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Simulation modelling in a BIM environment: the case of school re-opening during Covid-19 pandemic

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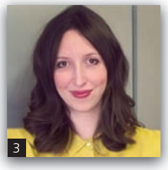


The Covid-19 pandemic influenced the way that buildings are used and experienced. In particular, educational facilities were among the most affected by the pandemic in terms of use processes. This paper presents a methodology developed to reorganise spaces in a school building, a real case study, to allow safe reopening. Social distancing and availability of learning spaces were taken into account to simulate the use of the educational facility according to the emergency protocols. Based on a digital survey of the existing building, a building information model was generated and used as a basis for spatial analysis and crowd and agent-based simulations. Additionally, interactive games and training videos were developed as communication tools to inform end users about the new rules to be respected inside the building. The digital approach adopted for the analysis of use processes as well as for communicating the results to the end users allowed them to experience the school fruition processes within a virtual environment before the school reopening. Future works could deal with the application of the same methodology in other schools, as well as in different contexts, going beyond the specificity of the pandemic emergency, and for other types of buildings.

Keywords: Building Information Modelling (BIM)/information technology/modelling/UN SDG 4: Quality education/UN SDG 9: Industry, innovation and infrastructure

1. Introduction

The Covid-19 pandemic has influenced the way that buildings are used and experienced, from both short- and long-term perspectives. During the pandemic period, many buildings have been closed or have reduced their employment capacity. This change has led to rethinking the organisation and the use of individual buildings to improve resilience and flexibility (Boland *et al*., 2020). In this context, schools and educational facilities are among the building typologies more impacted by the pandemic, with distance learning providing only a palliative solution to the education necessities of students.

In Italy, the critical situation forced Italian schools to close for 7 months, from February 2020 to September 2020, changing the teaching methodology from face-to-face to distance learning. The study by Di Pietro *et al*. (2020) underlined how the choice to carry out lessons remotely had repercussions on students' learning and their performance with both short- and long-term effects. For these reasons, during lockdown months, there emerged an increasing need to focus on how to reorganise school activities and recreate virtual scenarios to communicate the new behaviour rules and reopen school buildings safely.

1.1 Research background

1.1.1 Scan to building information modelling approaches and indoor mapping reconstruction

The use of the surveying technologies implies an improvement in the flexibility of data acquisition in comparison with the static equivalent (Oterio *et al*., 2020). It was shown by El-Omari and Moselhi (2008) that three-dimensional (3D) laser scanning and photogrammetric technologies can improve the accuracy and acquisition time at construction sites for monitoring and progress control, for both structures and engineering (Bosché *et al*., 2014). The results of the survey proposed by Alizadehsalehi *et al.* (2015) revealed the efficiency and effectiveness of using laser scanning in the construction industry as well. Alizadehsalehi and Yitmen (2021) proposed virtual reality (VR), augmented reality, mixed reality and extended reality to participate in immersive experiences and potentially improve architecture, engineering and construction (AEC) productivity. In existing buildings, these technologies can be used to assess the progress of work on-site, train users in building safety and educate students in design and construction (Alizadehsalehi and Yitmen, 2021).

Indoor mapping technologies have been developed to capture data, both geometric and non-geometric, on existing buildings. Traditional techniques are labour intensive and time consuming (Zhou *et al*., 2021). In recent years, special sensor-based automatic indoor mapping techniques have been used: laser based (Karam *et al*., 2019; Turner *et al*., 2015), depth camera based (Li *et al*., 2018), sonar based (Ismail and Balachandran, 2015) and multi-sensor fusion based (Luo and Lai, 2012). Zlot *et al*. (2014) proposed the indoor mobile mapping (iMMS) approach to acquire data and simultaneously record images. The iMMS used is based on the simultaneous localisation and mapping approach, which allows mapping and surveying sites without the presence of global navigation satellite system signals and the use of accurate and expensive inertial measurement unit devices (Cantoni and Vassena, 2019).

1.1.2 Crowd simulations and gamification approaches for educational facilities

In the past years, crowd simulation technology has been often adopted in the design phase of the building process to predict the occupancy of indoor spaces. In the architecture, engineering, construction and operation field, this process is usually adopted to examine the pedestrian movement in extensive buildings (i.e. airports, stations, stadiums etc.) (Lovreglio *et al*., 2018; Sung *et al*., 2004). Simultaneously, other research works have applied crowd simulation in different building typologies, such as educational facilities (e.g. Mastrolembo Ventura *et al*., 2016). In comparison with other buildings, educational facilities imply more structured analysis. In the past 10 years, to achieve high levels of realism in simulation, there has been a need to develop hybrid systems that integrate agents (bots), multiple players and smart narratives, supported by progressive training of agents using reinforcement learning techniques (Taylor *et al*., 2014). The use of these simulation tools applied to the pandemic conditions is quite unexplored, although some primitive studies analyse the required phases to secure the safe reopening of schools (Comai *et al*., 2020), and some useful pre-pandemic research dealt with aspects that are relevant for epidemics and related risk assessment, such as social distancing and exposure time (Harweg *et al*., 2020). Crowd and agent-based simulation technologies have been flanked with additional digital technologies to create a communication environment where end users can learn new behaviour protocols. Considering that risk assessment, as well as perception, is influenced by numerous individual, social, cultural and contextual factors (Cori *et al*., 2020), these communications proved to be very important for the transmission of information. In the past decade, technology education has been established as a new approach for all stages of education, in particular for children and teenagers. Computer games are an effective and highly motivational educational tool that has proved to be capable of changing users' attitudes and raising awareness in a great variety of fields, including healthy lifestyle promotion (DeSmet *et al*., 2014), prosocial behaviours (Calvo-Morata *et al*., 2020) and teaching of hygiene principles (Kostkova *et al*., 2010). Game principles are also useful for everyday activities and planning and organising tasks in a playful way (Szabo *et al*., 2020).

