Pesaro court registration number 3/2015 ISSN 2421-4574 (ONLINE)

Managing people's flows in cultural heritage to face pandemics: identification and evaluation of combined measures in an Italian arena

Abstract

The management of people's health and safety in cultural buildings has been drastically changed in view of the COVID-19 pandemic. The combined effects of crowding levels and people's flows are now associated not only with emergency conditions (i.e., evacuation) but also with ordinary fruition issues, given the possible spreading of the virus. Cultural buildings, particularly cultural heritage, are critical scenarios for emergency and fruition issues because of their specific geometric and technical features. They suffered from COVID-19 restrictions mainly due to physical distancing measures. Protocols have been developed during the last two years to manage pandemics in such contexts, and the increasing number of vaccinated people is also pushing toward a full return to pre-pandemic rules. However, they should be carefully evaluated and tailored depending on cultural heritage conditions. This work identifies and evaluates combined measures to manage people's flows (access, movement, queue) depending on boundary conditions at the overall (building capacity) and individual levels (face mask; vaccinated/recovered; "green pass"). The effectiveness evaluation is performed by using a simulation model that jointly represents the virus spreading and the people's flow. An Italian historical arena is selected as a significant case study. Results show that a higher occupants' number can multiply the contagion spreading. Still, a more significant impact on its limitation can be achieved by controlling infectors' access (supporting body temperature control with rapid tests) and occupants' movement during queues and pauses. The methodology can help decision-makers to balance a proper combined application of management measures.

Keywords: cultural heritage, pandemics, people's flow, simulation model

1. Introduction

The COVID-19 pandemic remarked that people's flows and activities can significantly affect the overall built environment safety, especially in spaces open to the public and characterized by long-lasting and critical crowd conditions [1]. The attractiveness of spaces with respect to their users can create ideal conditions for both emergency safety issues in buildings (e.g., fires, evacuation) [2] and ordinary fruition models in view of virus-spreading effects among building occupants [3]. Although pre-pandemic works underlined the impact of people's flows on individual health and safety in combination with management strategies and building systems use (e.g., ventilation) [4], the way the COVID-19 pandemic spread and the virus' effects on people (both from a physical and psychological perspective) magnified the importance of organizing effective risk-mitigation measures, especially in closed environments (thus both in buildings or also public transports) [5, 6].

In particular, cultural buildings and heritage, such as theatres, cinemas, public halls, museums and exhibition places, arenas and stadia, widely suffered from COVID-19. They were characterized by a high probability of hosting large numbers of people, for a significant permanence timing, interacting with each other, and also in possible overcrowding conditions, thus increasing the possibility of the virus spreading in case of poor safety management strategies [7, 8]. As an immediate response, these buildings were immediately closed because of the adopted widespread lockdown strategies, as for many other public indoor and outdoor spaces [9]. After the first lockdown phases, cultural buildings were reopened, and strict safety protocols were adopted according to World Health

Organization (WHO) criteria to reduce proximity conditions, exposure time, presence of infectors, and their effects. Besides facial mask use by occupants, protocols mainly involved access and occupants' movement control, as well as physical distancing [10]. Nevertheless, occupants' limits for many cultural buildings were initially provided without connection to the building surface and layout [11, 12]. For instance, tens of people were allowed in this first response phase, whereas hundreds were hosted before the COVID-19 pandemic. In the following pandemic stages, regulations were modified to enable a reduction of occupants' capacity in percentage terms, in respect of the full (standard) capacity, thus moving towards a gradual return to normality. Meanwhile, large-scale experiments were performed to understand the effective impact of indoor/outdoor events and how to overcome these critical limitations [7, 8]. They revealed that the total number of contacts lasting several minutes was relatively low during the event and a higher number of contacts occurred during admission to the venue and during the breaks. Thus, measures should combine occupants' capacity limitations to the management of attraction areas in the built environment [9], including collective (e.g., accesses control; possible infectors' detection, also via body temperature control; sanitizing actions; air flows) and individual (e.g., mask-wearing) strategies Similar strategies have been widely applied in a large number of building intended uses, and mainly in public and work spaces [9, 13, 14].

The progressive introduction of vaccines in several countries, the consequent reduction of infection rates and hospitalizations, and the parallel adoption of screening campaigns (e.g., "green pass" adoptions) have been encouraging a discussion on how the adaptation of COVID-19 measures can overcome occupants' capacity limits for public cultural events [9]. However, the possibility of applying measures and their effectiveness depends on the following:

- the type of event, the attractiveness of architectural spaces, and the social response of people during it. For instance, before the pandemic, proximity during festival and music events was not experienced as an invasion of personal space but as sharing 'social identity space', and therefore something tolerable or even positive [9];
- the geometrical and technical characteristics of the building hosting the events. This factor is a fundamental factor in the building heritage and generally affects the sustainable use and adaptation of cultural heritage over time [15], especially in connection with safety issues and crowd conditions [2].

In the context of such historical buildings, arenas, and theatres are still used to host theatrical, musical, and opera events, representing one of the most significant scenarios. According to the consolidated proximity, exposure-time and ventilation-based criteria for COVID-19 transmission [10] as well as to the aforementioned experimental results on public concert venues [7, 8], their risk for contagion spreading is significant mainly because:

- the audience contemporarily occupies the same closed built environment, which hosts both the parterre and the tiers, thus exposing, to the same conditions, a number of occupants that is generally higher than other conditions (including public transports);
- possible overcrowding conditions can appear over time also in the narrow and complex spaces to reach this audience space (i.e., entrance/exit queue, people's flows during breaks or towards internal attraction area, e.g., bar, foyer, toilets). General fruition conditions thus imply the overlapping of static use (i.e., in the audience space) with dynamic use (i.e., occupants moving and socializing before, during, or after the breaks).

Furthermore, these cultural buildings also generally imply the circulation of occupants in other community facilities that are external to the buildings themselves due to leisure activities in view of the venue [7, 8]. Tailored safety protocols should be provided and evaluated for such historical buildings, considering (1) the possibility of maximizing the occupants' number while (2) improving the final users' satisfaction, (3) the possible revenues for all the stakeholders, and (4) directly managing complex spaces with low impact solutions, as for general reuse, adaptation, and safety issues [2, 15, 16].

Simulation tools could be useful to effectively set up sustainable solutions from these perspectives [1, 13, 17]. A similar approach is shared by other safety-related issues in the cultural heritage (e.g., evacuation safety) [2] and was also applied by previous studies on airborne disease mitigation [4]. Some simulation approaches have been provided to evaluate the COVID-19 spreading in closed environments been performed for public spaces and closed built environments [1, 17, 18]. However, the development of measures was generally assessed in a separated manner [14]. Limited efforts to evaluate the effectiveness of safety protocols have been also provided [19], and thus joint optimization issues were not carried out according to structured approaches and by including vaccine effects. Furthermore, to the authors' knowledge, no works were performed in the context of cultural buildings, such as arenas and theatres, and specifically considering historical buildings because of their aforementioned intrinsic limits affecting risk.

