents of the simulation must follow: each agent profile has a distinct activity route, for a total of three activity routes. Able-bodied patients and disabled or pregnant patients perform all the activities, but while able-bodied patients are expected to use the stairs to reach the first floor, disabled or pregnant patients are expected to use the elevator. On the other hand, in-hospital patients come from other hospital departments and are not required to check in and register and have priority for the blood test. They come from the other building floors and use the elevator to reach the first floor.
- agent generators, i.e., the number of users created and the time they enter the simulation: for each simulated scenario (current conditions, peak attendance, etc.) three agent generators are required, one for each agent profile. Each generator creates a number of agents according to the average number of patients that are typically registered in the blood drawing center.

The outputs of the simulation with Pedestrian Dynamics are the following:

- density maps, i.e., graduated maps of the building floors plotting at each point in the space the maximum occupancy of people per square meter recorded during the whole simulation;
- data about travel times between two activities (plotted in charts);
- data about the average and maximum number of occupants recorded in specific areas or in all simulation spaces during the whole simulation (plotted in charts);
- analysis of the respect of the interpersonal distance among agents;
- 2D and 3D videos of the simulation.

2.2. Agent-based modeling

Following a standard ABM pipeline, the modeling effort begins with the representation of agents (according to specific variables) that act in an environment, according to specific rules. Regarding the environment, we adopted the 3D version of NetLogo that provide accurate detail of the two floors of the hospital service. In our effort, agents are both patients and operators, including variables representing their characteristics as defined in Section 2.1. For example, these variables assess whether patients are fast or slow, characteristics also determined by age or professional experience. Scheduling of service operations makes use of lists as queues into which patients presenting to the service are entered. Thus, we propose a list to access the registration desk and one for the blood test. The operators have a variable that defines their *state*. When an operator's *state* is "available," the first patient in the list (a FIFO queue) is called, and the *state* changes accordingly to *waiting* until the patient arrives, then becomes *working*. The view can be enriched with controls and monitors to improve usability, e.g., some sliders can define the number of operators, as well as monitors allow displaying the output of the variable of interest. From a decision-making perspective, managers can be able to add or remove operators to investigate the simulation output. A single run starts with the arrival of new patients in the environment according to the frequency from real data. A battery of 100 runs can provide more accurate results, such as calculating the median value and standard deviation. Moreover, the generation of many experiments can be automated with a specific tool (BehaviorSpace) for parameter sweeping.

2.3. Simulation-based improvements and optimizations

The results of the simulations performed with the two selected tools according to the proposed methodology are then analyzed proposing possible optimizations. In particular, solutions that include activities and people flow management improvements or little changes to the spaces, such as changing the space function, are preferred as opposed to modifications to the space layout, which are more expensive solutions and can cause inconveniences to the users and interruptions of the hospital activities.

2.4. Comparison between simulation tools

The methodology proposes the comparison between the selected tools based on the simulations that are set with equal parameters regarding agent characteristics, activities to be performed by the agents, space features, and investigated scenarios. The two tools are compared by identifying the main advantages and disadvantages regarding for example available features, open or proprietary tool and import formats.

3. Cottolengo Hospital blood drawing center: case study results and discussion

The proposed methodology via BIM and crowd simulation methodology and techniques are applied to the Cottolengo Hospital for scenario analysis, verifying the patient paths, travel times, and crowding levels of the hospital blood drawing center. Two scenarios are simulated: the standard conditions with a total of 140 patients accessing the blood drawing center and the peak attendance scenario with a total of 220 patients.

3.1. Analysis of blood drawing center travel times and crowding levels through BIM and crowd simulation

The two scenarios were simulated with Pedestrian Dynamics, based on the BIM model of the facility, obtaining a total duration of the two healthcare processes equal to 166 and 240 minutes in the scenarios with 140 and 220 patients respectively. The worst outputs belonged to the peak attendance scenario (220 patients). Figure 1 shows the density maps of the peak attendance scenario: the waiting area W2 (space #5) and nearby corridors on the first floor were the most overcrowded spaces, exceeding the COVID-19 pandemic requirement of a maximum of 2 people per square meter in most of the area. Furthermore, the chart in Figure 1 shows the average and maximum occupancy of the waiting area W2 during the whole simulation, highlighting that the maximum capacity of the room (i.e., 13 patients) was exceeded by almost double for three out of four hours simulation. The analysis identified the blood testing activity as the cause of this overcrowding phenomenon.

