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ÍNDICE DE COMUNICACIONES Y PONENCIAS

3. EXPERIENCIAS REALES CON BIM

SAFE SCHOOL REOPENING DURING CORONAVIRUS PANDEMIC: A TOOL FOR SCHOOL MANAGERS BASED ON BIM AND CROWD SIMULATIONS

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Abstract

School closures were among the first measure to face the epidemic of coronavirus disease in 2020. Negative effects related to school closures (in social, cultural, educational, and health-related terms) suggest to investigate re-opening strategies implementing safety measures. This paper presents a tool to help school managers in guaranteeing a safe and quick reopening, based on minimal inputs and able to support the evaluation of rapidly changing situations. The proposed approach covers three aspects; the first to verify capacity of spaces, based on the definition of a grid in a BIM model thanks to Dynamo. The second phase provided a dynamic analysis of scholars flows based on crowd simulations, and resulted in density maps highlighting critical moments in the school timetable. Crowd simulations allowed the setting of parameters related to speed and times depending on space layouts and features of the buildings. The third phase is related to ventilation rates required depending on rooms and windows dimensions and features. This approach was tested on a case study building thanks to a BIM model, and was later synthetized and resulting in an online tool adopted from the schools of Regione Piemonte to evaluate school spaces and simulate flows of entrance and exits.

Keywords: *crowd simulation, school safety, coronavirus disease, space management, ventilation.*

Resumen

El cierre de escuelas fue una de las primeras medidas para hacer frente a la epidemia de coronavirus en 2020. Los efectos negativos del cierre de escuelas (en términos sociales, culturales, educativos y sanitarios) sugieren investigar estrategias de reapertura que implementen medidas de seguridad. Este artículo presenta una herramienta para ayudar a los gestores de escuelas a una reapertura segura y rápida, basada en datos mínimos. El enfoque propuesto abarca tres aspectos; la verificación de capacidad de espacios, basado en un modelo BIM gracias a Dynamo. La segunda fase proporcionó un análisis dinámico de los flujos de académicos basados en crowd simulation, y dio lugar a mapas de densidad que destacaban los momentos críticos del horario. Crowd simulation permitió establecer parámetros de velocidad y tiempos en función de los espacios y las características de los edificios. La tercera fase está relacionada con las tasas de ventilación necesarias en función de las dimensiones y características de las salas y ventanas. Este enfoque se probó en un edificio gracias al modelo BIM, y dio lugar a una herramienta en línea adoptada en las escuelas de la Regione Piemonte para evaluar los espacios escolares y simular los flujos de entrada y salida.

Palabras clave: *crowd simulation, seguridad escolar, coronavirus, gestión del espacio, ventilación.*

Introduction

When the pandemic from COVID-19 diffusion erupted, schools were the first buildings to undergo closures. The effects of those closures on communities are relevant, and have just started to be evaluated: it will take time to properly understand what signs they have left. Research interest towards the pandemic has been understandably increasing since spring 2020, including all research sectors and not limiting to health-related aspects. In architecture and construction sector, the main areas of investigation are linked to urban design, cities and urban health, proposing general guidelines or considerations focusing on public spaces and city scale (Capolongo et al., 2020; Cristina et al., 2020), analysing the virus spread in indoor environments and evaluating potential solutions (Dietz et al., 2020; Megahed & Ghoneim, 2020), focusing in some cases on the role of HVAC in virus spread in enclosed spaces (Morawska et al., 2020; Schibuola & Tambani, 2021a).

Considering building design, current research is especially linked to hospitals and health facilities (Agarwal et al., 2020), or housing (D'alessandro et al., 2020), with some first exploration on the potential of architecture in the prevention and control of epidemics based on its capacity to control space (Fezi, 2020).

Some research interest is directed towards the definition of safe protocols for school reopening (Bradley et al., 2020; Esposito et al., 2021); most of available resources are directed towards the evaluation of the effectiveness of specific measures (mask use, ventilation rates, online teaching) (Buoite Stella et al., 2020; Esposito & Principi, 2020b). A lack of holistic approaches to school reopening, that keep into account all available measures and adapt to school buildings features and needs, can be underlined. As school managers are the ones in charge of several decisions related to school safety, it is vital to provide them with simple and effective tool, supporting their decisions, to avoid further slowdowns of reopening.

