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EVALUATION OF SPATIAL LAYOUT IN HEALTH CARE WAITING AREAS BASED ON SIMULATION OF DROPLET MOVEMENT TRACE

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ABSTRACT

This paper addresses the issue of airborne transmission of diseases in relation to spatial layout in health care facilities. In particular, this study analyzes the occurrence of airborne transmission in the waiting areas of *puskesmas*, a form of primary health care facilities that are distributed in many cities and villages in Indonesia. The study uses computational fluid dynamics (CFD) analysis as a design tool to examine the potential for airborne infection by analyzing the simulated droplet movement in a waiting area layout. The findings of the study identify the distribution of areas where the droplets are likely and unlikely to spread and use this to suggest seating layouts in waiting areas to spatially reduce the potential for airborne infection.

Keywords: Airborne infection; CFD simulation; Droplet movement; *Puskesmas;* Spatial layout

1. HEALTH CARE FACILITY AND AIRBORNE INFECTION CONTROL

Health care facilities have been directly contributing both to the process of healing and transmitting diseases. The performance of health care facilities is closely related to their design (Johanes et al., 2015). Facility design, which includes spatial layout, material, and overall environment, plays a vital role in determining the performance of health care facilities, which is always aimed at the prevention of disease transmission and promoting a healing environment.

This paper addresses the contribution of the spatial layout of health care facilities to the transmission or control of health care-associated airborne infections. Many diseases are airborne-transmitted. Patients with a specific condition, such as infectious pulmonary disease, could become potential sources of infection by producing infectious droplets through coughing, talking, or sneezing (Memarzadeh et al., 2000; Gupta et al., 2009; VanSciver et al., 2011). As a result of a complicated process of interaction between pathogens and the environment (Jacob et al., 2013), an airborne transmitted pathogen, as indicated by several epidemiological and simulation studies, has the ability to spread in various distances and settings within health care facilities (Wong et al., 2004; Tang et al., 2006; Blachere et al., 2009).

Certain spaces in a hospital, such as patient and procedural rooms, are pressurized to control the airflow, thus limiting the potential for airborne infection (Ninomura & Bartley, 2001).

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Meanwhile, other spaces are overlooked, including spaces that are used publicly such as waiting rooms, where sick and healthy people gather, stay, and make contact both directly and indirectly. This paper discusses how airflow performs in waiting areas in a type of health care facility in Indonesia, *pusat kesehatan masyarakat* (*puskesmas*). The Ministry of Health of the Republic of Indonesia recorded that as of 2016 there were 9,767 *puskesmas* — 3,411 of them units with inpatient facilities — in Indonesia (Kurniawan et al., 2017). *Puskesmas* cater for large numbers of patients and non-patients. The interactions among users may potentially cause the spread of diseases. Therefore, *puskesmas* spaces might cause healthy people to become infected and sick people to become even sicker. A study to understand the potential for airborne infection in *puskesmas* is needed to identify preventive actions to reduce the potential for infection, especially through spatial design.

Many studies regarding health care facility-associated airborne infections have suggested that airborne infection could be influenced by many factors, such as spatial arrangement of the building, ventilation system, airflow conditions, air temperature and humidity, material, human body movement, and the movement of architectural features such as doors (Memarzadeh & Xu, 2011; Wang & Chow, 2015; Mousavi & Grosskopf, 2016). These studies, however, were unable to explain how airborne pathogens are actually transmitted. A pathogen's range of travel or how airflow-related factors influence the movement of a pathogen in the air does not necessarily inform us of the pattern of airborne transmission in space. Some simulation studies used computational fluid dynamics (CFD) (Tung & Hu, 2008) to analyze airborne transmission in several health care settings. The studies explain how the airflow occurs but not how the pathogens actually travel.

The infection potential and the spreading movements of pathogens within health care settings are the basis for the present study. As health care facility design should be based on evidence (Johanes & Atmodiwirjo, 2015), this study aims to collect evidence by using CFD simulation to trace the distribution of pathogens and their movement patterns. Consequently, the result of the simulation study and analysis have the potential to contribute to design considerations. In particular, this study can be used as a reference for redesigning the seating arrangements in the waiting areas of the observed *puskesmas*, hence contributing to the prevention of health care facility-associated airborne infections.

