SIMULATION-BASED APPROACH TO ENHANCING INDOOR AIR QUALITY FOR HEALTHIER HEALTHCARE ENVIRONMENTS IN PUSKESMAS GONDOMANAN

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ABSTRACT: *Indoor air quality (IAQ) is a critical aspect of healthcare facilities, affecting the health and well-being of patients and staff. This study focuses on Puskesmas Gondomanan in Yogyakarta, Indonesia, which faces significant IAQ challenges due to the region's tropical climate and prevalent air pollution. Despite some improvements in outdoor air quality, indoor pollutant levels can be substantially higher, posing health risks, particularly to vulnerable populations. This research aims to assess the effectiveness of IAQ improvement strategies, including ventilation optimization, air purification, and building modifications, using computational fluid dynamics (CFD) simulations and building performance modeling. The study evaluates whether the current IAQ control measures at Puskesmas Gondomanan meet the minimum standards for health facilities and identifies the most effective strategies for enhancing indoor environmental quality. The findings from this research are intended to inform policymakers, healthcare administrators, and building professionals in implementing measures to create healthier indoor environments and improve the quality of care in Puskesmas facilities.*

Keywords: *Air Pollutant, Building Simulation, Computational Fluid Dynamics, Gondomanan, Indoor Air Quality*

INTRODUCTION

Background

Indoor air quality (IAQ) is an important parameter in healthcare facilities, where patients and staff spend significant time in indoor spaces. In Indonesia, primary health centers (Puskesmas) play a vital role in delivering essential healthcare services to communities. However, ensuring optimal IAQ in these facilities faces significant challenges, particularly in regions like Kota Yogyakarta, characterized by tropical climates and common air pollution. Among these centers, Puskesmas Gondomanan stands as a critical healthcare hub, serving a substantial population. The quality of indoor air within such facilities directly impacts the health and well-being of occupants, including patients seeking medical care and healthcare workers providing essential services. Despite the recognized importance of IAQ, existing ventilation systems and pollutant control measures in Puskesmas facilities may not always meet the minimum standards, leading to potential health risks and discomfort for occupants.

The Yogyakarta City Environmental Service (DLH) recorded air quality in Yogyakarta City from June to August 2023 in the Air Pollution Standard Index (ISPU) below 50 in the good-moderate category. The increase in air quality to the good-moderate category approximately was due to the dry season. Factors such as burning rubbish, increased dust, and rising transportation activities contribute to air pollution (Dewani, 2023). The improvement in air quality, particularly in the PM2.5 category (particles equal to 2.5 μm or smaller), was significant during this period. Other parameters, including PM10, SO2, CO, O3, NO2, and hydrocarbons (HC), remained in the good category. However, poor air quality can worsen health conditions, especially for vulnerable groups like the elderly, pregnant or nursing women, and children. Especially because indoor pollutant levels can be up to five times, or even 100 times, higher than outside pollutant levels, giving rise to significant concern as the average person typically spends about 90% of their time indoors (Ibrahim, F., 2022).

Therefore, addressing IAQ issues in healthcare settings needs a multifaceted approach that considers the unique environmental conditions, building configurations, and operational requirements of each facility. This research uses computational fluid dynamics (CFD) simulations to assess indoor air quality (IAQ) control measures at Puskesmas Gondomanan. Traditional methods for assessing and improving IAQ often rely on simple models or data, which may not be suitable to capture the complex factors influencing indoor air dynamics. Computational fluid dynamics (CFD) simulations offer a promising method to gain deeper insights into airflow patterns, pollutant dispersion dynamics, and thermal comfort levels in indoor environments. CFD employs numerical methods to analyze fluid flows, involving millions of calculations to simulate interactions of air and surfaces under specific conditions. CFD is particularly useful in healthcare for analyzing air movement and contaminant distribution in environments where direct sampling is challenging (R. Yam, 2011).

By using advanced simulation techniques, researchers can analyze the effectiveness of various IAQ improvement strategies and optimize ventilation systems to enhance indoor environmental quality. Accurate CFD simulations, especially those analyzing the combined effects of outdoor and indoor air flows, are essential for designing natural ventilation strategies, with sensitivity analyses ensuring reliable results (R. Ramponi, 2012). The findings from this research help to inform policymakers, healthcare administrators, and building professionals in implementing measures to create healthier indoor environments and enhance the quality of care provided in Puskesmas facilities.