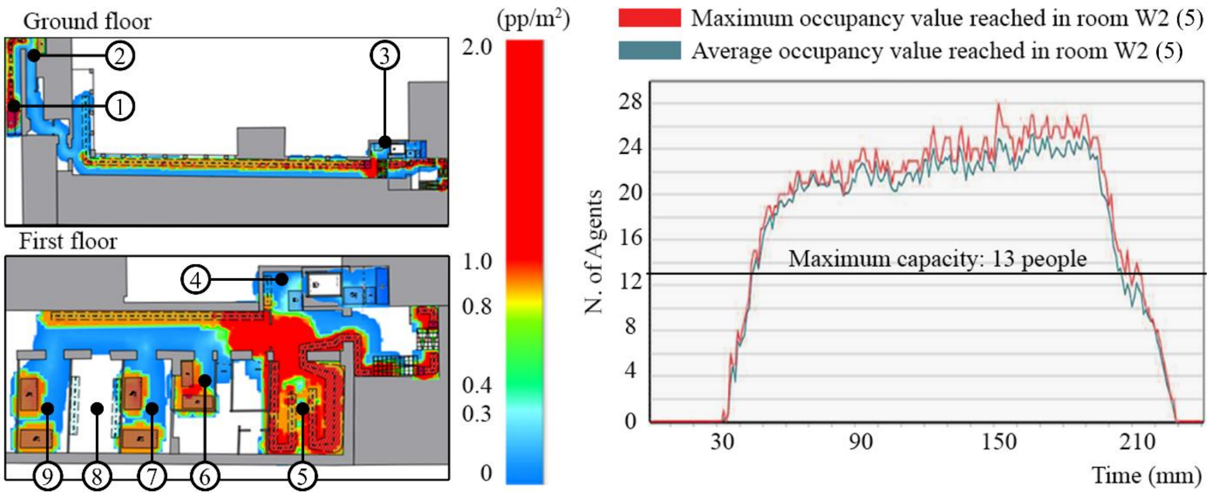

Figure 1. Density maps (on the left); average and maximum occupancy in waiting area W2 (space #5) during the whole simulation compared with the maximum room capacity (on the right).

3.2. Agent-based modeling of healthcare processes

The modeling of the hospital service can be performed with a stylized but realistic representation, as depicted. Figure 2, on the left, describes the controls that allow decision-makers to set the number of operators and display the results. The programming code remains separate in the Code area. The 3D visualization allows users to appreciate the movements of patients with bottlenecks or peaks during the day, and the trends according to the initial parameters. The results obtained on 100 simulations with BehaviorSpace allows an estimation of the duration of the healthcare process in both the simulated scenarios with 140 (median value of 187 minutes, and standard deviation of 2.6) and 220 patients (288 and 3.2 minutes). This opens the way for conducting a scenario analysis.

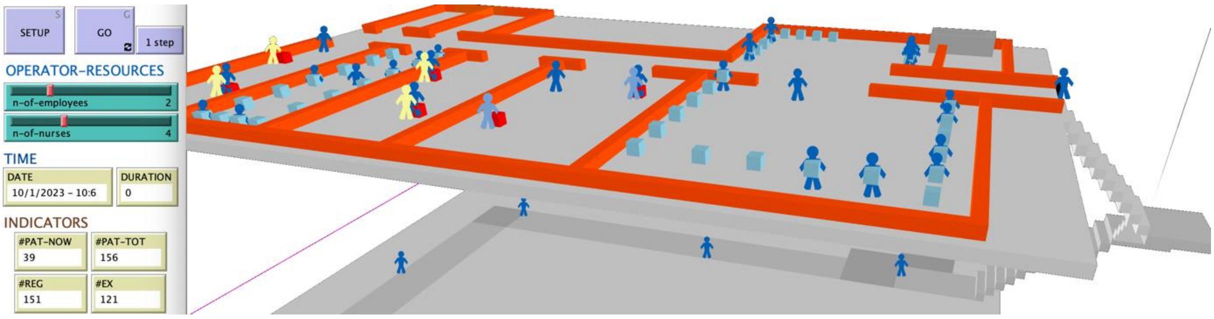

Figure 2. The 3D agent-based model of the movements of patients in the hospital service