2. THE USE OF CFD: FROM SIMULATING PATHOGEN MOVEMENT TO EVALUATING SPATIAL LAYOUT

The use of computation in architecture presents the possibility for simulations that could resemble complex environments such as health care facilities (Johanes et al., 2015) and analyze their performance. The use of CFD for architecture especially presents a novel and promising opportunity to discover the conditions of our surroundings (Addington, 2017). In general, CFD simulation can analyze the nature of airflow in certain contexts (Ramdlan et al., 2016). It could generate an accurate prediction of airflow patterns (Yu et al., 2004), and thus becomes an appropriate tool for simulating the pattern of air movement in certain spaces. CFD airflow modeling has been used to perform analyses of airflow patterns and substantial dispersion (Memarzadeh et al., 2000), to predict the diffusion of an airborne contaminant in a space (Xing et al., 2001), and to model a hospital ventilation system (Qian et al., 2010; Colquhoun & Partridge, 2003). The above range of CFD utilization has been made possible because CFD has the capacity to produce various forms of simulation representation.

CFD simulation has the capability to visually present the simulation result by illustrating the details of distribution in the space and the effects of each parameter involved in the simulation (Memarzadeh wt al., 2000). In this study, the simulation representation of particle movement in the air could be useful for studying the potential for airborne infection. If the simulated particle is assumed to be an infectious droplet, the simulation result, through further analysis, would benefit us by providing the potential indication of infection in space.

Furthermore, this indication is closely related to the environmental and engineering control necessary for preventing airborne infection (Atkinson et al., 2009). Environmental and engineering control strategies deal primarily with the physical aspects of a health care building that relate to the health care activities inside the building. These strategies include designing a layout and using technology that could support infection control inside the building. While infection control could be achieved primarily through the use of technology, such as by increasing air changes per hour or employing a specific ventilation system (Fernstrom & Goldblatt, 2013), thoroughly considered building layouts could also contribute substantially to the control of airborne infection. Retrospectively, this is the area in which the indication of the potential for infection that resulted from the CFD's droplet movement simulation could contribute to airborne infection control. Through droplet movement simulation, one would be able to suggest a building layout that could prevent the occurrence of airborne infection within the building.

3. METHOD OF STUDY

The study was conducted in two *puskesmas* located in North Jakarta and Bogor, respectively. For the purpose of the study, the *puskesmas* will be coded as *Puskesmas* A and *Puskesmas* B, and the study focuses on the waiting areas of both *puskesmas*. The digital models of the waiting areas of both *puskesmas* were based on the measurement of space that included the observed relevant architectural elements in each waiting area, such as doors, windows, fans, and air conditioners (see Figure 1).