Problem Statement

1. What are the specific indoor air quality (IAQ) challenges faced by Puskesmas Gondomanan in Yogyakarta due to its tropical climate and common air pollution in the region?
2. Do the Puskesmas Gondomanan building analysis results from computational fluid dynamics (CFD) simulations and building performance modeling meet the minimum requirements of the indoor air quality (IAQ) standards for health facilities in Yogyakarta?
3. What are the most effective IAQ improvement strategies, such as ventilation optimization, air purification, and targeted building modifications, that can be recommended for enhancing the quality of care in Puskesmas Gondomanan based on simulation insights?

Research Purpose

1. Assessing the effectiveness of IAQ improvement strategies, including ventilation optimization, air purification, and building modifications, in Puskesmas Gondomanan.
2. Utilizing computational fluid dynamics (CFD) simulations and building performance modeling to provide insights and recommendations for creating healthier indoor environments.
3. Enhancing the quality of care provided to patients and staff by improving IAQ within the healthcare facility.

Research Boundaries

1. Focus only on Puskesmas Gondomanan in Yogyakarta, without extending to other healthcare facilities or regions.
2. Limited scale to CFD simulations and building performance modeling, excluding experimental validation or on-site implementation of recommended measures.
3. Exclusion of broader environmental factors or external sources of pollution beyond the indoor environment of the healthcare facility.

LITERATURE REVIEW

Impact of indoor environmental quality (IEQ) factors on occupants' environmental perception and satisfaction in hospital wards

The hospital ward's environment significantly influences the health and well-being of its occupants, particularly patients (Q. Wu, 2023). This study investigated the impact of various environmental factors (thermal, acoustic, luminous, and indoor air quality - IAQ) alongside self-reported health conditions on occupants' subjective environmental perception and satisfaction within hospital wards. Conducted during winter in a large general hospital in Changsha, China, the study involved a field survey of 156 occupants, including patients and visitors, utilizing a combination of environmental measurements, questionnaires, and interviews. Results indicated a comprehensive influence of environmental factors on occupants' perceptions, with lower air temperatures enhancing acoustic perception, reduced noise levels positively affecting IAQ perception, and lower CO2 concentrations improving thermal perception in warmer environments (Q. Wu, 2023).

The study also revealed significant impacts of occupants' health conditions on environmental perception, with acoustic, IAQ, and luminous perceptions notably affected. Those with poorer health conditions reported noisier acoustic environments, worse IAQ perceptions, and lower overall environmental satisfaction. Acceptable environmental thresholds varied among individuals with different health conditions, with stringent requirements observed for those categorized as "very weak" or "weak" (N. Li, 2023).

The study highlighted the significance of sound pressure levels in influencing overall ward satisfaction, emphasizing the need for low-noise environments with effective sound insulation to enhance occupants' overall satisfaction. Additionally, poor indoor air quality emerged as having the most significant negative impact on overall satisfaction, underscoring the importance of addressing IAQ concerns in hospital wards.

Hospital indoor air quality and its relationships with building design, building operation, and occupant-related factors

Indoor air quality (IAQ) in hospitals has become increasingly important in light of concerns about airborne transmission of respiratory diseases, particularly in the context of the COVID-19 pandemic (F. Ibrahim, 2022). Understanding the determinants of IAQ in hospital environments is crucial for developing effective strategies to improve it. This mini-review synthesizes existing literature to explore the relationships between hospital IAQ and various factors related to building design, building operation, and occupant behavior.

Studies have identified numerous aspects of building design that influence IAQ in hospitals. Factors such as space dimensions, ventilation system design, and building materials have been shown to impact IAQ. For instance, inadequate ceiling height can result in substandard airflow rates, while room configurations and ventilation practices can affect microbial diversity and composition (F. Ibrahim, 2022). Moreover, the choice of construction and finishing materials, as well as furnishings, can introduce pollutants such as volatile organic compounds (VOCs) and contribute to indoor air contamination (F. Ibrahim, 2022).

Building operation practices play a significant role in maintaining IAQ within hospitals. Proper ventilation system operation and maintenance are crucial for controlling air-exchange rates, contaminants, and occupant comfort levels. However, poorly maintained ventilation systems and inadequate cleaning practices can lead to increased indoor pollutant levels, facilitating the transmission of infectious pathogens (F. Ibrahim, 2022). Access control measures for personnel, patients, and visitors also influence IAQ by impacting building occupancy density, which in turn affects indoor air quality levels.