This research regards an early experiment carried out to evaluate school reopening in accordance with social distancing and other legislative requirements that led to the definition of an online free tool supporting school managers in safe reopening.

1. Effects of school closure

Italy was one of the first Countries to proceed in school closure, in 2020 (on March, 5th). There have been since then some re-openings and further closures. Nonetheless, there is a lack of protocols addressing school reopening measures in a structured and model-based way. The effectiveness of school closure is in any case under discussion, as long-term effects of coronavirus are still unknown.

Allowing uncertainties related to the effectiveness of school closure, it is solidly known that they lead to negative side effects, affecting miscellaneous fields. Negative effects are summarized in the following table:

Table 1. Negative effects of school closures

Type of effect		Reference
Social effects	Consequences on families: childcare costs increase, work-family balance should be negotiated	(Fontanesi et al., 2020)
	Increase of iniquity between higher and lower income classes	(Esposito & Principi, 2020a)
	Risk of exclusion and lack of socialization	
	Nutritional problems deriving from the absence of free school meals	(Viner et al., 2020)
Psychological effects	Adverse effects of quarantine on children and adolescents	(Cao et al., 2020)
	Social isolation for populations who are not	(Caffo et al., 2020)

	able to access technology	
	Confusion and stress for teachers	(UNESCO, n.d.)
Health related effects	Gaps in childcare that can lead to risky behaviours	(UNESCO, n.d.)
	Unintended strain on health care systems	(Bayham & Fenichel, 2020)
Economic effects	GDP reduction	(Nicola et al., 2020)

These effects emphasize the relevant impact deriving from school closures on families and society, underlining how adverse effects damage vulnerable and disadvantaged communities above all. The urge of school reopening shall be a primary concern for governments that should set protocols and politics to guarantee a secure school management.

1.1. School re-openings policies and Italian framework

The differences among education systems of different countries have conditioned their response to coronavirus crisis. In peak time of the first outbreak (spring 2020), the only Country that did not proceed in school closures was Sweden. Several Countries modified the dimensions of school classrooms to facilitate physical distancing (Belgium, Denmark, France, Germany, Greece, South Korea, Taiwan, Vietnam). Temperature checks were introduced in Japan, South Korea, Taiwan and Vietnam, combined with contact tracing. Some Countries proposed flexible solutions of hybrid education or rotations (remote and in presence), depending on epidemiological situations (Krishnaratne et al., 2020).

Masks are commonly recommended both for students and for staff, especially if adequate physical distancing is impossible to achieve. Mask wearing for students depends on their age and situation (e.g., particular behavioural or medical conditions) (Rozhnova et al., 2021). Physical distancing is one of the most diffused measures; recommended distances may vary and shall be obtained modifying existing spaces, reducing the number of persons per single room, and including external spaces in learning activities (Lo Moro et al., 2020).

As coronavirus is a respiratory syndrome, it appears that its diffusion is mainly airborne. For this reason, increasing ventilation rates in indoor environments appears as a viable and effective strategy to contain COVID-19 contagion (Schibuola & Tambani, 2021b). Cleaning rates are also increased, and hygiene (hand washing, use of disposable tissues) is encouraged especially for younger ages' pupils.

Italian guidelines for school reopening are constantly updated, and available on the website of the Ministry of Education (Ministero dell'Istruzione, 2021).

Mask are compulsory in any case, not depending on physical distancing, and shall be wore by every person inside or outside school buildings. Children under six, and pupils with specific medical conditions are allowed to not wear masks. Temperature checks are not performed at school, but shall be carried out independently at home, to guarantee that temperature does not overcome the limit of 37,5°C. Teaching activities widely vary depending on: (i) the school grade, (ii) the epidemic situations of the Region where the school is located, (iii) for University, the decisions taken by the school itself.