1.1.3 Digital approaches to Covid-19 risk management

Since the beginning of the Covid-19 pandemic, the AEC community – both research and practice – has been investigating the impact of new digital approaches in predicting and managing the risks related to this highly diffusive disease. In particular, much attention has been paid in studying the indoor environments of public facilities, where virus spreading is facilitated by some conditions such as poor air change or close presence of many people. Pavón *et al*. (2020) proposed the use of building information modelling (BIM) facility-management (FM) systems to support the estimation of the presence of people based on mathematical modelling of movements and busy areas, while Leon *et al*. (2021) highlighted the power of BIM in supporting rethinking of spaces and furniture as per Covid-19-related protocols. In the same context, Gao *et al*. (2022) presented the increasing interests in BIM during the pandemics as a way to improve building efficiency and management. Lin *et al*. (2021) investigated the potential integration of BIM in smart-building-management systems. Altamini *et al*. (2021) and Delval *et al*. (2021) integrated BIM modelling and ventilation models to assess Covid-19 spread in closed spaces, even considering pedestrian dynamics. BIM models are also considered as being able to formalise health indicator information (Rice, 2021) and were also investigated a s a way to guide robotics operations in indoor environments such as item disinfection during the Covid-19 pandemics (Giusti *et al*., 2021).

By looking into the different works described in this brief state of the art, a heterogeneous list of major challenges can be derived and organised based on the specific technical area (BIM, simulation etc.) (Table 1).

1.2 Structure of the paper

This paper describes a real case study in which the school manager and the operators were supported in the reorganisation of spaces and a typical day (activities, exit and entry times etc.).

Section 2 presents the case study and the methodology developed to reopen the school safely. Section 3 discusses the results and presents the limitations of the research and further considerations for future work.

2. Research methodology

The research work described in this paper was developed by adopting an existing educational institute located in Milan. This building welcomes 2- to 10-year-old students, and it consists of four floors: three floors above ground and one semi-basement. On the latter floor, the kitchen and the canteen are located; the ground floor comprises common spaces such as the atrium and the

Table 1. Major challenges in digital techniques for Covid-19 protocols in educational facilities

Major challenges	Technical area	Impact on Covid-19 digital risk management
Limited semantics in reconstructed geometries	Indoor mapping	Much effort is required in defining the categories and attributes of objects
Staticity of BIM FM models	BIM	Difficulty of expressing dynamic data during occupancy
Lack of building use information sets	BIM	Information regarding Covid-19 and use processes cannot be stored
Interaction between air quality and real use of the building	Air quality simulation	Simulation results can diverge from actual phenomena due to different use processes
Lack of empirical data	Air quality simulation	Inaccuracy of Covid-19 spread prediction
Difficulty of representing children's behaviour	Crowd simulation	Inaccuracy of simulated building use phenomenon simulation
Accuracy of behaviour simulation in buildings	Crowd simulation	Low reliability of simulative approaches
Communicating protocols to children	Simulation interface	Communication of Covid-19 protocols is a key aspect in reducing infection risks
Recognition of the school and its environments	Simulation interface	Much effort to include details of rooms in the model and simulations to make the school environment recognisable
Effective communication of new behaviours	Communication tool	Different levels of education require different methods of communication

gymnasium, the nursery classrooms (4–5-year-old children) and the kindergarten classroom (2–3-year-old children). On the first floor, there is a nursery room for 3-year-old children, while the second floor contains the classrooms of the primary school (6–10-year-old students). To narrow down the scale of the research, a target group (i.e. 6- to 10-year-old students) was considered.

The research developed is empirical. It stems from the need to reorganise a typical day for students attending an existing school and to communicate new rules of behaviour to reduce the spread of the virus.

The reference structure where the research was carried out is an existing building. The focus was on the most used and therefore most critical spaces, which are the common spaces (i.e. atrium). Classes were considered to verify the maximum number of students that the school can accommodate. The reference population was the students and teachers attending the school. Kindergarten students (2–3 years old) and students with disabilities were excluded, as they follow a different path. A standardised behaviour of the end users was assumed. To have more realistic simulations, the students' and teachers' speeds and the interpersonal distances to be maintained were customised.

The different phases (Figure 1) that allowed the generation of this methodology can be distinguished into the following.

- Normative text study (Italian protocols). This phase allowed collecting data from Italian protocols, which describe the action necessary to reduce the spread of the Covid-19 virus.
- Model generation. This phase included the generation of the information model of the school building (including furniture and devices related to Covid-19 protocols).
- Occupancy analysis. This phase allowed the analysis of the spaces used for teaching and the identification of new spaces to respect the safety distances during school lessons.
- Simulation-based prediction. In this phase, crowd simulations were carried out to reorganise commonly used scenarios and agent-based simulation was adopted to assess the behaviour of single students.
- Communication tool development and testing. In this phase, new digital technologies were applied to teach end users the

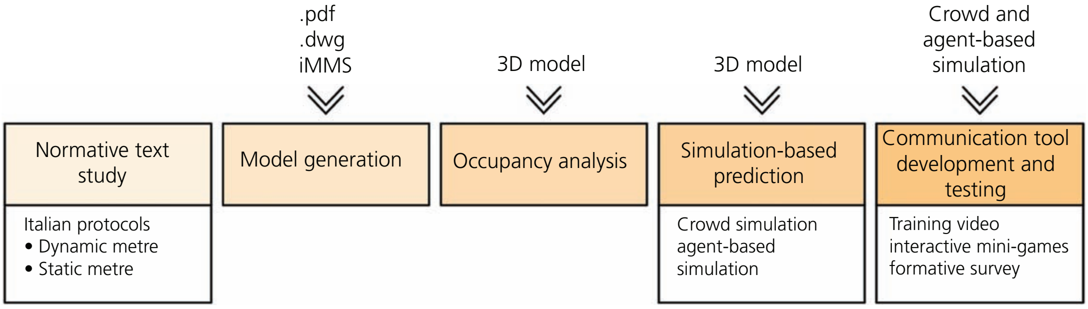


Figure 1. Research phases

new behaviours required to be adopted both inside and outside the school.