Rethinking Hospital General Ward Ventilation Design Using Computational Fluid Dynamics

Effective indoor ventilation is crucial for controlling airborne infections in hospitals. The research explores how ventilation can prevent and control infections in general hospital wards, proposing a cost-effective design to reduce cross-infection risks. Using Computational Fluid Dynamics (CFD) analysis, the study compares various ventilation systems' effectiveness in removing microbes.

Instead of the traditional corridor air return system, the proposed design controls ventilation within the ward cubicle. CFD results show that this approach significantly improves air ventilation rates and microbial removal, matching the performance of isolation rooms but at a lower cost (P. L. Yuen, 2011). The new ventilation parameters are recommended for new hospital ward designs and can also be retrofitted into existing wards with minimal disruption and cost.

Good ventilation reduces the spread of airborne diseases like measles, tuberculosis, and SARS in hospitals. The study used CFD to simulate different ventilation systems, focusing on improving air quality and reducing infection risks in hospital wards. Instead of the conventional corridor air return, the new design uses a ducted return strategy from within the ward cubicle, enhancing air change efficiency and microbial removal (P. L. Yuen, 2011).

The proposed design offers a cost-effective alternative to constructing isolation rooms, with the potential for retrofitting existing wards. The study suggests adopting the new ventilation design widely in hospital general wards to minimize cross-infection. This approach not only improves patient and staff safety but also provides a practical solution for enhancing hospital ventilation systems without extensive renovations (P. L. Yuen, 2011).

CFD Simulation of Cross-Ventilation for a Generic Isolated Building: Impact of Computational Parameters

Accurate Computational Fluid Dynamics (CFD) simulations are crucial for designing effective natural cross-ventilation strategies in buildings. These simulations are highly sensitive to various computational parameters set by the user. This study conducted by Ramponi, shows a comprehensive sensitivity analysis to evaluate how different computational parameters affect simulation results, providing guidance for future CFD studies.

Using a series of 3D steady RANS simulations for a generic isolated building, the study validated results through wind tunnel experiments with Particle Image Velocimetry (PIV). The parameters tested included the size of the computational domain, grid resolution, turbulence model, inlet turbulent kinetic energy profile, discretization schemes, and iterative convergence criteria.

The study found that the inlet turbulent kinetic energy profile significantly impacts simulation results. This large effect has not been widely reported before and highlights the lack of consensus on how to calculate this profile from mean wind speed and turbulence intensity (B. Blocken, 2012). The SST k–ω turbulence model performed best, while other models could not accurately reproduce key flow features (B. Blocken, 2012).

Simulations showed oscillatory convergence due to the intrinsically unsteady nature of the flow, which is forced into a steady solution by the RANS approach (B. Blocken, 2012). This necessitates careful result extraction from such simulations. The study confirmed that second-order accurate discretization schemes and stringent convergence criteria are essential for accurate results.

RESEARCH METHOD

This research employs 2 methods, Computational Fluid Dynamics (CFD) simulation (Air Velocity and Air Flow Pattern) and Air Changes per Hour (Ac/H) calculation. Using CFD software, a virtual model of the indoor environment is constructed, incorporating detailed geometric information and assumptions about airflow patterns and pollutant dispersion. A computational mesh discretizes the space into smaller control volumes, which is crucial for solving fluid flow and heat transfer equations. Mesh quality is ensured by refining areas with high gradients of velocity, temperature, or pollutant concentration. The CFD simulation, performed three times with air velocities of 1 m/s, 4.2 m/s, and 7 m/s, illustrates air movement based on average yearly air velocity in Yogyakarta (Meteorology, Climatology, and Geophysics Agency D.I. Yogyakarta, 2019). The Ac/H calculation is used to determine if Puskesmas Gondomanan indoor environment meets the standards set by SNI 03-6572-2001, which specifies a minimum of 3 air changes per hour for public areas (BSN, 2003). This calculation helps assess whether the Puskesmas ventilation is adequate according to these guidelines.