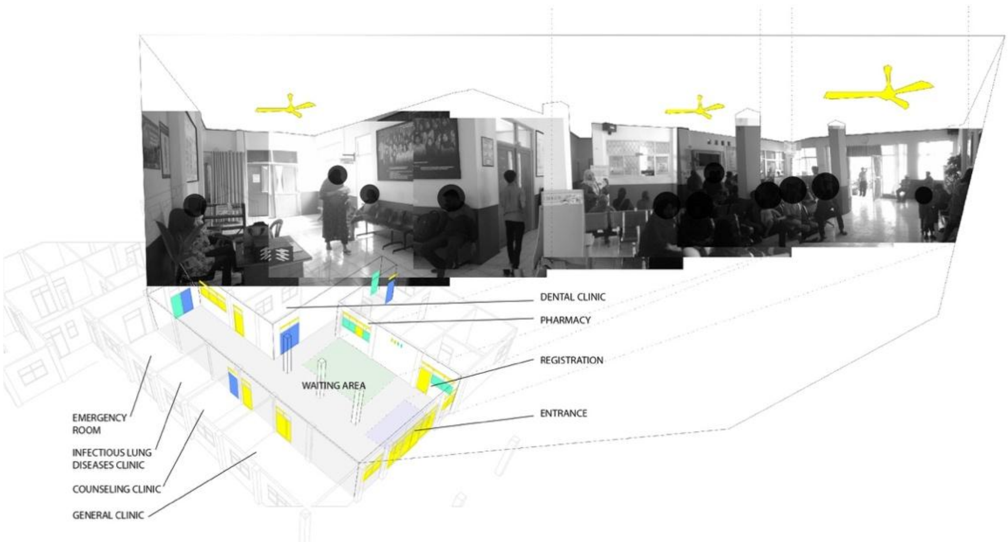

Figure 1 The diagram of existing conditions of *Puskesmas* A waiting area

To obtain overall illustrations of how airborne infection could potentially occur within the spatial arrangements of *Puskesmas* A and *Puskesmas* B, the observed waiting areas of each *puskesmas* were divided into 11 and 13 zones, respectively (see Figure 2). The divisions of the zones were based on the grid indicated by the existing architectural elements, such as columns and walls. The pathogens that are represented with droplet samples were located in the middle of each zone at the height of 85 cm from the floor level, representing the height of a person's mouth and nose while sitting. In this preliminary study, the characteristics of the droplets, such as size, weight, and relative span to remain contaminated, are not considered in the analysis.

Figure 2 The zones within *Puskesmas* A (left) and *Puskesmas* B (right)

For the simulation, Autodesk CFD was used and the models of the waiting areas of both *Puskesmas* A and B were given several assumptions of environmental condition: Outdoor temperature is 31°C, indoor temperature is 30°C, air pressure is 1 atm, and internal fan velocity is 390 m^2/min. To approximate the real condition of the waiting areas, the CFD analysis for each observed waiting area was conducted under three different space conditions with regard to their respective existing architectural elements, which were apertures (doors and windows) and fan or air conditioner. The first condition was when the fan/air conditioner was on and the apertures were opened. The second condition was when the fan/air conditioner was on and the apertures were closed. The third condition was when the fan/air conditioner was off and the apertures were opened. The three conditions represent the conditions that could possibly occur in the *puskesmas* waiting areas. Thus, by simulating the three conditions, it is possible to analyze the potential occurrence of airborne infection in the everyday use of the waiting areas.