In the Italian context, school managers are the ones required to set specific measures to guarantee safety for scholars, teachers, and staff. School managers are therefore committed with a great deal of responsibility. Nonetheless, there is currently a lack of methods, guidelines, or tools that could help school managers to set a complete strategy for school safety. The situation of school buildings in Italy does not facilitate the definition of a national common approach; the building stock mainly consist of obsolete buildings (dating back before 1974). Italian government indicated that one third of the school buildings need severe maintenance interventions (ANCE, 2013). In addition, school buildings present diverse morphologies, depending on the school grade, the geographic position, and the construction period (Tagliabue & Villa, 2017). In some cases, schools are hosted in pre-existing buildings, adapted to the new use or in listed buildings. Besides the complexity of building stock, that obstacles the creation of common guidelines or protocols to be widely used, another main barrier is that of the urge of intervention. Coronavirus crisis aroused in few months; school managers need to quickly evaluate the strategies to adapt their school buildings to novel and rapidly changing conditions.

2. **Methodology**

The method here proposed was developed in late spring 2020, in collaboration with the Municipality of Melzo, to evaluate potential strategies for school reopening. Through a combination of tools and methods, it was possible to provide quick guidelines to Melzo school managers to guarantee a safe response. The approach was performed on two school buildings with different features. As this approach was smoothly adopted, the method was extended to fit different schools and contexts and implemented in an online tool, freely available. This paper presents the activities carried out for Melzo and the results of the implementation in the online tool.

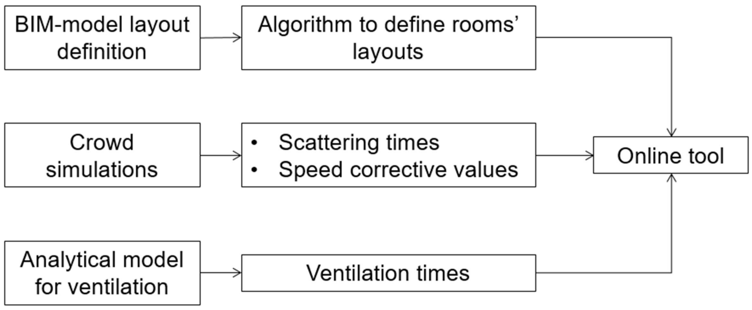


Fig. 1 General methodology adopted in the research

Three main activities were carried out: (i) the definition of a BIM-based layout evaluation, with the goal of creating an algorithm for rooms' layouts, (ii) crowd simulations, with the goal of identifying scattering times and corrective values to be applied to students' speeds, and (iii) the definition of an analytical model for ventilation providing ventilation times.

The goals of this approach were the definition of the internal layout guaranteeing compliance with legislative requirements, the definition of entrance and exit times (including potential scatterings), and the definition of ventilation times to assure safety of rooms.

3. **Application**

3.1. **Internal layout**

In order to guarantee internal distancing in all school rooms, the internal layout of the school has to be modified. Laboratories, administrative spaces, canteen, and gym, have to be re-invented to accommodate teaching activities. A BIM-model of the school was already existing (Di Giuda et al., 2020); the model was used as base for the definition of a Dynamo node that, based on the features of the rooms, and on the physical distancing, simulated the maximum number of students in each room.

The algorithm allows to describe several typologies of classrooms through input data, that include the dimension of desks, and the dimensions of the room. The output provided are the room layout based on distances and maximum number of students. The algorithm is also based on fixed data: (i) the interpersonal distance (assumed of 100 cm as for legislative requirements), and some dimensions related to the room, such as the distance between teacher's desk and pupils' desks. The algorithm defined by the Dynamo node was then implemented in the online tool.

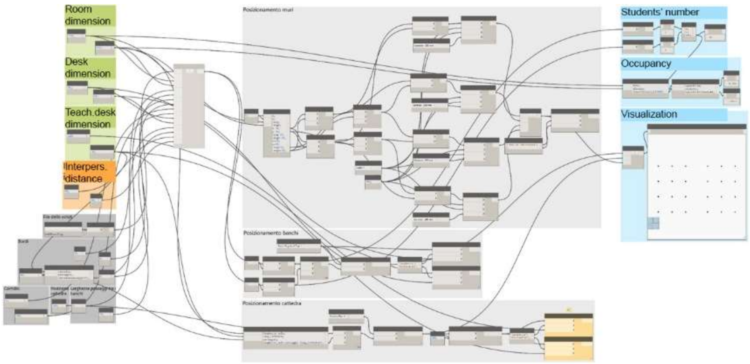


Fig. 2 Scheme of the Dynamo node used to define optimal layout of the classrooms

3.2. **Crowd simulation**

Crowd simulations are used to create a reliable model of students' movements. The use of crowd simulations permits, through the combination of agent-based and narrative-driven approaches, to simulate the activities of autonomous users, interacting with each other based on simple rules, and move in the environment.