CFM x 60 / Room Volume

Minimum air changes per hour for public area: 3
Standard air conditioning CFM: 350-400

RESULT



Fig 1. Building Floor Plan



Fig 2. Waiting Area



Fig 3. Waiting Area



Fig 4. Lobby Area



Fig 5. Children Playground



Fig 6. 1st Floor Plan

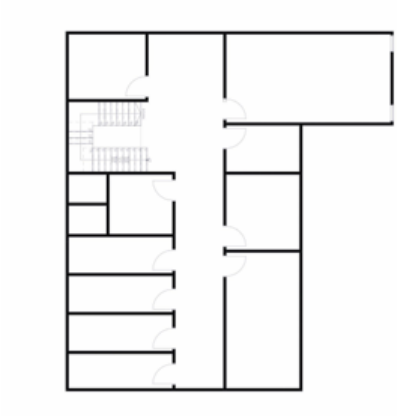


Fig 7. 2nd Floor Plan

Computational Fluid Dynamics (CFD) Indoor Air Velocity Simulation

Based on the CFD simulation, it was observed that when the outdoor air velocity was 1 m/s, the indoor airflow in Puskesmas Gondomanan ranged from 0 to 1.2 m/s in the lobby area and near large openings. However, in the interior rooms, the indoor airflow mostly ranged from 0 to 0.6 m/s, indicating a lack of sufficient air exchange. The airflow predominantly circulated around the large openings and failed to penetrate deeper into the interior rooms. This suggests that at a lower outdoor air velocity, the indoor environment experiences poor air circulation, especially in areas far from openings.

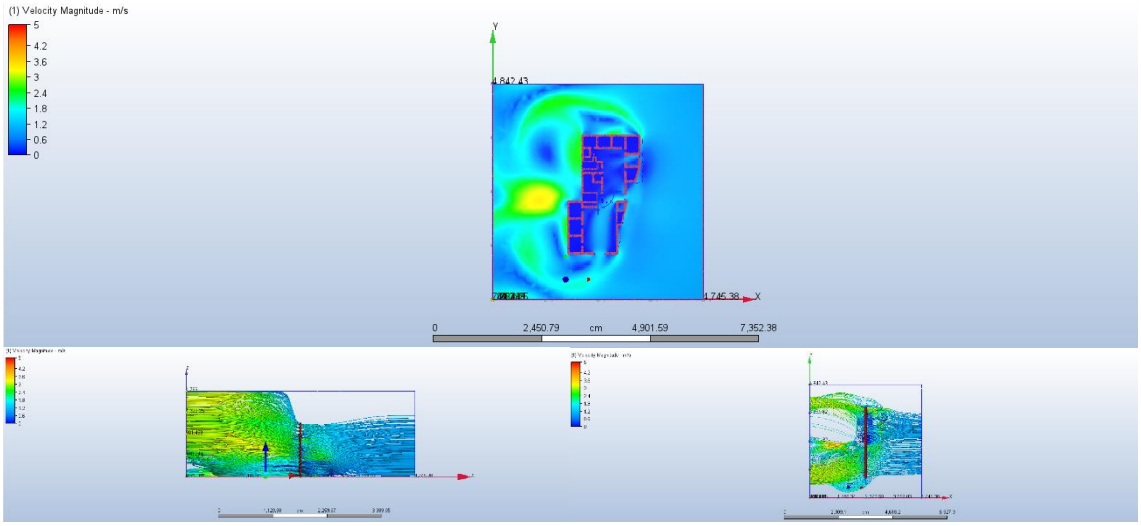


Fig 8. CFD Analysis (1 m/s)

When the outdoor air velocity increased to 4.2 m/s, the indoor airflow showed some improvement. The indoor air velocity rose up to 1.8 m/s, indicating an enhanced air exchange rate. However, the areas that experienced increased airflow were still mainly around the openings, and the air did not flow effectively throughout the entire interior. The airflow within the interior rooms remained stable at 0 to 0.6 m/s. This limitation is likely due to the small size of the ventilation openings in the lobby area, which restricts the distribution of air deeper into the building.