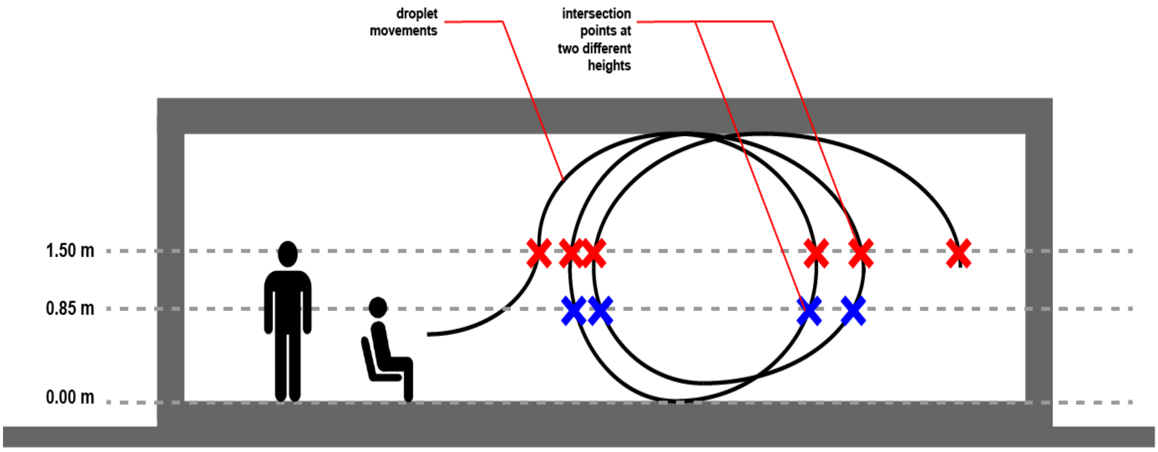

Figure 3 Illustration of the virtual horizontal planes at two different heights

The CFD simulations were performed in 100 iterations to simulate the movement of the droplets in each location and in each condition, resulting in the pattern of movement of the droplets. The pattern of movement showed how the droplets were distributed within the space. To count and map the distribution of the droplets, virtual horizontal planes were positioned at two different heights that were 150 cm and 85 cm from the floor, representing the approximate heights of the position of the mouth and/or nose of a person while standing and sitting (see Figure 3). Every time the path of the droplets intersects with either of the heights, the intersection points were marked, mapped, and counted. The purpose of the counting was to identify the possibility of interaction with the particle carrying the infectious substance while a person is standing or sitting. The result of the droplets count will be marked and mapped within the floorplan drawing and layered with the seating layout. Figure 4 shows an example of the map and the sum of the intersection points of the droplet path from one zone, indicating which zone of the space contributed less to airborne infection and which contributed more to airborne infection. These findings could become the basis for the rearrangement of the spatial layout of waiting areas in future research.