2.1 Normative text study (Italian protocols)

The first methodological step involved data collection from the Italian protocols on the new rules for the reduction of the Covid-19 virus spread. In fact, the need to control the severe acute respiratory syndrome coronavirus 2 pandemic had required a drastic change in the behaviours to be maintained inside buildings, and for these reasons, the Italian government has developed new rules, which include

- social distancing in both the circulation paths and learning spaces of educational buildings
- mask-wearing in circulation paths
- body temperature checking before school access through thermo-scanner (37.5°C is the maximum temperature allowed)
- frequent hand disinfection with a hydro-alcoholic solution and by washing
- micro-community organisation and segmentation
- regular and adequate room ventilation.

Besides the protocols issued by the Italian government, two guidelines have also been issued by the Italian Technical Scientific Committee (CTS). These technical documents indicate the behavioural rules that end users have to follow in didactic spaces. More specifically, the protocols contain rules regarding interpersonal distances and the maximum number of people allowed in classrooms and circulation paths.

The first guideline, *Official Report Number 82* (CTS Covid-19, 2020a), determines that at least 1 m of interpersonal distance must be respected between end users, both sitting at school desks or in circulation paths (called dynamic metre). The second guideline, *Official Report Number 94* (CTS Covid-19, 2020b), was published to facilitate school directors to guarantee in-presence teaching activities and determine the observance of 1 m of interpersonal distance in classrooms (called static metre).

2.2 Model generation: surveying of the state of the art and generation of the BIM model

The second phase is collection of data about the school building to know the state of the art of the school building and generate a 3D model. The school manager provided plans and elevations in dwg and pdf formats, and these data were integrated with a digital survey using the iMMS survey technology to acquire 3D geometries and digital photographic documentation of the spaces.

The iMMS was carried out using and testing the innovative Heron Twin double-head Slam-based mapping system (Sánchez Belenguer *et al*., 2020), which can be transported like a light backpack by the operator. The surveying phase was carried out in a 1 h walk within the various school areas, providing, as the first result, a colourised 3D point cloud model, with a 2 cm accuracy (Figure 2) and the surveyor trajectory connected with the panoramic view. As deliverables, plants and elevations were provided in the form of an X-ray scaled image, importable in the most common computer-aided design (Cad) platforms or measurable using a free software tool provided with the Heron system. The survey results were also shared on the web using different web platforms, allowing all the researchers involved in the project to visit and measure easily the different elements and areas of the school. 3D Mapping Cloud from Orbit and WebShare from Faro were used to view the internal and external spaces of the school. The possibility to take 3D measurements directly on the images that hide in the background of the 3D point cloud was a very useful tool, accessible also to Cad or lidar non-experts, and allowed remote collaboration from the different partners. Thanks to the collection of these data, it was possible to generate manually the 3D model of the existing facility. The model was generated from dwg format and was refined with the information gathered during the digital survey. In particular, the dimensions of the rooms and building elements (e.g. walls, windows) were obtained from dwg format, while the heights (of rooms, window sills etc.) were extrapolated from the point cloud. From the point cloud, the types of windows and fixed furniture in the school were also extrapolated. The 3D model of the school was subsequently used to find the square footage of the teaching rooms to study the new layout and to study crowd and agent movement simulations.

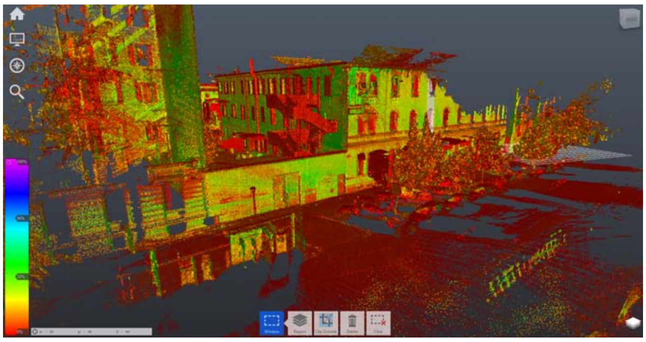


Figure 2. Three-dimensional point cloud model of the main elevation of the school

2.3 Occupancy analysis

The aim of this phase was the analysis of the space used for teaching before the pandemic and the definition of the new spaces to be used for the teaching activities in respect of the interpersonal distances. The space analysis began with generation of an abacus of the spaces within the modelling software and the extrapolation of the classroom plans directly from the 3D model. More specifically, the teaching rooms were taken into account, and for the occupational analysis, two classrooms were identified: the largest (55 m^2) and the smallest (40 m^2). The two classrooms were used as a basis for carrying out an analysis of the minimum dimensions required for each student to maintain the correct distance and the distribution of school furniture according to the rules established by the CTS.

To determine the maximum number of students allowed in the building and in learning spaces at the same time, three normative texts were interpreted:

(*a*) Italian decree law of 18 December 1975
(*b*) CTS's technical paper of May 2020 – that is, dynamic metre
(*c*) CTS's technical paper of July 2020 – that is, static metre.