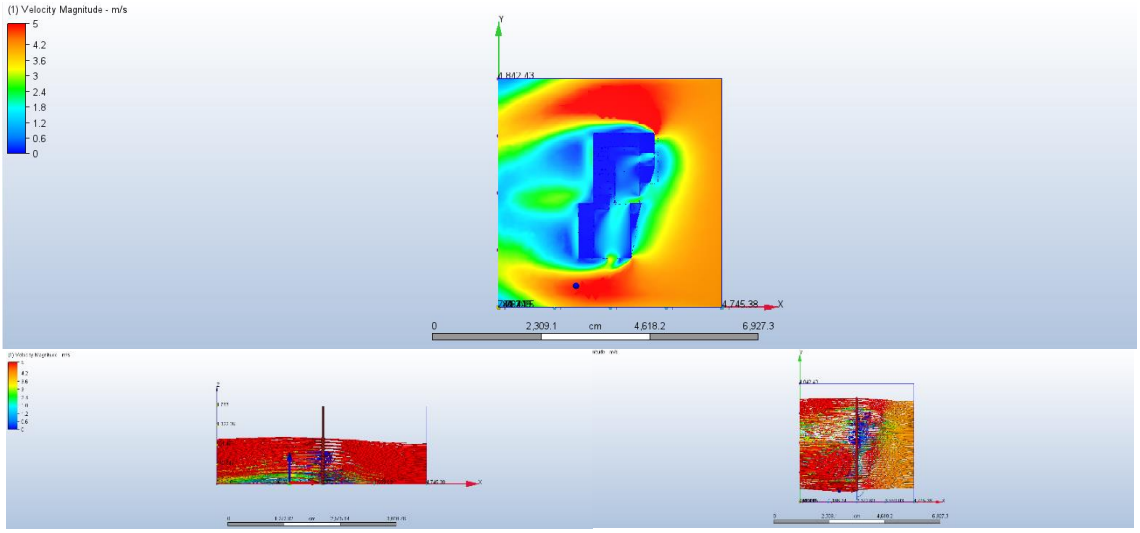


Fig 9. CFD Analysis (4.2 m/s)

In the simulation with the highest outdoor air velocity of 7 m/s, the indoor airflow exhibited the most significant movement. The air exchange rate improved, particularly in the vicinity of the openings and areas that were previously less accessible at lower velocities. The indoor airflow in the lobby area increased to a range of 0.6 to 3 m/s. Some interior rooms also showed improvement, with airflow ranging from 0 to 0.6 m/s. However, this improvement was not consistent across all interior rooms, indicating that even at higher outdoor air velocities, certain areas within the building still experienced insufficient air circulation.

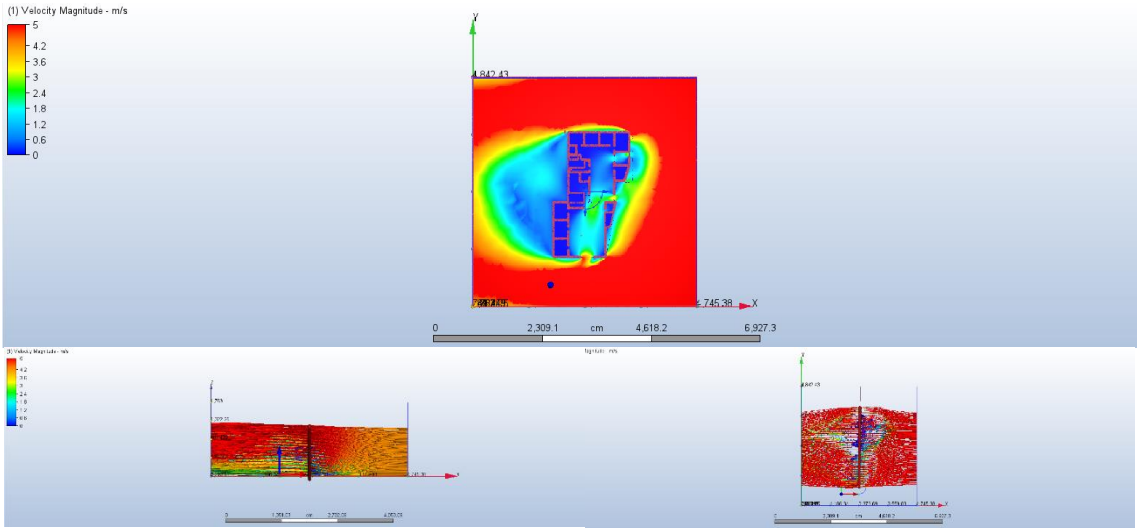


Fig 10. CFD Analysis (7 m/s)

The simulations for Puskesmas Gondomanan at varying outdoor air velocities (1 m/s, 4.2 m/s, and 7 m/s) reveal significant insights into the indoor airflow dynamics. At lower outdoor air velocities, the indoor environment suffers from poor air circulation, particularly in areas away from large openings. As the outdoor air velocity increases, the indoor air exchange rate improves, but the airflow distribution remains limited to regions near the openings. Even at the highest simulated velocity of 7 m/s, certain interior rooms continue to experience inadequate air movement.