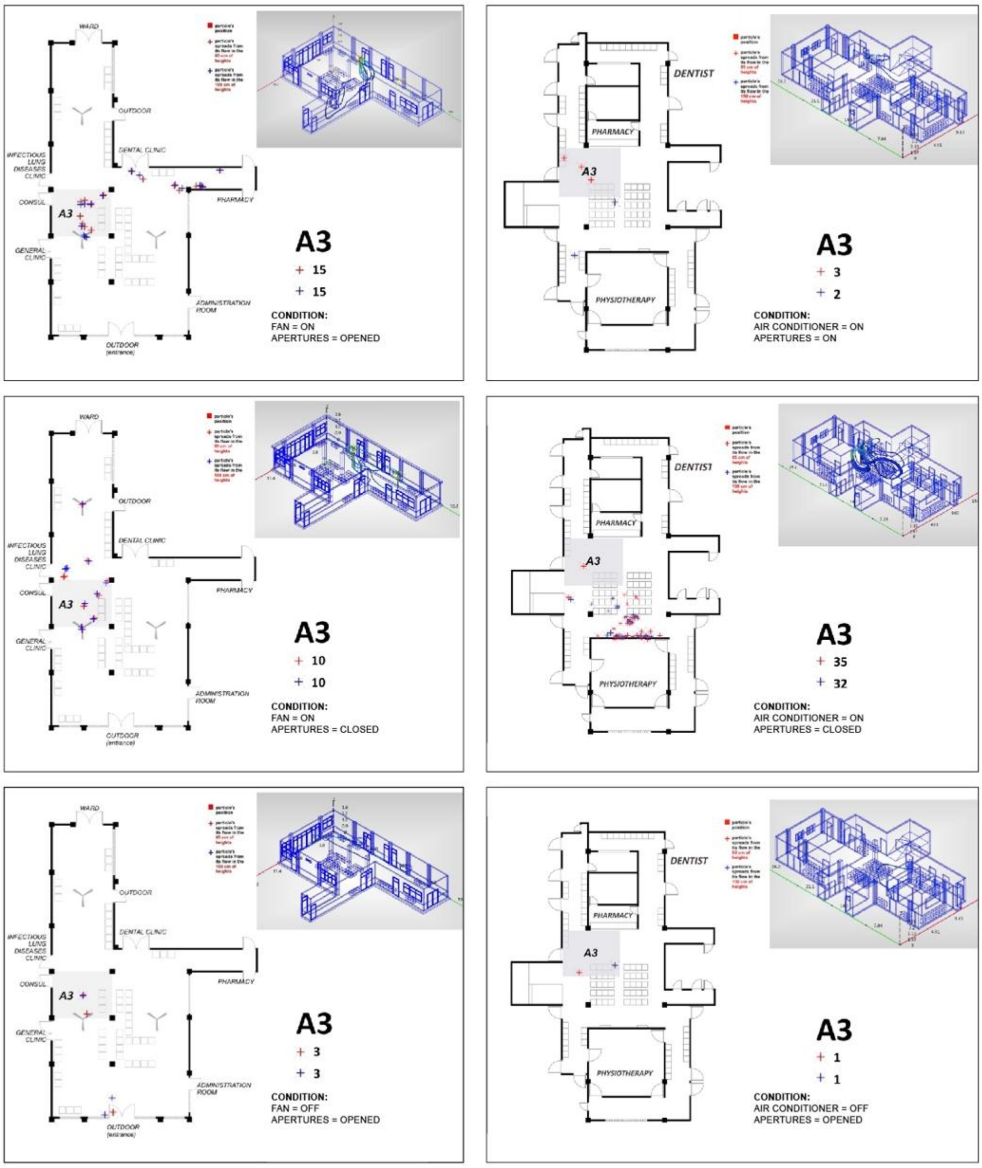

Figure 4 Intersection points in each simulation condition in zone A3 at *Puskesmas A* (three on the left) and *Puskesmas B* (three on the right)

4. FINDINGS

4.1. Architectural Elements and Droplet Movement

The CFD simulations of the waiting areas for both *puskesmas* with three different conditions indicate how the architectural elements within the waiting areas affected the movement of the droplets. Generally, the simulated droplet movement within the observed *puskesmas*' waiting areas in all three simulation conditions shows a certain pattern, which apparently indicates the effect of architectural elements on the movements of the droplets.

For example, the two types of air conditioner in *Puskesmas* A and B, which were hanging internal fan and standing air conditioner, both seem to create a vertically circular pattern of droplet movement around them when they are turned on. This circular pattern shows what would happen when one produces an infectious droplet at the exact sample spot and its possible transmission occurrence. Figure 5 (left) shows how the hanging internal fan in *Puskesmas* A, the presence of which is intended to provide a comfortable environment for those in the waiting area, undermines the very purpose of *puskesmas*, which is to provide a health care service. Not only does the vertically circular pattern of the droplet movement cause the droplet to move around in a particular area close to the air conditioner, but these objects tend to increase the intensity of the flow within the area as the vertically circular patterns are repeated. Both of these implications may increase the possibility of infection in the waiting areas.

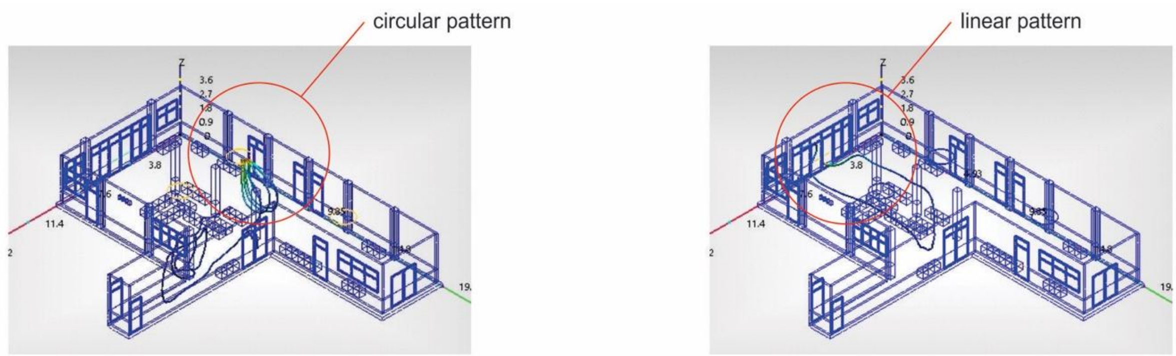

Figure 5 Circular and linear pattern at *Puskesmas* A waiting area

Conversely, architectural elements such as apertures, both window and door, in the observed waiting areas influence the droplet movements differently. A linear movement is more likely to occur with a droplet that is moving toward apertures that are opened. This compromises a movement that transfers the droplet to the outside environment of the waiting area. This linear droplet movement not only reduces the span of the droplet movement within the waiting area, but also decreases the area of the movement as well. Accordingly, it is argued that existing apertures are a significant architectural element that could reduce the potential for infection within the waiting area.