(*a*) requires that for each student, there must be at least 1.80 m^2. (*b*) requires a distance of 1 m between pupils in both static and dynamic conditions. (*c*) requires a distance of 1 m between students in static conditions. Taking into account the two areas indicated earlier and the requirements of the three technical documents, it was possible to calculate the maximum number of pupils that can be in the learning space at the same time (Table 2). The following is the occupational analysis divided into the three requirements: (*a*) a simple calculation was performed by dividing the available area by 1.80 m; (*b*) the footprint of classroom furniture was taken into account and a minimum movement space of 1 m was considered both between seated students and between seated and mobbing students; and (*c*) the footprint of classroom furniture was taken into account and the metre distance between seated students was maintained.

To establish the spatial layouts in accordance with regulatory requirements (*b*) and (*c*), the standard dimensions of the bench were considered: 50 cm depth and 70 cm width. In Figure 3(a), it is possible to see the layout that respects the requirements of standard (*b*), while in Figure 3(b), the layout refers to (*c*). In both cases, the main movement paths of different dimensions were identified according to the requirement. In general, one way was identified at the entrance and the others are perpendicular to it. In all layouts, a space between the last column of the desk and the wall with the windows was considered, so that the windows can be opened without interfering with the students.

Table 2. Maximum number of students allowed to stay in classrooms A and B according to normative texts and CTS's technical report

Classroom (i.e. learning space)	Area: m^2	Students (*n*) option (*a*) (area/1.80)	Students (*n*), option (*b*)	Students (*n*) option (*c*)
A	55	30	18	24
B	40	22	11	18

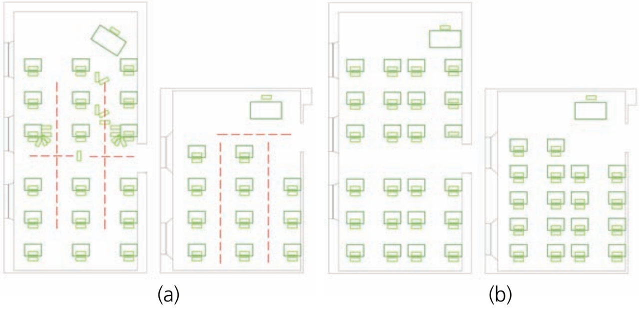

(a) (b)

Figure 3. (a) Application of option (*b*) in classrooms A (left) and B (right); (b) application of option (*c*) in classrooms A (left) and B (right)

As shown in Table 2, normative requirements for school reopening issued in May and July 2020 imposed a reduction in the number of students in each classroom. For that reason, to keep the same number enrolled in the school, additional learning spaces were identified. In particular, the total amount of floor area for 6-to-10-year-old classrooms was increased by 130 m^2, more than half of the initial one. In Figure 4, one can see the change in the use of spaces. Classrooms are green, laboratories red, teachers' rooms pink and toilets purple. On the second floor, the spaces dedicated to the laboratories of music, drawing and informatics were changed into spaces for teaching and the activities were reorganised to carry out laboratory activities in the classrooms.

2.4 Simulation-based prediction

To support the reopening process, tools for the simulation of people flows were developed at both crowd and agent-based levels. These simulations describe children's movement flows in the common spaces. In particular

- for students of all three levels of education, entrance and exit processes from the building were studied
- for primary school students, which represent the central focus of this work, the lunch break movements were also considered in the simulations.

The most congested environment that needed the most attention was the atrium. As a student-welcoming and student-sorting environment, it has a high risk of overcrowding. Therefore, a more in-depth analysis was carried out through discussions with the school staff, which enabled space requirements and movement and waiting zones

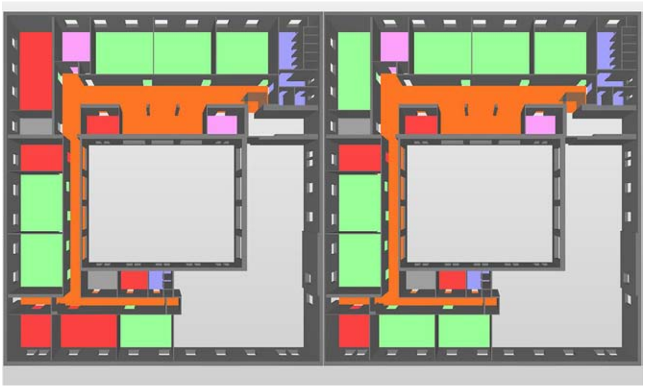


Figure 4. Change in the locals' use destination on the second floor of the school building. In green are the classrooms, and in red are the additional educational spaces

to be established. To ensure the safety of the users during the entry and exit phases, the hall of the school was divided into different zones (Figure 5), allowing the simultaneous presence of children belonging to different micro-communities (so-called bubble groups). The first area, near the entrance, houses the thermo-scanner checkpoint for measuring body temperature and the dispenser for hand sanitation. The second area, the central part of the atrium, was divided into five play spaces used for the preschool of children from 2 to 5 years old. The side area near the columns of the atrium hosts students from 6 to 10 years old. In this zone, the students are divided into rows and wait on special horizontal signs until they are escorted to their classrooms on the second floor. The remaining areas of the atrium were divided into circulation paths, which connect the previous areas. This distinction of functions made it possible to calculate the maximum number of students who could be present at the same time in the hall. Furthermore, these data were used to organise school timetables for students' entrance and exit from the building considering the need to guarantee a minimum interpersonal distance.

Two different software packages were used to develop the simulations: MassMotion was used for the crowd analysis, while Unity3D was used for the agent-based simulations. In both software programs, the 3D model of the reference building divided into floors had to be imported. In the MassMotion software, building elements (walls, stairs, columns etc.) were set as 'barrier' elements so that avatars could not pass through. To identify the zones previously explained, the 'waiting zones', 'circulation path' and 'link' were inserted. Avatars were set up with customised characteristics that distinguish primary students, nursery students, teachers and parents by means of a colour scale. In Figure 6, it is possible to identify the barriers in blue, the waiting zone in purple and the circulation path in pink lines. The avatars were identified with different colours: in green are the teachers, in orange the primary students, in yellow the nursery students and in pink the parents.