Air Changes per Hour (Ac/H) Calculation
ACH= CFM x 60 / Room Volume
= 350 x 60 / 264 (**9323 cubic feet**)
= 21,000 / 9323
= **2.2**

The final calculation of the Air Changes per Hour (Ac/H) for the indoor environment of Puskesmas Gondomanan was determined to be 2.2. This value falls below the standard requirement of 3 Ac/H. The insufficient air exchange rate indicates that the current ventilation system is not meeting the established standards for adequate air circulation. This shortfall can lead to poor indoor air quality, which may negatively affect the health and comfort of the occupants.

Computational Fluid Dynamics (CFD) Indoor Air Flow Simulation

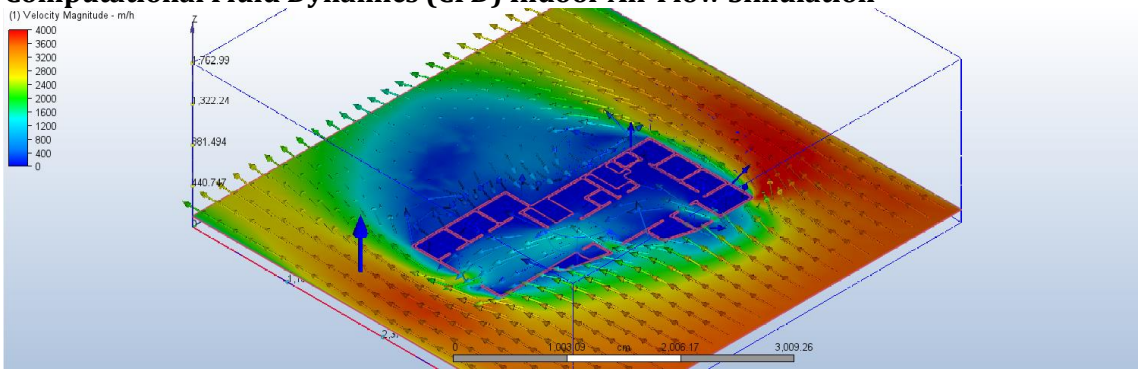


Fig 11. Indoor Air Flow CFD Simulation

In the original layout of the Puskesmas building, which is merged with an adjacent structure, the lack of direct ventilation openings to the outside space resulted in a restricted airflow pattern. The air in the building primarily circulated in the lobby area, leading to stagnant air conditions as it rotated in the same confined space without significant renewal from outside sources.

DISCUSSION
The CFD simulations at Puskesmas Gondomanan revealed crucial insights into the indoor airflow dynamics under varying outdoor air velocities. At an outdoor air velocity of 1 m/s, the indoor airflow ranged from 0 to 1.2 m/s in the lobby area and near large openings, while interior rooms experienced airflow mostly between 0 to 0.6 m/s. This indicates a significant lack of air exchange in areas away from openings, which can lead to stagnant air and poor indoor air quality (IAQ).

As the outdoor air velocity increased to 4.2 m/s, the indoor airflow showed some improvement, with velocities rising up to 1.8 m/s. However, the airflow remained primarily around the openings, and the interior rooms still exhibited limited air movement. This suggests that the current ventilation system's capacity to distribute air throughout the building is insufficient, primarily due to the small size of the ventilation openings.

At the highest simulated outdoor air velocity of 7 m/s, the indoor airflow exhibited the most significant movement. The air exchange rate improved, particularly near the openings and areas previously less accessible at lower velocities. The indoor airflow in the lobby area increased to a range of 0.6 to 3 m/s, and some interior rooms showed slight improvement, with airflow ranging from 0 to 0.6 m/s. However, this improvement was not uniform across all interior rooms, indicating persistent areas of inadequate air circulation even at higher outdoor air velocities.

The Air Changes per Hour (Ac/H) calculation further highlighted the inadequacy of the current ventilation system. With a final Ac/H value of 2.2, the system falls short of the standard requirement of 3 Ac/H. This insufficiency can result in suboptimal IAQ, adversely impacting the health and comfort of patients and staff.