This study aims to develop an approach to identify combined measures for contagion-spreading mitigation in the context of building heritage used for cultural purposes and then verify their joint effectiveness to define efficient and tailored protocols against COVID-19. The approach relies on the joint simulation of people's flows, virus-spreading rules, and specific health and safety protocol measures. A simulation model developed and validated by previous research group works [19] has been modified to ensure its application in the cultural heritage context. Considered measures are consistent with Italian Government regulations (https://bit.ly/3Eb96CE, checked: 14/04/2022), as well as with national and international guidelines (including the ones of WHO) [14, 20], and mainly comprise people's flows management tasks such as access, queue, and movement control, in respect to occupants' capacity at the overall level and individual features. The approach capabilities are shown using a significant case study, the "Arena Sferisterio" (Macerata, Italy), a famous historical arena with a capacity of 3000 people, used to host operas, concerts, and other theatrical events for over 100 years. The model predicts the effectiveness of safety protocol measures in terms of the probability of new contagions at the end of an event. Thus, such results can support the decision-makers in evaluating the best combination of strategies to be adopted in the theatre.

2. Methods

This work is organized into 3 steps: 1) the identification of combined measures in the cultural heritage context by focusing on theatres and arenas and their implementation in a simulation model [19] in synergy with the virus spreading and people's flows rules (Section 2.1); 2) the definition of criteria to perform and analyze simulation results (Section 2.2); 3) the application to the selected case study by tailoring measures according to the current scenario and decision-makers choices (Section 2.3).

2.1 Combined measures identification and modeling approach

Measures to manage health and safety against COVID-19 in cultural buildings can be arranged into 3 different classes, according to national decrees and national/international guidelines the decree requires (e.g., https://bit.ly/3Eb96CE, [14, 20]): 1) people's flows management, in terms of minimum physical distancing (≥1m) and other control actions, such as ticket booking and access supervised and regulated by dedicated personnel (i.e., body temperature control, <37.5°C; "green pass" control); 2) overall control measures, focused on maximum building capacity, body temperature check, and sanitizing measures; 3) measures at the individual level, i.e., face-masks use (independently by the mask type), being vaccinated, having a "green pass". These measures are combined in order to be represented in a multi-agent simulation model, which can hence evaluate the effectiveness of measures in the safety protocol, depending on people's flow, behaviors, and interactions induced by the event organizers, the geometry of the cultural building and the attractiveness of its composing spaces.

According to previous works of the research group [19], the model considers that each individual in the environment can: 1) be an infector or a susceptible person; 2) wear a face mask of a certain type; 3) can have a "green pass" and/or being vaccinated or not. On such bases, the model jointly represents: 1) the position of each individual in the areas of the arena, over time, depending on the environment layout, its use, the event organization, and adopted measures (Section 2.1.1); and 2) the virus transmission between people depending on their positions and according to a probabilistic approach (Section 2.1.2).

2.1.1 Layout, use, and combined measures

The simulation environment is composed of: *"waiting areas"* that are placed near the entrance gates, *"sectors"* where the audience attends the event, and "*other attraction areas*" such as common spaces and toilets. People can spend time in such areas according to the event schedule. In addition, not accessible areas and main obstacles to occupants' presence (i.e., the stage) are also taken into account. Thus, the environment surface A [m^2] is defined as the sum of the surfaces of such areas.

The number of simulated *initial people* [pp] depends on the specific occupants' capacity according to the considered safety protocol scenario. A specific status (infector/susceptible, "green pass"/vaccinated or not, face mask type) is assigned at the start of the simulation to each simulated individual [19]. The model considers that people just enter the environment at the beginning of the event and can leave it at the end.

Initially, people are randomly distributed in the *"waiting areas"*, respecting the minimum physical distancing requirements (1m). They can move into their "*waiting area*", respecting the physical distancing. This distancing assumption is also compatible with real-world behaviors retrieved in public buildings [21], where only a marginal number of people (up to <20%) seem to assume lower distance values in building fruition and movement. After a *queue time*, people move to the "*sector*" corresponding to their "*waiting area*". A random position is attributed to them respecting the criteria of minimal safety distance (1m) between seats, which is consistent with seat occupation criteria in the case study (compare Section 2.3). The "act" phase starts when the event begins, and all agents remain in their assigned seats without moving. Only a limited number of people has been characterized by the ability to move (arbitrarily assumed equal to 5%, thus representing a marginal impact of such behaviors during the "acts") towards specific "attraction areas" (i.e., toilets). At the end of each "act", that is, during the pause, each individual can move towards the "attraction areas", depending on his/her possibility of "moving at pauses". According to an example of typical opera acts' scheduling (e.g., considering the Sferisterio organization and most represented operas [22]) this work considers a simulation step equal to 15 minutes. This work considers three "acts" (30 minutes each) and two pauses between the acts (15 minutes each). At the end of the last "act", people return to the entrance gate where they were initially placed to leave the building, depending on the *queue time*.

People's position modeling is aimed at representing the overall contagion-spreading effects on the whole population, depending on the attractiveness of the space, with a time discretization of 15 minutes as a consistent threshold for the increase of contagion probability [13, 23].

2.1.2 Virus transmission

Consolidated *proximity and exposure-time-based rules* represent high-risk and close contact between the occupants. Considering a distance between a susceptible occupant and an infector <2m, the probability of being infected P_C [%] (Eq. 1) increases with: 1) the infector's transmission efficiency of the virus i_{eff} [-], calculated as the ratio between the current time from the virus contagion and the virus incubation time (capped at 1); and 2) the exposure time Δt [h]. P_C can be hence reduced by: 1) the mask filter of the infector ($prot_i$) and of the susceptible occupant ($prot_j$) for each individual depending on the EN 149:2009 classification [19] (maximum protection when $prot_i$=$prot_j$=1; and 2) the antibody efficacy V_{eff} [-], for vaccinated/recovered people [24]. P_C is capped at 100% (maximum probability). This approach has been validated according to real-world experimental data [19].

$$P_C = i_{eff} \cdot \Delta t \cdot (1 - prot_j) \cdot (1 - prot_i) \cdot V_{eff} [\%] \qquad \text{(Eq. 1)}$$

According to the Wells-Riley approach (Eq. 2), given the number of susceptible people S [pp] in the environment, the probability of being infected because of *ventilation-based rules* P_V [%] depends on the number of infectors C [pp] and the quantum generation rate produced by each of them q [h^{-1}], on the pulmonary ventilation rate of a susceptible occupant p [m^3/h], on the exposure time Δt and on the ventilation rate of the environment Q [m^3/h]. In Equation 1, one quantum q represents "a collection of pathogen particles that can infect susceptible people", and the q values derived for the COVID-19 context range from 14 to 48 h^{-1} [17].

$$P_V = \frac{C}{S} = 1 - e^{-\frac{q \cdot p \cdot \Delta t}{Q}} [\%] \qquad \text{(Eq. 2)}$$

Transmission modes due to surface contamination also have been not considered because of the constant sanitizing activity [20].

For each susceptible occupant, P_C and P_V are calculated at each simulation step, and his/her infection probability is associated with the maximum value between them. Then, the infection probability is compared to a random number (varying from 0 to 100%), and the susceptible occupant is stochastically infected when the infection probability is equal to or greater than this random number. It is also considered that this newly infected occupant cannot infect other people because his/her i_{eff} tends to zero while remaining in the environment (see Eq. 1).

2.2 Simulation setup and results evaluation criteria

The multi-agent NetLogo platform (version 6.2) [25] is used to implement the model. The space is divided into squared patches, which sides are equal to 1m. The model running is performed through a script in R programming language (version 4.0.5), in particular using the NLRX package to ensure repeated tests according to the probabilistic approach (https://cran.r-project.org/web/packages/nlrx/index.html). More than 300.000 simulations have been performed, including different simulation setup organizations on the case study, as reported in Table 1, according to Section 2.3 assumptions. All the simulations consider that infectors are asymptomatic persons who are not revealed by controls before the event (e.g., by swabs) or at the building access by body temperature control.