4.2 Evaluation of Layout based on Droplet Counts

Figure 6 shows the final results of the mapping and counting of the CFD simulations in *Puskesmas* A and *Puskesmas* B in three different conditions. Even though the results from both *puskesmas* produced different numbers, the overall comparison of the three simulations suggests similar situations. In both *puskesmas*, the highest amount of droplet distribution is shown in Simulation 2 with the condition of the fans/air conditioners on and the apertures closed. Simulation 1, when the fans/air conditioners are on and the apertures are opened, shows less droplet distribution compared with Simulation 2. Simulation 3, when the fans/air conditioners are off and the apertures are opened, however, shows the lowest amount of droplet distribution among the three simulations. These readings reflect the findings from the previous stage in which the existence of a fan/air conditioner might increase the distribution of the droplets, while the opening and closing of the apertures might decrease the distribution of the droplets. These results imply the potential of the location of architectural elements to increase or decrease the possibility of airborne infection.

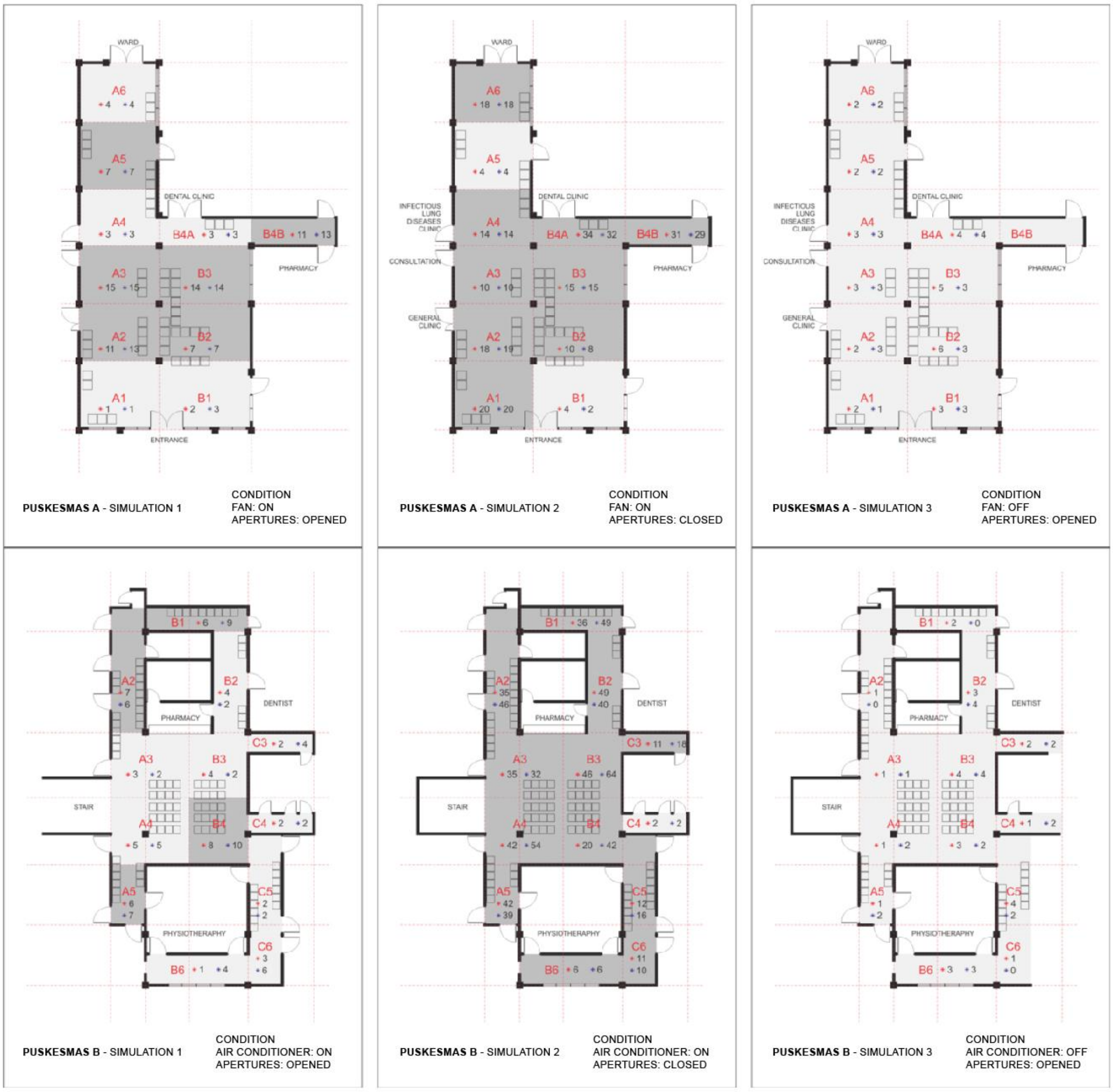

Figure 6 The intersection point counts and infection potential indication of each simulation scenario in *Puskesmas A* (upper three) and *Puskesmas* B (bottom three)

Figure 6 shows the distribution of the droplets throughout the waiting areas. The zones with darker values represent a higher number of droplet traces, which indicates the zone with a higher potential contribution to airborne infection. The zones with lighter values represent a lower number of droplet traces, which indicates the zone with a lower potential contribution to airborne infection. Figure 7 summarizes the findings from the three simulations in Figure 6, which were then used to evaluate the layouts of the seating areas. The summing was done by taking the dominant condition of each zone. For example, if one zone is dark in Simulations 1 and 2 and light in Simulation 3, this zone will be considered dark because it is more likely to happen in the three simulations.

Figure 7 The sum of potential infection indication from the three simulation conditions in *Puskesmas* A (left) and *Puskesmas* B (right)

The final results of the simulation of *Puskesmas* A show that the current seating area in the existing layout is overlapped with the dark zones, such as zones A2, A3, B2, and B3. This indicates that most of the seating area is located in the zone with a high number of droplet traces, which is considered to have a higher potential for airborne infection. The final results of the simulation of *Puskesmas* B also show that the current seating area in the existing