CONCLUSION

This research highlights the challenges faced in improving indoor air quality (IAQ) at Puskesmas Gondomanan in Yogyakarta, Indonesia. Using Computational Fluid Dynamics (CFD) simulations and Air Changes per Hour (Ac/H) calculations, we assessed the effectiveness of existing ventilation systems and explored potential improvements to enhance IAQ.

The simulations revealed that the current ventilation design, characterized by limited openings between interior rooms and the lobby, results in insufficient air exchange rates, particularly at lower outdoor air velocities. Even with increased outdoor air velocities, the airflow distribution remains inadequate, failing to penetrate deeper into the interior rooms. The airflow pattern in the Puskesmas building was highly restricted due to the lack of direct ventilation openings to the outside, primarily causing air to circulate repetitively within the lobby area. This led to stagnant air conditions and poor indoor air quality.

One of the primary problems identified is the structural limitation of the building, which is merged with an adjacent structure, preventing the installation of additional direct ventilation to the outside. This significantly restricts the potential for natural ventilation and underscores the need for alternative strategies. To address these challenges, we recommend implementing mechanical ventilation systems, using air purification units, and modifying the building layout to manage airflow and prevent cross-contamination. These measures can enhance IAQ and create a healthier indoor environment.

RECOMMENDATION

Based on the findings and conclusion from the CFD simulations and Ac/H calculations, several recommendations can be made to enhance the indoor air quality (IAQ) at Puskesmas Gondomanan. The primary focus should be on optimizing the ventilation system to ensure adequate air exchange throughout the facility, especially in the interior rooms.

1. Increase Ventilation Size:

The initial ventilation opening from the interior rooms to the lobby was 70 x 40 cm. The simulation results suggested increasing the size to 70 x 100 cm. However, this adjustment did not yield significant improvement in airflow distribution. The limited effectiveness of this change indicates that merely enlarging internal openings is insufficient to address the IAQ issues.

2. Direct Ventilation to Outdoor Space:

A significant problem found is the lack of direct ventilation from interior rooms to the outside. The current building design, where Puskesmas Gondomanan is merged with an adjacent building, restricts the possibility of adding external ventilation openings. This constraint significantly hampers the ability to achieve adequate natural ventilation and air exchange rates, as the interior rooms rely heavily on airflow through the lobby, which is not sufficient.

Recommendation Simulation: Enlarging Opening Size

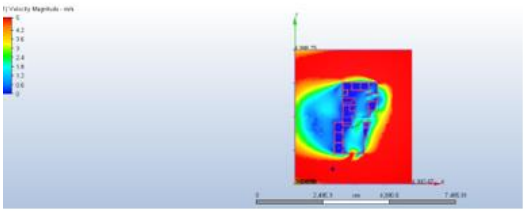


Fig 12. CFD Simulation

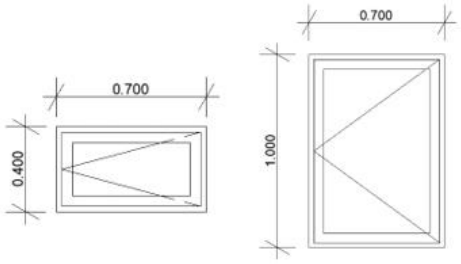


Fig 13. Before (left) and After (right) Size

When examining the effects of ventilation size changes in the Puskesmas Gondomanan, the initial setup featured a ventilation opening measuring 70 x 40 cm between an interior room and the lobby. To enhance airflow, the size of this ventilation opening was increased to 70 x 100 cm. However, subsequent simulations demonstrated that this alteration did not result in a significant improvement in indoor air quality (IAQ).

The lack of noticeable improvement can be attributed to the fact that the building's design inherently restricts effective ventilation. Specifically, the Puskesmas building is physically connected to an adjacent structure, which prevents the installation of additional direct ventilation openings that could facilitate better air exchange with the outside environment.

Recommendation Simulation: Changing Building Layout

The second method is to reverse the floor plan of the Puskesmas building, to position the interior room for direct access to outdoor space and adding additional openings, significantly improved ventilation. CFD simulations showed that this change increased the indoor air velocity in the lobby to 3-3.6 m/s, with some areas reaching 5 m/s, and boosted the interior room's air velocity to 3 m/s, compared to the previous layout's 0-0.6 m/s. This demonstrates that repositioning rooms and adding openings can effectively enhance indoor air quality despite structural constraints.