Table 1. Model parameters setup for simulation.

Parameter by typology	**Unit of measure**	**Values range in this work**	**Notes**
Environment and global parameters			
A	m^2	4500	The overall surface of the Arena Sferisterio (see Section 2.3)
Δt	exposure time as the simulation step	1 step = 0.25h (15 minutes)	Simulation step provided according to critical exposure-time values in consolidated proximity-based criteria for contagion spreading, to typical opera scheduling and to the queue time according to the case study application (see Section 2.3)
Individual's features			
i_{eff}	-	0 to 1	infector's transmission efficiency of the virus, randomly assigned to each infector
Vaccinated/recovered percentage	%	30 to 70%	Percentage of vaccinated/recovered occupants who can enter the building
V_{eff}	%	85% to 95%	Effective coverage of the antibodies from the infection; randomly assigned to each individual; evaluated starting from vaccine-related data
init-infectors-percentage	%	0.2 to 4	How many individuals could be infectors at the start of the simulation
$prot_i = prot_j$	-	0 to 1	Uniform mask types distribution is considered for the individuals, based on the criteria from EN 149:2009 on maximum aerosol drops penetration percentage. Limits of each type refer to: FFP3≥98%, FFP2 95-98%; FFP1 80-95%; surgical 54-88%; community masks and no-protection limit<54%.
Safety protocol			
initial people	pp	600 - 1100	Number of people in the environment ranging from about 2/3 of the maximum COVID-19 capacity to +20% of the maximum capacity. Although 842 people (see Section 2.3) is the maximum allowed capacity for the case study stakeholder, the maximum number of people has been increased to better stress the capacity effects on the contagion spreading.
Moving-at-pause	%	5 to 100%	Maximum number of people moving during the pause phase between two consecutive acts
Queue time	-	1 or 2	entrance and exit queue time: 1 stands for 15 minutes-long queue; 2 stands for up to 30 minutes-long queue

At the end of each simulation, results have been organized to evaluate the contagion spreading reduction due to combined measures, considering a single event. Thus, the contagion spreading after each event is expressed through the final infected people percentage *dI* [%], which depends on the final S_f [pp] and initial S_i [pp] number of susceptible people according to Eq. 3 [19]:

$$dI = \left[1 - \frac{S_f}{S_i}\right]\% \qquad \text{(Eq. 3)}$$

dI ranges from 0 (no new infections at the end of the event) to 100% (all the susceptible people become infected at the end of the event). Successful measures should minimize *dI*. *dI*<5% is also assumed as a reasonable threshold for contagion spreading discussion. *dI* values are mainly correlated to:

- the combination of measures on *initial people* (to consider the maximum number of allowed occupants), *init-infectors-percentage* (to assess the effectiveness of access control procedures), *moving-at-pause* (to evaluate the internal displacement possibility for the audience by the staff members' control);
- and the contextual factors at the national level in terms of *vaccinated/recovered percentage.*

dI values are traced according to 2D Kernel Density, thus pointing out the *dI* probability depending on the parameter range. Results are organized by, firstly, discussing the impact of each aforementioned parameter condition by itself and then combining them. In this sense, the median *dI* is assumed as a risk index to compare each measure's effectiveness.

2.3 Case study application

The Arena Sferisterio (or just the "Sferisterio") of Macerata is one of the most prominent architectural structures of the late European Neoclassical Style in the Papal State and betrays a Palladian influence [26, 27]. Built in the '20s of the 19th Century by Salvatore Innocenzi and Ireneo Aleandri, the Sferisterio is characterized by an open-air semi-elliptic layout (Figure 1). Since the end of the '80s, it has regularly hosted the international "Macerata Opera Festival" during the summer. Most of the audience is hosted in the parterre, placed at the ground level, assigned to two main sectors and several sub-sectors, with fixed seats divided by corridors. The C-shaped building comprises several levels hosting: at the ground floor, a portico to grant space for people waiting to enter the arena, artists' rooms, toilets, and corridors to the parterre; at the 1st level, the terraces, with fixed seats, which are served by a long corridor, toilets, and technical rooms; at 2nd and 3rd levels, tiers (4 to 6 seats for each tier), divided into boxes, which are served by a long corridor as for the first level; at the last level, the building flat roof hosting the "loggione", without seats.