Crowd simulations are pre-occupancy analyses that simulate the movement of users in an environment (in this case, a building). Crowd simulations are often used to evaluate evacuation and users' movements in emergency situations (Almeida et al., 2013). Two main typologies of crowd simulations can be used: agent-based simulations allow to simulate space use modelling the system as the sum of behaviours of the users (agents), that are controlled by a distributed Artificial Intelligence (Zheng et al., 2009). Narrative-driven simulations allow to create complex systems of actions, formalizing the activities taking place in a space or a building (Schaumann et al., 2017). To minimize disadvantages related to both approaches, this research uses a combination of the two, that creates a simulation where users can react autonomously to the context through simple rules, and at the same time they move in space following a list of arbitrary activities.

The simulations were performed with Pedestrian Dynamics.

Crowd simulations were used to simulate the behaviour of the students, considering as input data (i) the number of students, (ii) internal path to be covered (from the entrance to the desk), (iii) speed of the users. Crowd simulations allowed to visualize through a density map how people was spreading inside: it was therefore possible to visualize and underline points of confluence. To avoid those points, an iterative approach was adopted: the scattering at the entrance was modified to provide a density map without "red points". Crowding points were defined as those where two or more people were standing closer than 1-meter distance.

Fig. 3 Density map resulting from crowd simulation on the school of Melzo (one of the two case study buildings used for crowd simulations)

Several simulations were performed to identify the optimal scattering time avoiding internal crowding (identified in the map with red areas). The use of crowd simulations also allowed to define corrective values of speed to be used in the online tool. These values were used to correct speed values considering obstacles (e.g., stairs). Simulations were performed on two different school buildings with features that are representative of typical Italian school buildings, in terms of internal layout. Crowd simulations allowed to include behavioural aspects that can modify (slowing or fastening) speed of the users.

The output of this phase, that was later implemented in the online tool, were scattering times, and corrective speed values.

3.3. **Ventilation**

A proper ventilation system has proven to be a crucial aspect to guarantee an adequate IAQ (Indoor Air Quality). This aspect is particularly challenging in case of existing old building, where internal conditions in terms of comfort and wellbeing can be critical; a controlled mechanical ventilation (CMV) system can manage ventilation to match with provided benchmarks. School buildings are in several cases not equipped with those systems, and it is therefore necessary to use natural ventilation to regulate internal conditions.

Recent researches show that increasing ventilation rates can help in containing contagion in indoor environments (Schibuola & Tambani, 2021b). The contagion appears to be strictly related to the users' proximity and sharing of a common space, whether transition spaces such as corridors appear to be less relevant. The interpersonal distance of 1 meter has been defined for stationary people; in case of moving persons, it is necessary to avoid in-line paths, as the air flux can transport droplets.

An analytical model of the classroom was created in a digital environment using the OpenFOAM numerical simulation code for computational fluid dynamics (CFD) analysis. A model of the classroom with the air inlet and exhaust openings with respect to two modes of operation was then created: (i) Standard, supply and return air performed by the CMV system; and (ii) Safe, external air intake and extraction through the CMV system recovery.

In the first case, the air vents are located on the wall opposed to the windowed surface, which is kept closed. The supply air vents introduce air into the confined space, the flow descends towards the users' positions and is taken up by the central extraction vent.

The CFD simulation shows the airflow pattern in standard operation in which the established air changes are provided with respect to the occupants and activity in the confined space, using ventilation rates compatible with indoor environmental comfort conditions. In this case, the airflow descends from the supply air vents and then rises back up to be extracted from the central extractor carrying the particles.