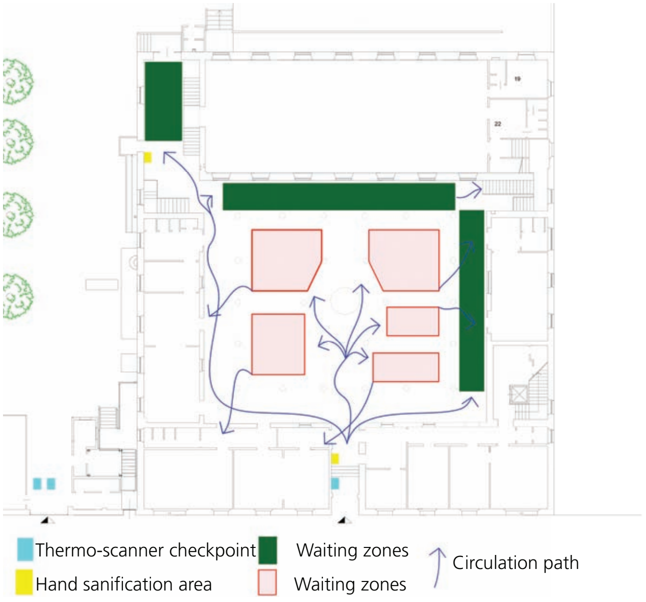


Figure 5. Schematic diagram of the spatial configuration of the school atrium

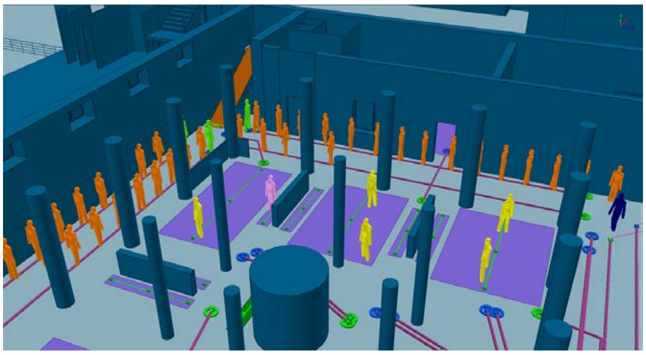


Figure 6. Simulation in the collective scenario

To achieve a more realistic crowd simulation, the software settings were calibrated with the children's real movement speed (m/s) and with an interpersonal distance of 1 m (static metre). Despite the introduction of the most realistic parameters possible, the software used does not have the ability to assume the unpredictable children's behaviours, so it is based on the effective observance of the rules.

2.4.1 Step 1: students' entry into the school building

At the entrance to the school, there is a large hall where students are invited to wait before reaching their classrooms. The organisation of this space was difficult due to the simultaneous presence of students belonging to different levels of education. Kindergarten, nursery and primary school students are present at the same time (Figure 6). Also, to make the simulation more realistic, the parents who have to enter to accompany the nursery and 2–5-year-old children and define their movement path were also taken into account. To avoid crowds of both students in the hall and parents outside the school, two entrance shifts lasting 10 min each were organised. Once inside the building, vertical and horizontal signs were placed to support the movements of the students towards the waiting areas. Given the observations described earlier regarding the entry requirements, the preliminary validations of the simulations were carried with MassMotion.

2.4.2 Step 2: students' exit from the school building

The same considerations and the same logic adopted to describe the students' entry process were applied to determine the outgoing movement flows, allowing the school management and its team to plan different exit times for each micro-community. In such a context, it was decided to use the space inside the schoolyard to allow parents to wait for their children in compliance with the rules of physical spacing. This space is equipped with horizontal signs to highlight the positions where each parent must stop and wait for their child or children.

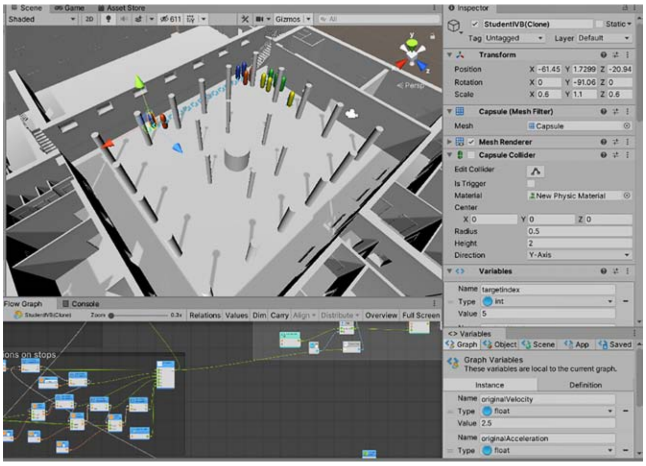
2.4.3 Step 3: lunch break

The third type of simulation developed concerns the movement from the didactic spaces to the canteen. This represents the second most critical scenario in the management of daily activities in a pandemic situation. Indeed, students have to stop in the canteen for an average time of 20 min to eat their meal without wearing a mask; therefore, the rules of social distancing became of primary importance. To allocate the entire canteen space to students aged from 6 to 10, it was decided to keep children aged from 2 to 5 years old in their learning spaces during lunch break. Based on the number of tables and seats available in the canteen, the most functional layout and the maximum capacity allowed for this space (59 people) were identified. For this reason, two shifts were defined for the four-class lunch break. Between the two shifts, a 25 min break was left, necessary to sanitise the environment as required by national protocols.