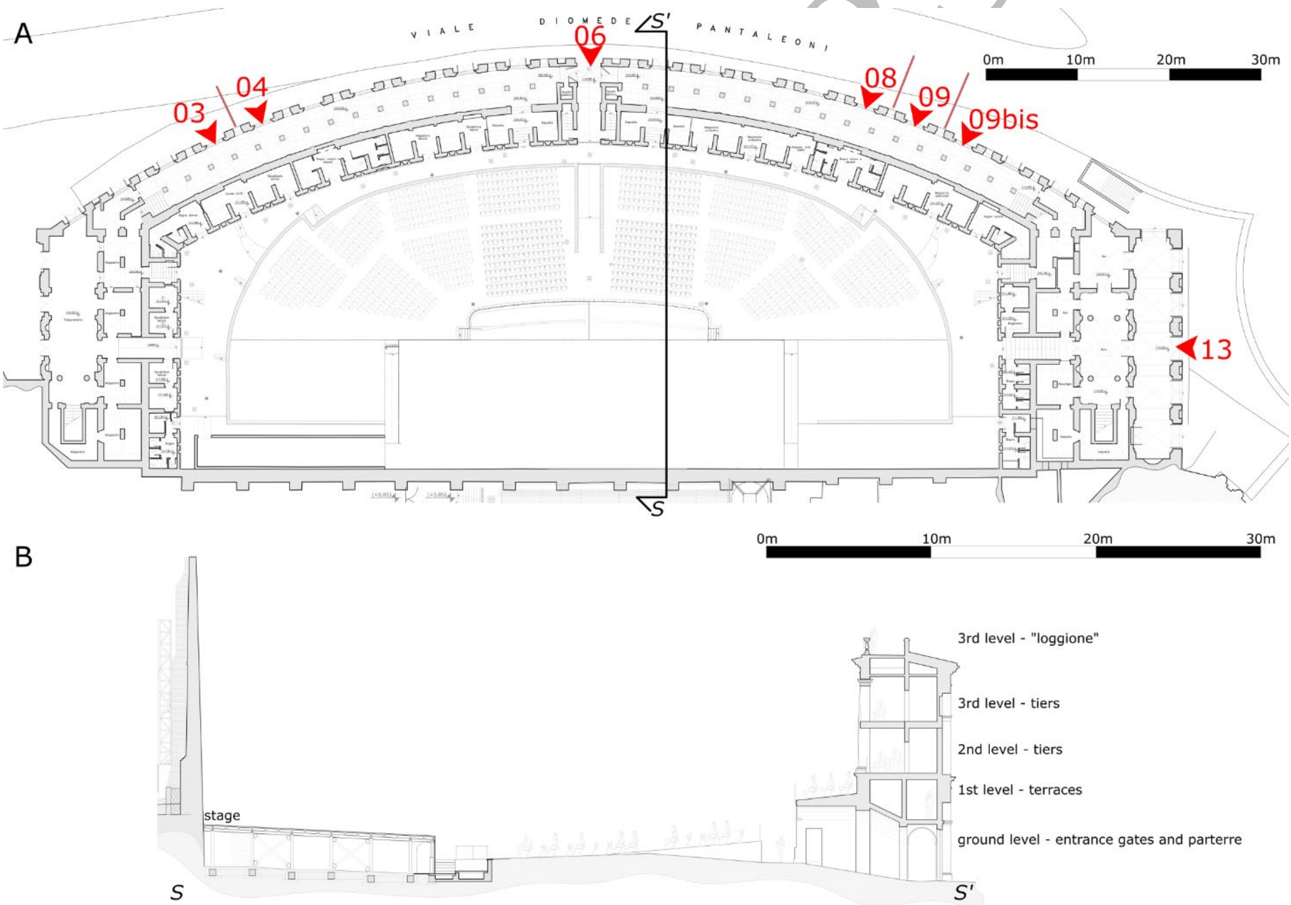

Figure 1 Arena Sferisterio layout: A-. plan view of ground level, showing the parterre, the main portico, and the main entrance gates; B- section view (S-S') showing the 4 levels of the open-air theatre. The entrance gates' codes are shown according to COVID-19 safety shown in Table 2. Courtesy of "Sferisterio Arena Association"

The following simulation scenarios are based on the tailored protocols adopted by the Sferisterio managers in the 2021 seasons (starting in June), to consider more restrictive conditions and pursue a conservative approach to regulations applications. Thus, infectors' data affecting individual measures refer to the same period (i.e., end of May 2021).

People's flow management and overall control measures are based on the audience's division into 6 sectors and subsectors, as in Table 2. The number of people in each area is defined depending on the seat position (which are fixed at the ground) and number (to grant the minimum physical distancing). Furthermore, the access to each sector/sub-sector is associated with a specific entrance gate, which is graphically shown by the codes and the red arrows in Figure 1-A (compare Table 2 for the same codes). Only 7 gates were left open. This type of organization was introduced to reduce the interactions between people while moving to seats assigned in different sectors, as well as to limit the queue while entering. Two values for the *queue time* are considered (15 and 30 minutes) thanks to the support of 60 staff members, who were assumed in 2021. The queue time is due to the staff's ticketing service and support for automatically checking people's body temperature via infrared cameras. The staff additionally: 1) controls and reduces people's flow and interactions during the queues and the event; 2) assists people and grants a constant sanitizing activity (seats, doors, toilets, etc.). From an individual level, people are obliged to wear a face mask. Still, no limitations for the type of mask (surgical, FFP, etc.) are considered in this work to verify the effects of different protection levels on the contagion spreading.

Since the model is based on 15 minutes-long simulation steps, 8 simulation steps correspond to the 3 acts-2 pauses structure, while the duration of the overall event depends on the queue time (10 steps for 15 minutes-long queue; 12 steps for 30 minutes-long queue). Preliminary simulations were performed to assess the impact of *ventilation-based spreading* with respect to the *proximity and exposure-time-based rules*. P_C is assessed as the prevalent transmission mode in case of more than 4 complete air changes per hour, seeming in line with previous works [17]. Therefore, since the arena is an open-air environment, the influence of the ventilation can be reasonably excluded.

Sector name	**People**	**Entrance gate code (Figure 1) – sub-sector name: number of people [pp]**
Parterre	388	06-central: 224 pp; 08-lateral left: 82 pp ; 04-lateral right: 82 pp
Terraces	172	09-lateral left+journalist tribune: 92 pp; 03-lateral right: 80 pp
Tiers (I order), divided into boxes	120	09bis-lateral left: 60 pp; 09bis-lateral right: 60 pp
Tiers (II order), divided into boxes	114	13-lateral left: 60 pp;13-lateral right: 54 pp
"Loggione"	48	13-unique sub-sector: 48 pp
Total	*842*	

Table 2 Maximum number of people for each sector/sub-sector and association with the entrance gates.

3. Results and discussion

Figure 2 shows *dI* depending on the number of *initial people* attending the event, according to a 2D kernel density (0-1 scale) visualization. This 2D kernel density value expresses the probability of having a specific *dI* value depending on the *initial people* value. As expected, the number of people attending the event impacts *dI* in a direct manner. For instance, the probability of maintaining *dI*<5% decreases when the *initial number of people* increases: up to 700 people, 90% of probability; between 700 and 850 people (actual maximum capability), 80% of probability; over 950 people, 70% of probability.

Figure 3 shows the 2D kernel density of *dI* vs. the initial infectors percentage. The comparison of Figure 2 and Figure 3 demonstrates that the initial infectors percentage seems to assume a more important rule to reduce contagion spreading. Maintaining the number of initial infected people <0.5% (see Section 2.3) gives a 90% probability of limiting *dI*<5% (Figure 3).

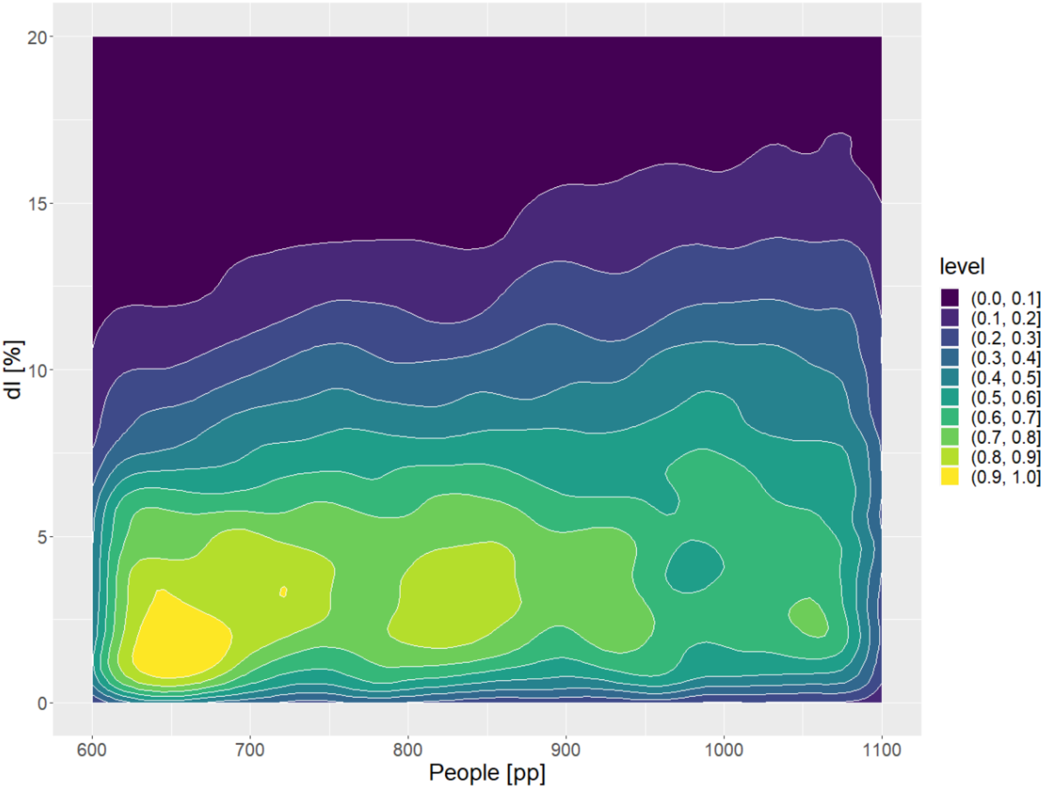

Figure 2 dI versus the number of initial people: color represents the 2D kernel "density" (adjusted density on a scale of 0-1)