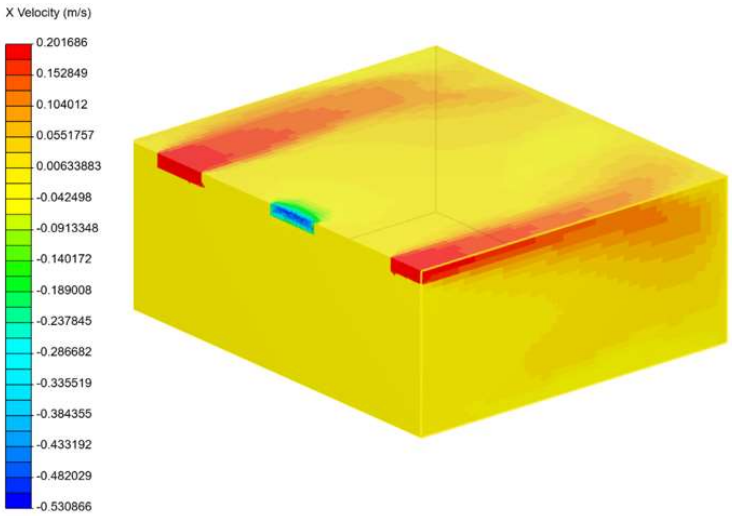


Fig. 4 CFD simulation of the classroom with standard CMV

The second case, combining CMV and natural ventilation, the air extraction has a higher speed, and allow the used air to be taken away through the return vent. Ventilation is therefore distributed on the whole external side of the classroom through the windowed area, and a more uniform flow is extracted from the vent positioned at the top. The mix of natural and forced ventilation keeps the extraction flow upwards.

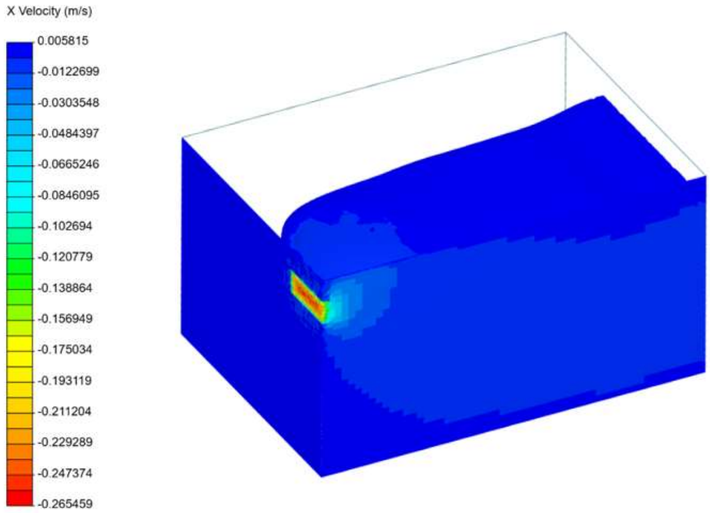
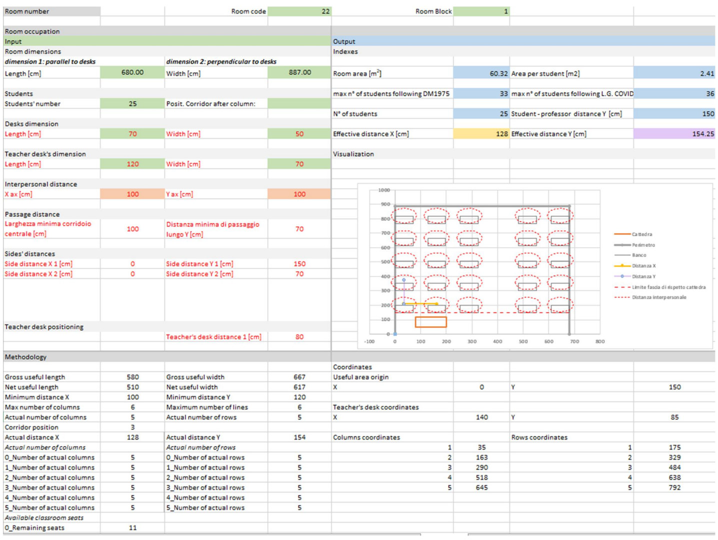


Fig. 5 CFD simulation of the classroom with mixed ventilation

4. “Spazio alla Scuola”: an online tool for school managers

The steps described represented the first part of analysis, necessary to define further developments. as previously stated, simulations and analyses were used to define parameters and mathematical formulas to be implemented in the online tool by the developers. The Dynamo node described in 3.1 was useful as it allowed the visual representation in the BIM model of the school of internal layouts respecting legislative requirements in terms of distancing; nonetheless, an investigation through interviews with school managers of Melzo and other municipalities revealed that none of them owned the technical equipment and expertise to use BIM-related software. For this reason, all the information flows managed in Dynamo were translated in a calculation sheet, showed in Figure 6.