3.3. Proposing improvements and optimizations for the case study

The results of the analyses performed with Pedestrian Dynamics and NetLogo highlighted some issues in the current management of spaces and patient flows in the blood drawing center of the Cottolengo Hospital, such as excessive crowding in the waiting areas on the first floor for patients waiting for the registration and the blood test. Some possible improvements in flow and space management were proposed, prioritizing the ones with the lowest impact on the building layout and activities:

- equally distributing the patient accesses over 3 hours via an online booking system staggering the accesses, thereby reducing the initial flow and preventing the creation of crowded situations;
- changing the function of an under-utilized waiting area transforming it into an additional blood draw room to speed up the identified most critical activity, i.e., the blood sampling.

The proposals only involve changes in room functions without modifying the space layout, allowing for the implementation of the proposed hypotheses in a short time, without interrupting or disturbing hospital activities, and with minimal costs. The solutions can support the facility managers to avoid, or at least minimize, crowded situations during which is not possible for the patients of the hospital to respect COVID-19 restrictions.

3.4. Comparison between Pedestrian Dynamics and NetLogo

Table 1 describes the main advantages and disadvantages of the tools, as identified via the case study.

Table 1. Main advantages and disadvantages of Pedestrian Dynamics and NetLogo.

	Pedestrian Dynamics	NetLogo
Advantages	Possibility to import open and proprietary BIM model formats	Free and open-source tool Several extensions available (e.g., GIS, SNA)
	2D and 3D visualization of the simulation	Construction of the Log
	Crowd simulation and people behavior management tool	BehaviorSpace tool
Disadvantages	Unmodifiable source code	Rigid, non-modern graphics
	Proprietary tool - need of a license	Not import BIM formats
	Specific coding language for advanced functions	3D version not fully developed

The table and case study results in Sections 3.1 and 3.2 show that the two investigated tools are both useful for people's behavior and travel times analyses. The comparison highlights the following main differences between the two tools: the possibility to extract graphics and visualizations (Pedestrian Dynamics), which can be useful when sharing the outputs of a simulation with non-experts; the possibility to import BIM formats (Pedestrian Dynamics) ensuring time savings in the modeling of the simulation spaces; being a free and open-source tool (Netlogo); the availability of several extensions (NetLogo), which can be useful to expand and customize the analyses.

4. Conclusions

The study proposes the use of crowd simulation and ABM methodology and tools to analyze and propose optimizations of people flow and space management. In particular, two tools are selected, i.e., Pedestrian Dynamics and NetLogo. The methodology was applied to a case study, i.e., the blood drawing center of the Cottolengo Hospital located in Turin, and two scenarios in standard and peak attendance conditions were investigated. The methodology through ABM and the integration of BIM and crowd simulation proved useful to investigate the current space and building flow conditions in a virtual way, uncovering crowding issues and the difficult respect of the interpersonal distance according to COVID-19 pandemic regulations. Some solutions could be proposed and modifications to the flow management and space functions were preferred, ensuring lower costs and avoiding inconveniencing users and interrupting hospital activities. The proposed solutions can support the facility managers to avoid, or at least minimize, crowded situations during which is not possible to respect COVID-19 pandemic regulations. Furthermore, the proposed and tested methodology will allow better and informed management of possible future emergency situations, enabling the testing of different scenarios and hypotheses in a virtual way during the design and in-use phases.

Finally, the comparison between the two tools via the case study application allowed the identification of the main advantages and disadvantages of the tools. The two tools are both useful for people's behavior and travel times analyses and the total simulation times obtained with the two tools are comparable. The comparison (Section 3.4) highlighting the main differences and strengths of the two tools can support future studies regarding the choice of the simulation tool according to the specific needs in terms of tool features and involved stakeholders.

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