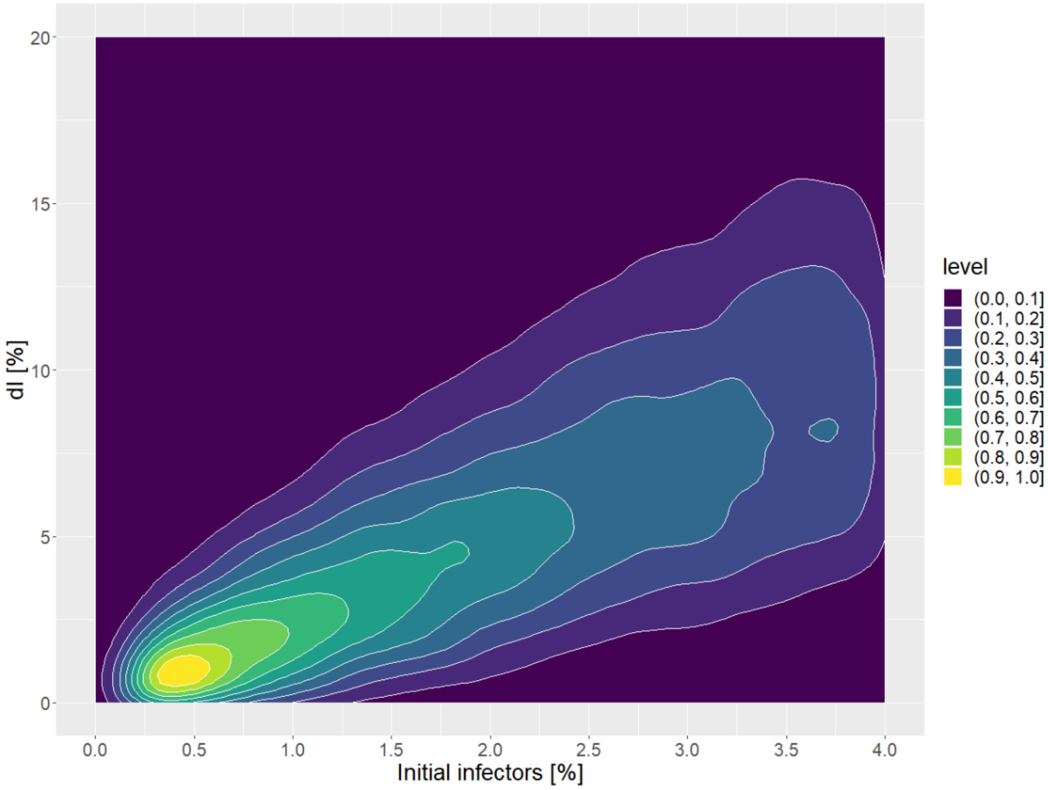

Figure 3 dI versus the initial infector percentage: color represents the 2D kernel "density" (adjusted density on a scale of 0-1)

Figure 4 shows a 2D kernel density of *dI* depending on the percentage of people allowed to move during each pause to reach "*other attraction areas*" (e.g., bar, toilets). The probability of maintaining *dI*<5% ranges from 60 to

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ISSN 2421-4574 (ONLINE)

80%. The general *dI* trend is close to the one due to the *initial people* values (Figure 2), as shown by the shape and width of the 2D kernel density areas**.**

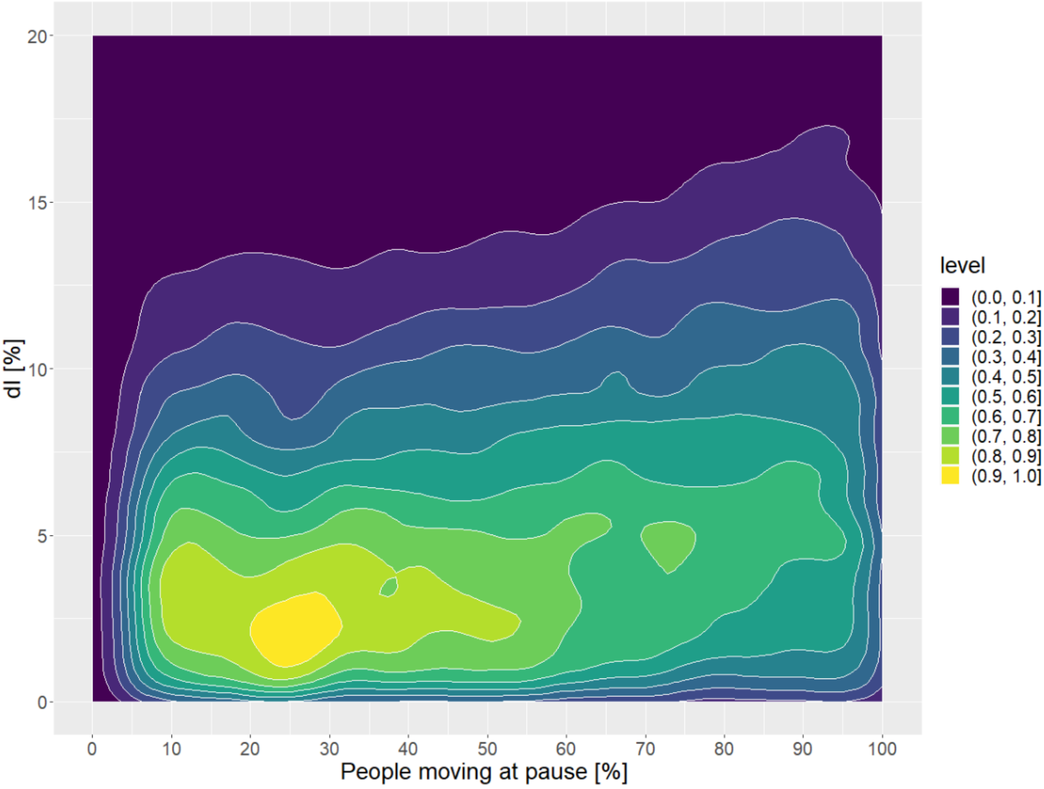

Figure 4 dI versus the percentage of people moving at the pauses (moving-at-pause): color represents the 2D kernel "density" (adjusted density on a scale of 0-1)

Figure 5 shows the significant influence of the *queue time* (15 and 30 minutes) on the probability of a contagion spreading, depending on the *initial people*. For queue time equal to 15 minutes, the probability of having *dI*<5% always varies between 80% (lower *initial people*) and 60% (*initial people* tending to 1100 pp). On the contrary, when the *queue time* increases, the probability decreases to 50% for more *initial people*.

Although the queue is organized by dividing people into different groups depending on entrance gates/"waiting areas" and assigned sectors, the *queue time* appears to be the most critical aspect to control due to the possible interactions between people while waiting. This result is mainly confirmed by data for extreme *initial people* values, which can amplify these contagion-spreading interactions.

Let's assume a marginal probability of 10% in *dI* values (moving to dark blue areas in Figure 5) to point out a contagion spreading threshold with lower confidence but not negligible. When *initial people* tend to 1100pp, *dI* tends to 1) 15%, for queue time is equal to 15 minutes; 2) 20%, for queue time equal to 30 minutes. The same 10% probability always describes critical *dI* values for maximum parameters conditions that are lower than those of the queue time-related impact:

- for maximum values of *initial people* (Figure 2) and initial infector percentage (Figure 3), *dI* up to about 16%, regardless of the other measures;
- for maximum values of *moving-at-pause* (Figure 5) implies *dI* up to about 18%.