Room number		Room code	22	Room Block	1		
Room occupation							
Input				Output			
Room dimensions				Indexes			
dimension 1: parallel to desks		*dimension 2: perpendicular to desks*					
Length [cm]	680.00	Width [cm]	887.00	Room area [m²]	60.32	Area per student [m2]	2.41
Students				max n° of students following DM1975	33	max n° of students following L.G. COVID	36
Students' number	25	Posit. Corridor after column:					
				N° of students	25	Student - professor distance Y [cm]	150
Desks dimension							
Length [cm]	70	Width [cm]	50	Effective distance X [cm]	128	Effective distance Y [cm]	154.25
Teacher desk's dimension				Visualization			
Length [cm]	120	Width [cm]	70				
Interpersonal distance							
X ax [cm]	100	Y ax [cm]	100				
Passage distance							
Larghezza minima corridoio centrale [cm]	100	Distanza minima di passaggio lungo Y [cm]	70				
Sides' distances							
Side distance X 1 [cm]	0	Side distance Y 1 [cm]	150				
Side distance X 2 [cm]	0	Side distance Y 2 [cm]	70				
Teacher desk positioning							
		Teacher's desk distance 1 [cm]	80				
Methodology							
				Coordinates			
Gross useful length	580	Gross useful width	667	Useful area origin			
Net useful length	510	Net useful width	617	X	0	Y	150
Minimum distance X	100	Minimum distance Y	120				
Max number of columns	6	Maximum number of lines	6	Teacher's desk coordinates			
Actual number of columns	5	Actual number of rows	5	X	140	Y	85
Corridor position	3						
Actual distance X	128	Actual distance Y	154	Columns coordinates		Rows coordinates	
Actual number of columns		*Actual number of rows*		1	35	1	175
0_Number of actual columns	5	0_Number of actual rows	5	2	163	2	329
1_Number of actual columns	5	1_Number of actual rows	5	3	290	3	484
2_Number of actual columns	5	2_Number of actual rows	5	4	518	4	638
3_Number of actual columns	5	3_Number of actual rows	5	5	645	5	792
4_Number of actual columns	5	4_Number of actual rows	5				
5_Number of actual columns	5	5_Number of actual rows	5				
Available classroom seats							
0_Remaining seats	11						

Fig. 6 Calculation sheet used as basis for the development of the online tool

Crowd simulations performed as described in 3.2 provided the corrective values for users’ speeds, and scattering times. These values were also included in the calculation sheet that acted as a base for the online tool. These steps allowed to implement an online tool, called “Spazio alla Scuola”(*Spazio Alla Scuola*, n.d.); it was developed in collaboration with Fondazione Agnelli, to support school managers in simulating people flows inside and outside school buildings, to verify rooms' capacities depending on legislative requirements.

The tool, based on previously described methods, allows recreating the school environment with physical data regarding rooms, stairs, hallways, entrances and exits, and the number of students interacting in those spaces. The tool is freely available and is intended to facilitate a rapid and simple evaluation of existing school buildings. For each of the rooms, the tool provides the maximum capacity, depending on input data (room dimensions, interpersonal distance), the entry time, the order of scholars for entry or exit, and the internal layout. Input data are summarized in Table 2. Input data like the geometry of school rooms are manually filled by school managers in the tool.

Table 2. Input data of the tool

Input data
• School level: primary, secondary, high school. It is possible to include different buildings with different levels • Access: all potential accesses to the building shall be included • Stairs, to be associated with accesses creating paths (path length stair-access shall also be inserted) • Classrooms data: room sizes, desks dimensions, interpersonal distances, corridors. Each room is then linked to stairs, or to the access (for ground floor rooms), and the distance between room and stair/access is inserted. • Other rooms data, if needed • Students number, for each room

For each room, as in Fig.6, the tool provides a layout with maximum capacity of the space, total time required for entrance, and the order of entrance and exit of the students to avoid unsafe overlapping of the paths.