To validate qualitatively the simulations taking into account the activities that drive building use processes as well as introducing some subjective behavioural variances that can affect the straightforward agent-based simulation, some of the use scenarios were translated and executed within the Unity3D game engine. The use of a video game engine of this type, now widespread also in the AEC sector as shown by Simeone (2015) and Mastrolembo Ventura (2016), allowed integration in a dynamic simulation environment of the following:

- the information model of the school building, including furnishings and devices for controlling the infection from Covid-19
- an agent-based model that simulates the behaviour of individual building users, such as children and operators
- a 'process manager' able to coordinate the various activities to be simulated within the building model, following specific usage scenarios
- a user interface that allows real users of the building to interact with the simulation – for example, by driving avatars – improving the adherence of the simulation to the real use process.

In fact, this integration allowed the simulation to take into account more complex behavioural systems compared with the ones that can be represented through techniques such as crowd simulation, representing a structured set of activities to be performed during the building use process. Likewise, the adoption of a process manager improved the coordination of the individual behaviours of the various agents, ensuring that this aspect is also considered a possible variation of the crowd simulation results (Figure 7).



StudentIVB(Clone)
Tag Untagged
Layer Default
Transform
Position X -61.45 Y 1.7299 Z -20.94
Rotation X 0 Y -91.06 Z 0
Scale X 0.6 Y 1.1 Z 0.6
Capsule (Mesh Filter)
Mesh Capsule
Mesh Renderer
Capsule Collider
Edit Collider
Is Trigger
Material New Physic Material
Center X 0 Y 0 Z 0
Radius 0.5
Height 2
Direction Y-Axis
Variables
Name targetIndex
Type int
Value 5
Graph Variables
These variables are local to the current graph.
Name originalVelocity
Type float
Value 2.5
Name originalAcceleration
Type float

Figure 7. Behavioural simulation of school use as simulated in Unity3D

In this experiment, the informative model of the building was directly imported in the Unity 3D environment passing through one of the many applications already available, paying attention to the consistency of the non-geometrical information reconstructed in the game engine. Then, a behavioural engine for different agent/student typologies was constructed in the scripting editor, developing 'bot prefabs' that have rule variations once each student entity is instantiated in the model. Moreover, a high-level script – the process manager – was developed to drive the overall use scenarios by communicating data, activities status and movement targets to the behavioural engines of the bots during the simulation execution. All the scripts for the process manager and the bots were produced mixing the C# code and the visual programming tool Bolt.

Through a simplified interface developed during the project, it was also possible to involve real users in the simulation, allowing them to move virtually around the school model and to perform activities and actions following the protocols defined for Covid-19 containment, as described in the following section.

2.5 Communication tool development and testing

To mitigate the risk of contagion associated with possible wrong behaviours by end users, it was necessary to ensure the knowledge of the new anti-contagion measures by all the attendants of the institute. The effectiveness of the restrictive measures adopted, however, does not depend solely on the mere protocol but on the propensity of individuals to comply with the containment measures. Indeed, the different perceptions of the risk of the individual could affect the evolution of the epidemic, increasing the cases of positivity (Cori *et al*., 2020). A strategy adopted to mitigate the risks was to provide to the end users the appropriate tools to develop an awareness of a potentially dangerous situation, directing individual's choice towards objective and correct behaviours (Paek and Hove, 2017). In the specific case study, the transmission of information took place differently depending on the type of user considered:

- parents: information brochures
- students (primary school students): training videos, interactive mini-games and formative survey.

The use of new communication technologies in childhood education is becoming more and more relevant. Moreover, the Covid-19 emergency has pushed the use of new digital methods. These new digital technologies help build effective communication environments that stimulate the child's curiosity and make him have fun (Ar Rosyid *et al*., 2016). It was decided to produce training videos and interactive mini-games to communicate new rules of conduct to be followed to return to school safely, which are the results of the simulations previously described. Furthermore, a critical situation questionnaire was created to convey information on specific behaviours.

The training videos were composed of different media contents: simulations and formative signs. The crowd simulations allow students to learn the correct behaviours to be maintained in the circulation paths identified in the atrium and to avoid critical situations of overcrowding. Formative signs indicate the appropriate conduct to maintain inside and outside the school in specific situations. The same signs were placed in the real school building. The videos were complemented by a recorded voice explaining the new rules of behaviour using friendly and engaging rhymes. Considering the different capabilities of primary students, different groups of users were targeted with dedicated videos. Viewing images associated with reading and recorded voice creates a stimulating context for the student.

To generate interactive mini-games, activities were identified that children must learn to perform before returning to school. The mini-games were composed of explanatory illustrations and captions. The situations identified were.

- backpack preparation
- use of the thermo-scanner at the school entrance
- hand sanitisation at the entrance (Figure 8)
- social distancing outside and inside the school building.

Each game is associated with a text interface that allows understanding of its final purpose, while at the end of the game, a message of congratulations for having played the game correctly has been inserted (i.e. 'Great job! You disinfected your hands, now you can enter school!'). The identified activities are carried out at different points on the game map. To reach the exact points at which the mini-games start, the player can move around the school via the agent-based simulation interface.

These interactive mini-games teach children the importance of respecting the new rules to minimise the risk of Covid-19 spread.

2.5.1 Formative survey

The latest communication tool developed in this research is the formative survey aimed at teaching children how to behave in specific critical situations that can happen during the daily routine. It consists of 16 questions, each including a text and an illustration and with four possible answers. Each question deals with a critical situation (i.e. lending stationery in the classroom) and teaches the child how to behave in order to respect the new rules of behaviour.