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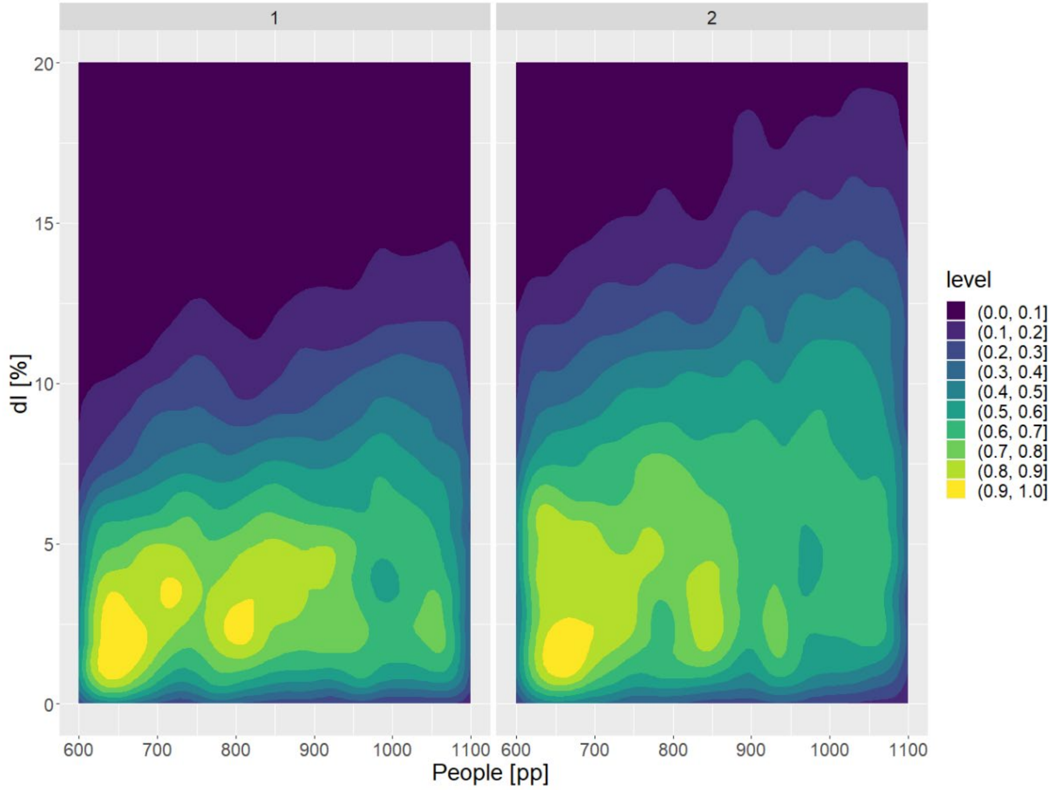
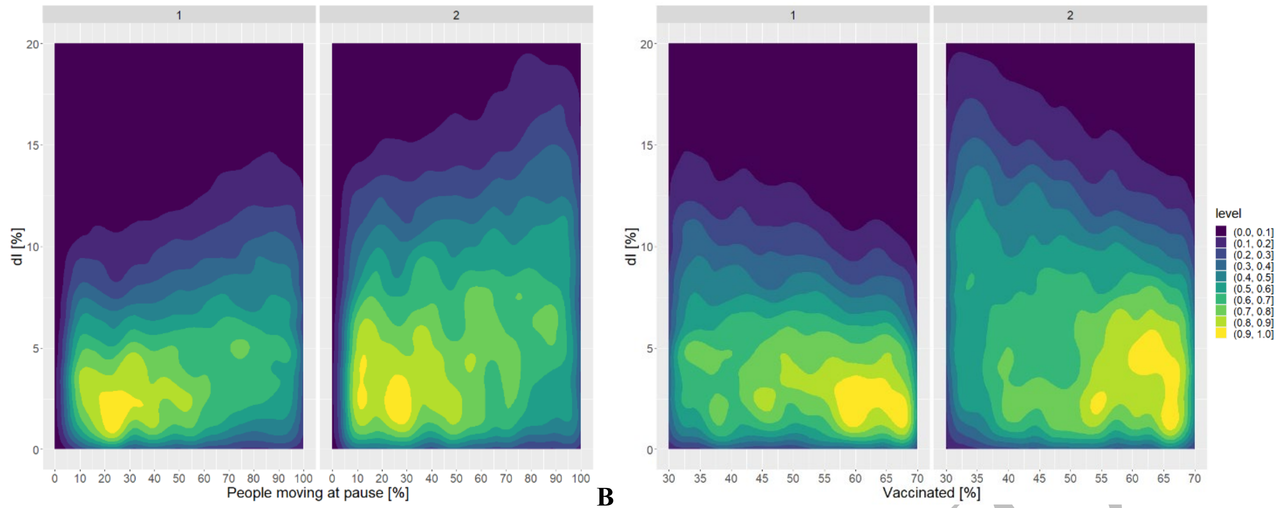


Figure 5 dI % versus number of initial people, depending on the queue time: 1-15 minutes; 2-30 minutes. Color represents the 2D kernel "density" (adjusted density on a scale of 0-1)

The combined increase of the percentage of *moving-at-pause* and the *queue time* could hence lead to severe risk levels. Figure 6-A compares the combination trends for *queue time* equal to 15 minutes (left) and 30 minutes (right). *dI<5%* can be achieved only if limited movement is allowed. When considering values of *moving-at-pause* <60%, the probability of having *dI>5%* increases by about 10 to 20% when *queue time* is equal to 30 minutes (density of about 0.7) with respect to 15 minutes (density of about 0.5), as shown by the 2D kernel "density" representation. The free movement towards different Sferisterio areas is the second critical risk factor, thus underlining how access, queue, and movement control should be strictly ensured. Such results can allow identifying the thresholds for the related safety protocol strategies to be guaranteed by the Sferisterio staff members.

Figure 6-B represents the influence of contextual factors at the national level in terms of *vaccinated/recovered percentage*, thus also considering the vaccine campaign advancement by distinguishing *queue time* trends of 15 minutes (left) and 30 minutes (right). As for the *moving-at-pause* trend, it is possible to observe the strong influence of the *queue time* on the contagion spreading, especially with a limited vaccinated/recovered population (e.g., for values of 40% and *queue time* of 30 minutes, maximum *dI* values for the residual probability of 10% can be equal to about 20%). Although the protocol cannot manage this factor because it mainly depends on the national context and the vaccination campaign, these results underline the importance of widespread vaccination of the population to safely restart cultural events, adapting the current regulation-based measures [9].



A B

Figure 6 dI versus: A- moving-at-pause; B- vaccinated/recovered percentage. Values are offered depending on the queue time: 1-15 minutes; 2-30 minutes. Color represents the 2D kernel "density" (adjusted density on a scale of 0-1 on the right)

Figure 7 resumes the combined effects on *dI* due to *init-infectors-percentage*, depending on *queue time* (left: 15 minutes, right: 30 minutes), *moving-at-pause,* and *initial people*, since these input parameters conditions can be effectively managed by the safety protocol measures.