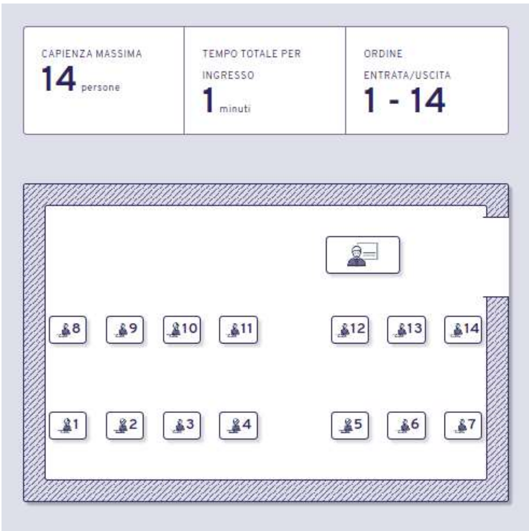


Fig. 6 Output data for a room of the building

Once all the data related to school rooms (including classrooms, and other spaces, with a distinction between big spaces and small spaces) are filled, it is possible to fill data related to the distance between each room and the stairs or the accesses. This information will be used to evaluate times to reach the rooms from the entrances.

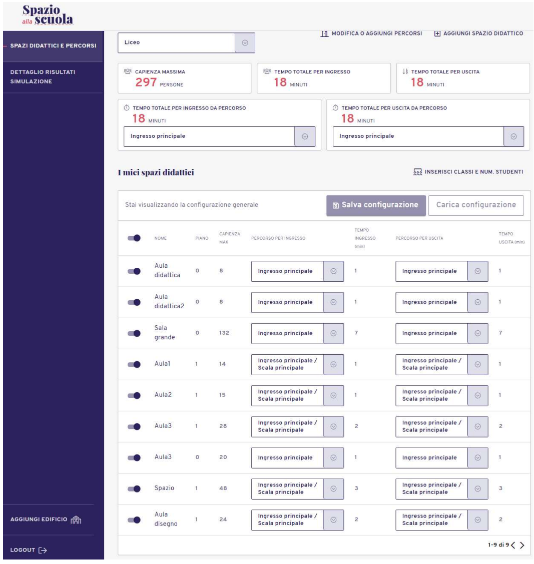


Fig. 7 General output data related to the building

It is possible to modify data at any time, e.g., to add rooms, or to remove stairs. It is also possible to add further buildings to the same school; each of them will be analysed separately. These modifications allow the school manager to immediately evaluate potential changes (e.g., using different accesses to better distribute the flows at entrance or exit). The general outputs provided by the tool (Fig.7) are a summary of the inserted spaces, linked to stairs or accesses, as well as the total time required for entry or exit, and the time required for entry or exit from each access. The tool also provides the maximum capacity of the school building(s).

For each room, suggested ventilation times are provided to guarantee hourly air change rates. The tool provides opening times for inswing windows or open flap windows.

5. **Conclusions**

Although a general consensus on the return to school has not been reached, there are evidences that school closures are having negative effects on several aspects, and therefore protocols and guidelines for safe re-openings are needed. Recommendations and guidelines for reopening generally agree on the relevance of rooms' layout and physical distancing, and on the increase of ventilation rates.

The definition of tools and methods to support safety measures' application and evaluation of their effectiveness can help school managers in their though task. The online tool presented in this manuscript, available online and based on Italian context can be useful to facilitate this task. The tool considers building layout, crowd simulations, and ventilation rates.

Further developments to reinforce the effectiveness of this approach include an in-depth analysis of the contribution of building services and their sanitisation and disinfection, taking into account their energy efficiency. This potential development could also take advantage of the installation of sensors in the school rooms, that allow a continuous monitoring of internal conditions (in terms of physical indicators, such as temperature, humidity, and IAQ, and in terms of sensors detecting presence).

Another relevant aspect that could find an application in the proposed tool is the integration of timetables and their consequent optimisation, to reduce students' movements during school times and to rethink internal layout with underused spaces.

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