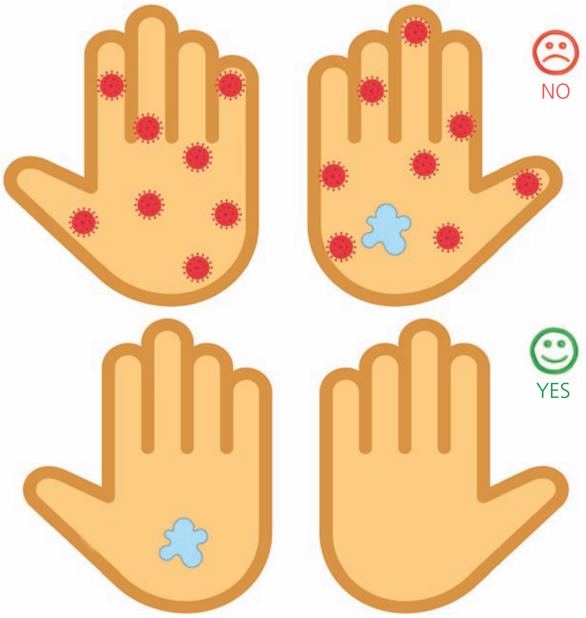


Figure 8. Hand sanitisation game

3. Discussion of results

Other papers have been published on the topic discussed in this paper, presenting results on the following topics: fast 3D digital survey by iMMS (Comai *et al.* 2020), digital communication technologies (Comai *et al*., 2021) and agent-based simulations (Simeone *et al*., 2022). The original and innovative contribution of this paper is the occupational analysis and crowd simulation. The following are the results of the crowd simulation.

The crowd simulations developed in this research proved to be crucial for the organisation of circulation routes in the common spaces. In particular, it was possible to extrapolate the maximum proximity map from the simulation of entry into the atrium, the most critical common space. Maximum proximity maps display the maximum number of agents that are close to each other in an area. Within the MassMotion software, the interpersonal distance value was set to a radius of 1 m. As can be seen in Figure 9, the red point near the scale is the most critical point. Then, two maps were generated: the time in proximity map (Figure 10) and the time occupied map (Figure 11). The first map shows the amount of time that the agents were in proximity to each other in a given area, and the second map represents the amount of time each point on the map was used by an agent during the simulation. These two maps indicate that the previously indicated critical point is actually a passing point where no agent stops, so the risk is minimised. Although the risk of the area is almost zero, it was decided to schedule precisely the departures of the students' rows, taking into account the class of students (from oldest to youngest) and the number of students in the class (from highest to lowest). By analysing both time maps, areas with a much higher than average value can be identified (red areas). These areas coincide with the waiting areas: centrally in the atrium

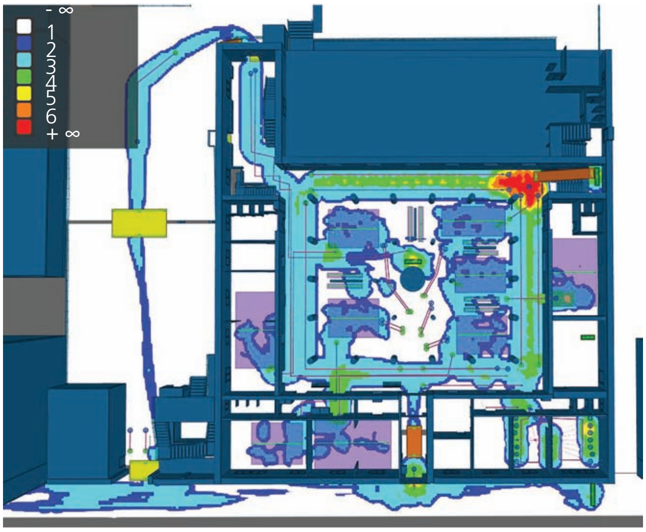


Figure 9. Maximum proximity map generated for simulated student entry into the school

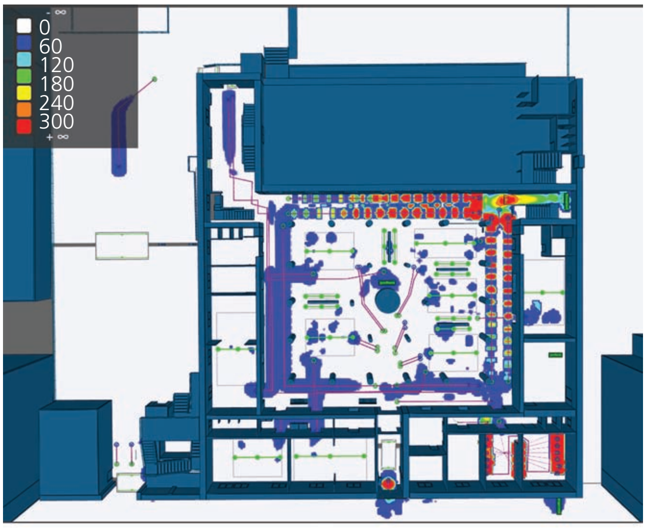


Figure 10. Time in proximity map generated for simulated student entry into the school

they coincide with the waiting areas for kindergarten students, at the top and to the right are the waiting queue areas for primary students and the red areas within the two classrooms are the areas where the 3–6-month-old children (not subject to the research) stay. Finally, the red area at the entrance to the building coincides with the thermo-scanner check in which the student must stop for at least 10 s to check their body temperature.

4. Conclusions

This paper describes all the analyses carried out to achieve a safe reopening of an existing building during the Covid-19 pandemic period. The geometric analysis of the building provided an overview of the volume and specific use of each room within the case study building. The analysis of the Italian standards published specifically for school environments allowed an in-depth analysis of the spaces and the definition of the maximum number of students for each classroom. This led to an implementation of teaching spaces, as the pre-Covid teaching environments were no longer sufficient.