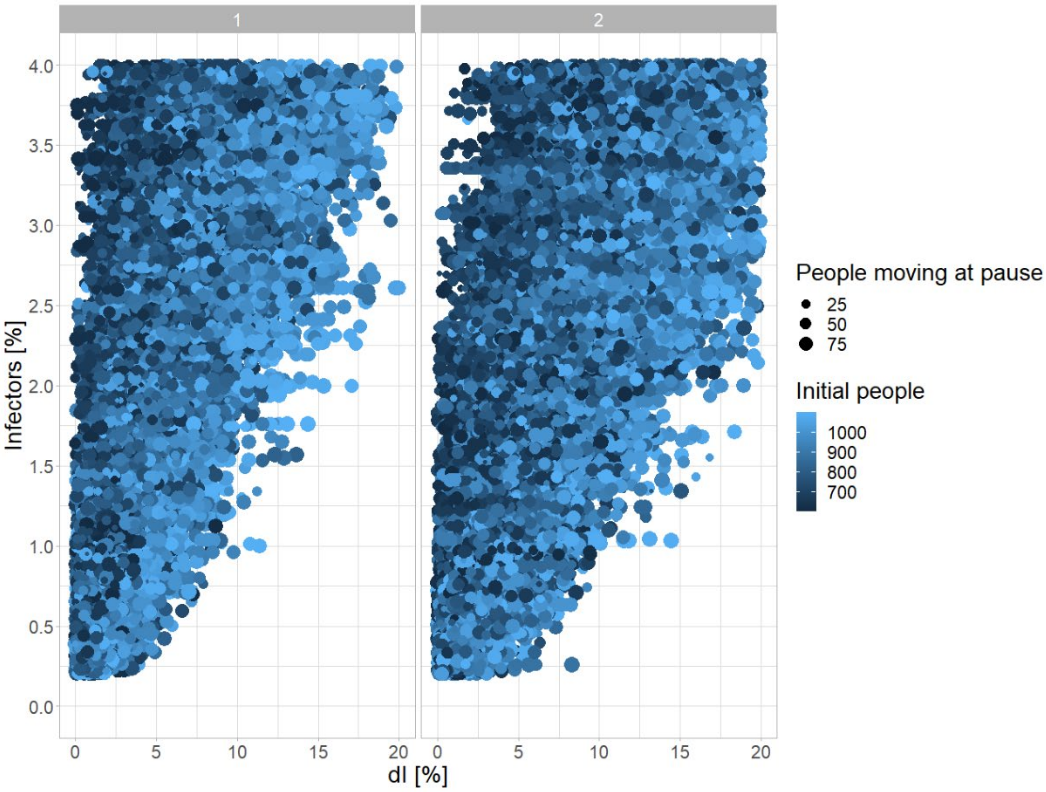


Figure 7 Scatterplot of dI versus initial infectors percentage depending on the queue time: 1-15 minutes; 2-30 minutes. The point size represents the percentage of people moving during the pauses (divided into 3 groups, up to the percentage values in the legend), and the color represents the number of initial people.

Results related to combined conditions confirm the outputs of each parameter condition. When the number of *initial people* tends to maximum values and *moving-at-pause* is over 75%, *dI* sensibly shifts (+5-10%) towards higher values while moving from 15 to 30 minutes of *queue time*. Limiting the *init-infectors-percentage* certainly appears to be a significant measure since it can reduce the overall scattering of the *dI* range and so the possibility that critical interactions among infectors and susceptible people can appear in the Sferisterio. In fact, *dI* ranges from about 0% to

Pesaro court registration number 3/2015 ISSN 2421-4574 (ONLINE)

5% for *init-infectors-percentage* tending to 0.2%, while it ranges from about 2% to 20% for *init-infectors-percentage* tending to 4%.

3.1 Insights on the effectiveness of the combined measures

Table 3 resumes the effectiveness of the alone and combined measures in the Sferisterio, showing the median value of *dI* and distinguishing two different intervals of related input parameters. Interval 1 in Table 3 traces the more limiting but more powerful conditions. Table 3 also resumes some possible proposals on improving each measure's effectiveness to move towards Interval 1 results. Moreover, the last column of Table 3 calculates the difference between *dI* in Interval 1 and Interval 2 conditions. This approach allows for obtaining simple but reliable feedback from the decision-makers.

Table 3 Impact of each safety protocol measure and their combination in terms of the median value of dI. For each measure, the input parameter in the simulation and the possible proposal on how to improve each measure's effectiveness are offered (n.a.= no additional details because of a simple measure to be implemented).

Input parameter	**Proposal on how to improve the effectiveness of the related safety protocol measure**	***dI* (input parameter range)**		**difference of dI (interval 1 – interval 2)**
		Interval 1	**Interval 2**	
Init-infector-percentage	supporting body temperature control with rapid test results	2.62 (0- 2%)	8.08 (2%-4%)	-5,46
Q - Queue time	staff members' control, possibility of evenly spaced access (e.g. event ticket with access time), and exit by the audience	4.95 (15 min)	6.67 (30 min)	-1,72
M - Moving-at-pause	staff members' control, higher level of internal division of common spaces/toilets by sectors	5.00 (≤50%)	6.55 (>50%)	-1,55
I - Initial people	n.a.	4.72 (600-750)	6.28 (750-1100)	-1,56
Combined (Q,M,I) depending on the init-infector-percentage	see above	3.59 (see above)	8.09 (see above)	-4,5

The *init-infector-percentage* control is the most useful measure to minimize the median *dI* value. Actions aimed at body temperature control should be supported by rapid tests (e.g., swabs relating to "green pass") to be performed before the event access (e.g., the day before) due to the possible presence of a significant number of asymptomatic people. As remarked by experiments performed on concerts, e.g., RESTART-19 [7, 9], such rapid tests seem to represent a compensative measure to support the increase of maximum occupants' capacity.

Considering each of the other measures by themselves, the second measure in importance order is the *queue time* control, which implies the limitation of free interactions between occupants while standing up in the "*waiting areas*", thus confirming previous works' results [9].

Limiting the maximum number of allowed people seems to have a smaller significance with respect to the possibility that the occupants can move during pauses. According to Table 3, the *dI* in Interval 2 for *moving-at-pause* is higher than that of *initial people*, while the difference of *dI* (interval 1 – interval 2) is almost the same. During the event, people's physical distancing can be ensured by the seats fixed at the ground, thus limiting the interaction between them also in case of higher building capacity. Thus, interactions at the pauses (when physical distancing cannot be ensured) become critical.

The combination of these measures amplifies the effects on *dI*, as shown by the last row in Table 3. The number of *initial people* has an obvious multiplier effect, but controlling infectors' presence, access time, and movement at the pauses reduces the contagion spreading.

4. Conclusions

Managing the safety of people in cultural buildings during pandemics means identifying and deploying effective measures to mitigate contagion risks while ensuring the proper fruition of the cultural facilities. Cultural heritage is a critical scenario in this sense, in view of its peculiar management and physical (including the layout of attraction spaces) features. Measures should be better tailored depending on these specificities, so approaches to support decision-makers in evaluating their effectiveness are also needed to better prepare for future critical conditions.

To this end, this work provides a methodology to identify, organize and evaluate combined measures to manage people's flow (access, movement, queue) depending on boundary conditions at the overall (building capacity) and individual levels (face mask; vaccinated/recovered; "green pass"). The attention is focused on historical theatres and arenas as significant scenarios.