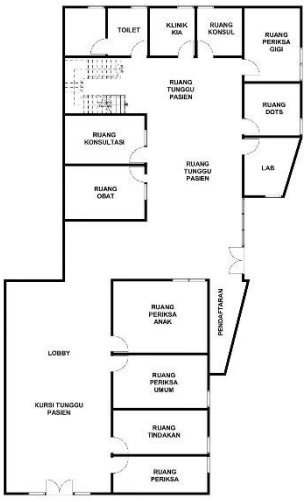


Fig 14. Modified Floor Plan

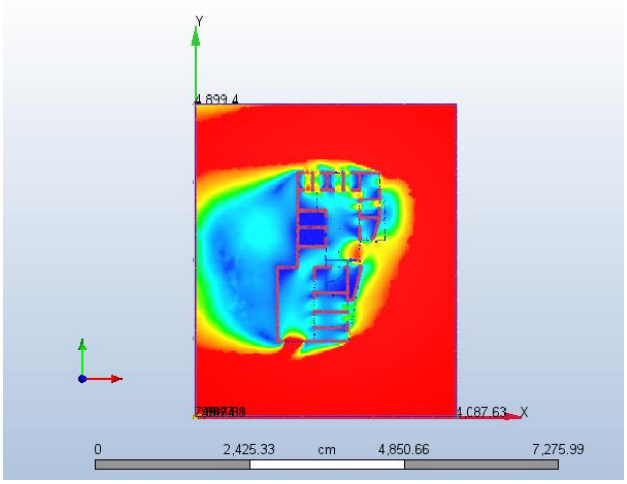


Fig 15. CFD Simulation

In the initial floor plan of the Puskesmas building, the lack of direct ventilation to the outside space caused the airflow to circulate repeatedly within the same area, primarily the lobby, resulting in stagnant air movement. After the floor plan modification, the air now moves more dynamically, expanding from one room to another, rather than being confined to a single area. This broader and more efficient distribution of airflow enhances overall ventilation.

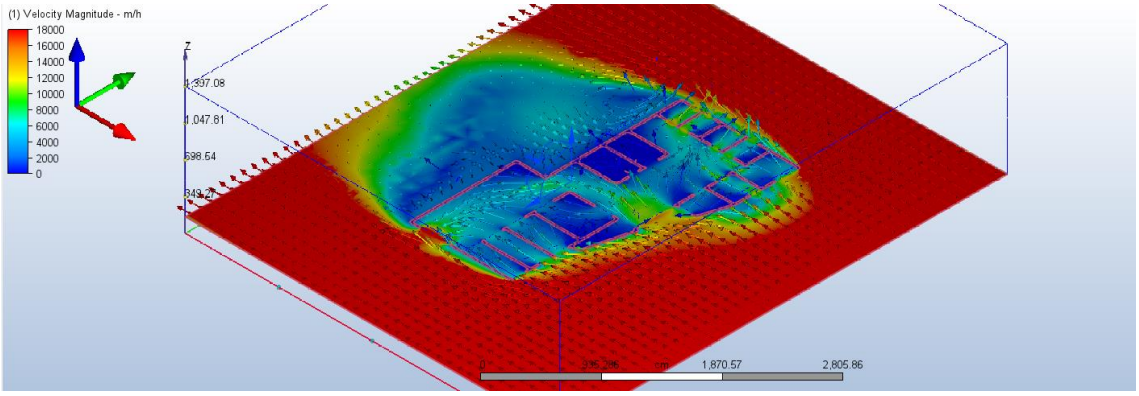


Fig 16. Indoor Air Flow CFD Simulation

Optimizing the ventilation system at Puskesmas Gondomanan is essential for enhancing indoor air quality (IAQ). Increasing the internal ventilation opening size from 70 x 40 cm to 70 x 100 cm did not significantly improve airflow due to the building's structural limitations, particularly its merger with an adjacent structure which restricts additional external ventilation openings.

A more effective solution was reversing the floor plan to give the interior room direct access to outdoor space and adding more openings. CFD simulations showed this change significantly improved air velocity and distribution, reducing stagnant air and enhancing overall IAQ. Therefore, modifying the building layout is a more effective strategy than simply enlarging internal openings, leading to a healthier indoor environment.

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