layout is overlapped with the dark zones, such as B4, A5, A2, and B1. This indicates that some seating areas are located in the zone with a higher potential for airborne infection. These dark zones within the layout should be avoided for locating seating in the waiting room. Meanwhile, the light zones could be suitable spaces for seating because, based on the simulation, these zones have less potential to contribute to airborne infection. This finding could be used as a basis for a reconfiguration of the spatial layout of the waiting areas that promotes the prevention of health care facility-related airborne infection.

5. CONCLUSION

The analysis of airborne infection using CFD analysis was performed by simulating the movement of droplets in the air and by calculating the traces of droplets at heights relevant to the human body while standing and sitting. From the tracing of the droplet movement, it is revealed that there is a significant influence of airflow-related spatial objects, such as internal fan, air conditioner, and apertures, on the droplet movement pattern. Moreover, further analysis of droplet movement simulation reveals the potential for each sample location to become the origin point from which a droplet of infectious disease might spread to other parts of the space and results in the zoning of the airborne infection contribution from each part of the space. These findings could be considered as an evaluation of the spatial performance of the simulated *puskesmas* waiting areas in relation to airborne infection control. The overall findings of this study can form the basis for a reconfiguration of the seating arrangements in the *puskesmas* waiting areas that promotes the prevention of health care facility-related airborne infection.

There are, however, some limitations in this study. The study only simulates the path of droplet movement, without considering the detailed characteristics of the particle, such as the size of the particle, the duration that particles can remain airborne, the distance that particles can travel, etc. These aerobiological factors should be considered in further research, thus obtaining more detailed information on the occurrence of airborne infection. Further research should also consider the possibility of a different kind of spatial intervention besides the arrangement of seats and should include other variables related to the architectural elements, such as the position of the internal fan and the exhaust fan, the arrangement of window openings, etc. By discovering how these elements contribute to the movement of particles in the air, more information will be gained as a basis for designing a layout for waiting areas that could minimize the occurrence of airborne infection.

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