The effectiveness evaluation is performed by using a simulation model that jointly represents the virus spreading and the people's flow, and that allows calculating a risk index expressing the probability that the contagion spreads during an event hosted in cultural buildings. This risk index calculates the newly infected people with respect to initially susceptible people by using a probabilistic simulation tool based on a multi-agent approach.

A case study application, the Arena Sferisterio (Macerata, Itay), one of the most famous Italian historical open-air arenas hosting operas during the summer, is chosen to evaluate the effectiveness of the safety protocol introduced to restart the cultural activity of the arena. According to the results of more than 300.000 simulated events, limiting the maximum number of allowed people in the arena has little significance, despite the rules adopted in Italy and other countries. The people's number can multiply effects, but a higher impact on the contagion limitation can be achieved through the control of infectors' access as well as of the interactions between people during the access/exit queues and the pauses between acts. However, it is worth noticing that results could be influenced by the behavioral modeling assumptions of users, including physical distancing (actually based on 1m distance protocols). To this end, the next works could test the effect of other minimum physical distancing values on the contagion spreading and include a random model of preferred distancing. In this sense, the model could also be varied to assume other simulation steps that would represent different dynamics of crowd and fruition modes, especially if moving towards a finer granular representation of the simulation time [8].

In conclusion, considering the economic impact of measures, the approach can help to find the optimal solution combining safety, practical and economic aspects in the specific situation. This approach can be easily applied or adapted to other historical arenas and theatres, to other historical buildings characterized by possible overcrowding conditions, and to other future critical conditions due to pandemics in intense crowd spaces (by varying the virus transmission rules, if similar to the ones assumed to this model).

5. Acknowledgment

The authors would like to thank the Arena Sferisterio Association and its President, Luciano Messi, for the availability of the material used in this work.

6. References

1. Chen L, Liu X, Hu T, et al (2022) Measurement of contagion spatial spread probability in public places: A case study on COVID-19. Applied Geography 143:102700. doi: 10.1016/j.apgeog.2022.102700

2. Bernardini G, Santarelli S, D'Orazio M, Quagliarini E (2019) A cognitive approach for improving built environment and users' safety in emergency conditions. TEMA: Technologies, Engineering, Materials and Architecture 5:47–60. doi: 10.17410/tema.v5i1.214

3. Prussin AJ, Belser JA, Bischoff W, et al (2020) Viruses in the Built Environment (VIBE) meeting report. Microbiome 8:1. doi: 10.1186/s40168-019-0777-4

4. Gao X, Wei J, Lei H, et al (2016) Building Ventilation as an Effective Disease Intervention Strategy in a Dense Indoor Contact Network in an Ideal City. PLOS ONE 11:e0162481. doi: 10.1371/journal.pone.0162481

5. Megahed NA, Ghoneim EM (2020) Antivirus-built environment: Lessons learned from Covid-19 pandemic. Sustainable Cities and Society 61:102350. doi: 10.1016/j.scs.2020.102350

6. Guo Y, Qin W, Wang Z, Yang F (2021) Factors influencing social distancing to prevent the community spread of COVID-19 among Chinese adults. Preventive Medicine 143:106385. doi: 10.1016/j.ypmed.2020.106385

7. Jones J (2021) Spectacular: 5,000 pack Barcelona rock concert after COVID tests. reuters.com 1.

8. Song V (2021) Concerts turned into live trials. New Scientist 250:10–11. doi: 10.1016/S0262-4079(21)00583-2

9. Drury J, Rogers MB, Marteau TM, et al (2021) Reopening live events and large venues after Covid-19 ‘lockdown’: Behavioural risks and their mitigations. Safety Science 139:105243. doi: 10.1016/j.ssci.2021.105243

10. Bruinen de Bruin Y, Lequarre A-S, McCourt J, et al (2020) Initial impacts of global risk mitigation measures taken during the combatting of the COVID-19 pandemic. Safety Science 128:104773. doi: 10.1016/j.ssci.2020.104773

11. Massachussets government (2021) SECTOR SPECIFIC WORKPLACE SAFETY STANDARDS FOR THEATERS AND PERFORMANCE VENUES TO ADDRESS COVID-19. 6.

12. Washington Government (2021) Theater & Performing Arts and Events COVID-19 Requirements.

13. Romero V, Stone WD, Ford JD (2020) COVID-19 indoor exposure levels: An analysis of foot traffic scenarios within an academic building. Transportation Research Interdisciplinary Perspectives 7:100185. doi: 10.1016/j.trip.2020.100185

14. D’angelo D, Sinopoli A, Napoletano A, et al (2021) Strategies to exiting the COVID-19 lockdown for workplace and school: A scoping review. Safety Science 134:105067. doi: 10.1016/j.ssci.2020.105067

15. Elsorady DA (2013) Assessment of the compatibility of new uses for heritage buildings: The example of Alexandria National Museum, Alexandria, Egypt. Journal of Cultural Heritage 15:511–521. doi: 10.1016/j.culher.2013.10.011

16. Moreno-Mendoza H, Santana-Talavera A, Boza-Chirino J (2020) Perception of governance, value and satisfaction in museums from the point of view of visitors. Preservation-use and management model. Journal of Cultural Heritage 41:178–187. doi: 10.1016/j.culher.2019.06.007

17. Dai H, Zhao B (2020) Association of the infection probability of COVID-19 with ventilation rates in confined spaces. Building Simulation 13:1321–1327. doi: 10.1007/s12273-020-0703-5

18. Zhang X, Pellegrino F, Shen J, et al (2020) A preliminary simulation study about the impact of COVID-19 crisis on energy demand of a building mix at a district in Sweden. Applied Energy 280:115954. doi: 10.1016/j.apenergy.2020.115954

19. D’Orazio M, Bernardini G, Quagliarini E (2021) A probabilistic model to evaluate the effectiveness of main solutions to COVID-19 spreading in university buildings according to proximity and time-based consolidated criteria. Building Simulation 14:1795–1809. doi: 10.1007/s12273-021-0770-2

20. Hu X, Ni W, Wang Z, et al (2021) The distribution of SARS-CoV-2 contamination on the environmental surfaces during incubation period of COVID-19 patients. Ecotoxicology and Environmental Safety 208:111438. doi: 10.1016/j.ecoenv.2020.111438

21. Bartolucci A, Templeton A, Bernardini G (2022) How distant? An experimental analysis of students’ COVID-19 exposure and physical distancing in university buildings. International Journal of Disaster Risk Reduction 70:102752. doi: 10.1016/j.ijdrr.2021.102752

22. https://www.sferisterio.it/?lang=en, https://www.romaoperacampus.com/novita/29-le-5-opere-piu-rappresentate-nel-mondo.html, https://bit.ly/3Gf4Rt5, https://bit.ly/3AdJtjS (last access: 14/11/2022)

23. Ronchi E, Lovreglio R (2020) EXPOSED: An occupant exposure model for confined spaces to retrofit crowd models during a pandemic. Safety Science 130:104834. doi: 10.1016/j.ssci.2020.104834

24. Olliaro P, Torreele E, Vaillant M (2021) COVID-19 vaccine efficacy and effectiveness—the elephant (not) in the room. The Lancet Microbe. doi: 10.1016/S2666-5247(21)00069-0

25. Wilensky U (1999) NetLogo. http://ccl.northwestern.edu/netlogo/. In: Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL.

26. Pennesi F (1982) Macerata e il suo sferisterio. 47.
27. Adversi A, Cecchi L (1972) Storia di Macerata. Tipografia Romano Compagnucci, Macerata