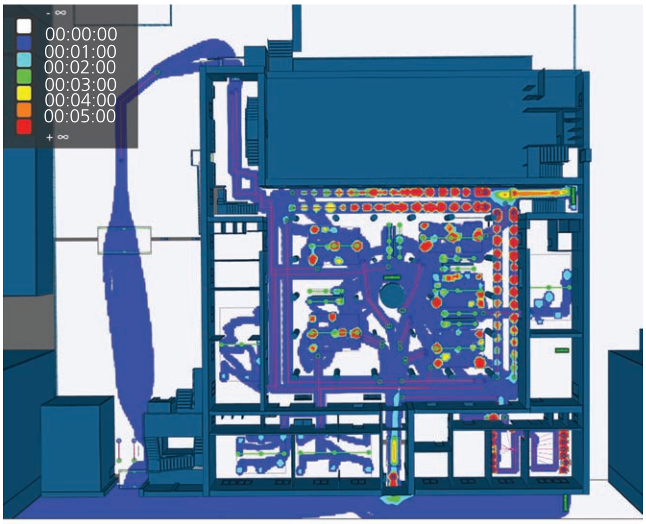


Figure 11. Time occupied map generated for simulated student entry into the school

The need to avoid overcrowding inside and outside the school led to an analysis of movement flows. Virtual simulations were therefore developed, based on both crowds and agents, which made it possible to organise common spaces better and identify the most critical points of movement. The canteen and the atrium are the two most critical environments that required more detailed analysis. The first one was problematic because the students remained for the whole lunch break without a mask, while the second one was problematic because of the risk of overcrowding due to the simultaneous presence of students in the school. After establishing the dynamics of movement and reorganising the typical day for each class, the research focused on developing effective communication, tailored to each level of education, for the new rules of behaviour.

The end users received video training, interactive mini-games and formative surveys and were able to learn the new rules the week before school started. This step was crucial, since in the first days of school, almost all students knew the route to take and knew where they could stop and where they had to walk.

From the point of view of the management implications, a number of advantages and difficulties in adopting a system of this type were defined, also through interviews with those involved in the management of the building and school processes. The decision to stagger both the arrival and leaving of students from the school, without changing the timetable of lessons, was associated with an increase in the time that teachers spent in the school. Moreover, the atrium, the most critical place in the school, needed more active surveillance, requiring a greater commitment of staff to control and avoid the occurrence of risk situations. This increased attention allowed a closer control of the students' behaviour and a more efficient organisation of the sorting of the children's entrance and exit. In addition to this, the fact that the students were already informed about the new behavioural rules made the sorting activity easier and allowed them to start their lessons on time.

The continuous dialogue with the school manager was fundamental in reorganising the school in a functional way, taking care, at the same time, of the needs of the end users. The school took as subject of this work adopted the new communication tools and the digital ecosystem presented earlier above in September 2020.

Thanks to this research, in the school year 2020/2021, few cases of contagion were reported in the classrooms of the school considered by the case study. In particular, four cases were reported to the Health Protection Agency (ATS) in October. While two of them belonged to two different primary school classes, the remaining two were discovered in the same section of the kindergarten. In all cases, these infections required the entire class to be quarantined. In November, two suspected cases were identified but, after more in-depth analysis, they were identified to be false positives and therefore cancelled directly by the ATS. The last case of contagion reported took place in February 2021, and it was associated with the infection of a teacher by the Covid-19 virus. As determined by the guidelines of the Lombardy Region in such a case, the class was not forced to quarantine.

This methodology can also be exploited for other building typologies. In such scenarios, it will be necessary to retrace the proposed methodology and customise it, according to the needs of the specific case. The application of this methodology to other case studies is possible since the skeleton of this study reflects the basis of the good behaviour rules for reducing the spread of the virus.

4.1 Limitations of the research

The first limitation of the research is related to simulations. Crowd simulations are based on effective compliance with the containment measures adopted by the school and do not take into account the possible behavioural choices of the end user and, consequently, do not allow the individual to perceive the risk subjectively. A person's behaviours have some unpredictability and are characterised by decreases in attention towards observing the rules. As discussed in Section 2.4, a partial solution to this issue is possible through the use of game engines, with extended artificial intelligence libraries, that can, at least in a simplified way, introduce some behavioural variations depending on subjective decisions. Although there is no certainty that the actual behaviour will be exactly the same as the simulated one, the use of reliable data – that is, derived from statistical analysis or post-occupancy evaluation techniques – can support the progressive refinement of behavioural engines to be included in these simulations.

A further limitation concerns the use of information content by end users. While the training videos were viewed by all, the interactive mini-games were used only by a small part of the students. Only after the opening of the school was it possible to investigate the reason, and it was understood that the installation procedure required time and memory on the devices and the end users did not want to install the game.

After the opening of the school, the teachers were asked to fill weekly diaries to evaluate the behaviour of the students during the school day. Only two teachers completed the diary in the first two weekends, so the data collected are not sufficient to generalise the results.

4.2 Future works

Future developments could envisage the use of VR technologies, immersive and not immersive, as a user engagement tool for assessing the effective added value of these applications in the communication and training of end users compared with the use processes and provisions in the real world. Serious games based on the simulations and the games reported in this paper could be developed to teach new behaviour rules. In fact, gamification represents an innovative and promising technology for stimulating learning. Furthermore, it would be of interest both to test the same methodology on other school building case studies and in other building typologies to evaluate its potential and limits of generalised implementation. Another element to be investigated further is the scalability of the proposed methodology, both to other school buildings and to other types of buildings. In each scenario, it will be necessary to retrace the proposed methodology and customise it according to the needs of the specific case.

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