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Enhancing Workshop Comfort: CFD-Based Analysis of Heating and Cooling Strategies

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Abstract

The escalating awareness of the profound qualitative changes in indoor air, coupled with the surge in pollutants and their recognized health impacts, emphasizes the critical need for well-being, hygiene, and health-conscious indoor spaces. With over 90% of time spent indoors, understanding and addressing indoor air quality (IAQ) has become paramount. This paper explores the pivotal role of Volatile Organic Compounds (VOCs) as major indoor pollutants and advocates for evidence-based insights into building performance. Employing both box-models using the mass balance approach and Computational Fluid Dynamics (CFD) models, the study aims to predict VOC concentrations in indoor environments.

The methodology encompasses environmental sampling, parameter definition for numerical models, simulations utilizing both box-models and CFD, and a comprehensive comparison of results. The findings demonstrate a robust correspondence between the two modeling approaches, underscoring the centrality of ventilation. The paper further proposes a guide value for IAQ-oriented building design, specifically focusing on indoor VOC concentrations originating from building materials. The discussion delves into the relationship between regulatory limits on emissivity of materials and Indoor Air Guide Values, offering valuable insights for designing healthier indoor environments.

Keywords: Design and health; materials; interior design; VOC; wellbeing; health; IAQ; box-model; CFD; building design.

1. Introduction

The imperative to regulate exposure levels to Volatile Organic Compounds (VOCs) has led international organizations, notably the World Health Organization (WHO), to establish Indoor Air Guide Values (IAGVs) for various pollutants of health and hygiene concern. The WHO guidelines for the European Region include specific recommendations for pollutants such as benzene, nitrogen dioxide, polycyclic aromatic hydrocarbons, naphthalene, carbon monoxide, radon, trichloroethylene, and tetrachlorethylene. While many countries, in line with WHO, set guide values for individual substances, only a few (e.g., Portugal, The Netherlands, Belgium) define an acceptability limit for Total VOCs (TVOC).

In Italy, there is no specific standard aligning with WHO guidelines, but the Minimum Environmental Criteria (Criteri Ambientali Minimi—CAM) for construction, established by the Ministerial Decree of October 11, 2017, identifies emission limits for materials without specifying indoor concentration limitations. The reduction of health risks associated with indoor air quality (IAQ) is emphasized by entities like the United States Environmental Protection Agency (EPA), highlighting the importance of better building design, construction, operation, and product development to mitigate exposures. Over the years, the concept of "Healthy Buildings" has evolved, encompassing factors beyond IAQ, such as ventilation, thermo-hygrometric comfort, lighting, and safety. The design and construction choices, along with material eco-compatibility, are crucial for creating buildings that contribute positively to occupants' health. Evidence-based design, involving systematic research and contemporary findings, becomes essential for enhancing environmental and technological quality in projects.

Numerical modeling, despite its original purposes, has become integral to IAQ studies, serving as an evidence-based design tool. Two main types of models are employed: box-models, which estimate concentration based on pollutant mass balance in confined spaces, and Computational Fluid Dynamics (CFD) models, which simulate spatial distributions in 2D and 3D. Both model types consider VOC sources, usually represented by imposing mass flow rates at volume-environment interfaces. This paper details the application of both box-models and CFD models in estimating indoor VOC concentrations from building materials, focusing on a real case study as part of the "BIM4H&W: BIM for Health and Wellbeing" research project.

2. Materials and Methods

The methodology consists of four sections: experimental sampling of Total VOCs (TVOC), defining VOC

material emission parameters for numerical models, developing a box-model for predicting VOC emissions, and performing CFD simulations of VOC concentrations. Experimental data were collected in two specific environments to assess air quality conditions and inform the models.
The study utilized both box-models and CFD models to simulate indoor dispersion of contaminants emitted by materials. A case study, considering standard conditions, aimed to compare results with IAGVs for TVOCs (Portugal) and emission limit values (CAM) for individual materials. Indoor VOC measurements, combined with the new building's conditions (unfurnished and unoccupied), allowed a focus on the building box, geometry, and materials.
The contribution of materials to indoor VOC concentration, in actual conditions, was estimated by considering exchanges with the external environment based on literature data. Both models focused on interior finish paint as the only VOC source, while other materials (metal countertops, stoneware floors) were deemed non-emissive.

3. Sampling Campaign

Experimental data were collected by RIELCO IMPIANTI S.R.L. in two rooms at the CNR Research Area in Pisa, Italy. The sampled environments included a meeting room (B2A2-2) and office 11 (B2A2-9). The data encompassed various environmental parameters and indoor contaminants. The meeting room showed higher temperatures in the morning, while office 11 exhibited increased temperatures in the late afternoon

4. Discussion

4.1. Validity of the Numerical Model and Control of TVOC Emissions for Building Design

An advantageous feature of box models lies in their ability to explore, with relative simplicity, diverse contributions to the overall indoor concentration. The quality and reliability of simulated results hinge upon the availability and accuracy of input data. In investigating indoor VOC concentrations, comprehensive data on material emissions, air circulation, external sources, and activities within the environment are indispensable. The analysis indicates that measured concentrations in both environments, averaging 25–30 μg/m³, are an order of magnitude lower than the Indoor Air Guide Values (IAGV) of 600 μg/m³. Concentrations derived solely from VOCs emitted by the walls amount to approximately 1% of the measured concentrations, irrespective of real or design ventilation. This outcome is attributed to the use of highly low-emissivity materials in the environments and model.
Comparing emissions due to an internal source for variable and constant ventilation conditions reveals the dilution effect exerted by the ventilation system on constant emissions, as opposed to a concentration increase for lower ventilation rates. Outdoor VOC contribution, despite being estimated at a relatively low 20 μg/m³, significantly impacts indoor concentration due to its introduction through the HVAC system. The study underscores the crucial role of outdoor contributions in shaping indoor concentrations, emphasizing their dependence on external factors such as wind field, building geometry, and pollutant sources. It is important to note that this discussion does not account for filtration phenomena through HVAC systems, which could further lower concentrations.

4.2. The Role of Building Materials Emissions in IAQ

Analyses reveal that adherence to emission threshold values (e.g., LEED and BREEAM protocols) and regulatory limits (CAM) does not guarantee high indoor air quality. The CAM upper limit (1500 μg/m³) needs contextualization based on actual air changes in the analyzed environment. Considering a minimum exchange of 0.5 volumes/h, the resulting indoor concentration surpasses IAGVs defined in scientific literature.
Air changes and HVAC system design play a pivotal role in IAQ evaluation. Greater ventilation rates facilitate substance dilution, emphasizing the significance of proper design. The method presented serves as an initial tool for designers to assess building IAQ performance. However, it offers a precautionary guide, with user, furnishing, and cleaning system contributions necessitating more intricate simulations in later building design stages.
Issues related to insufficient or unclear emission data on building materials highlight the need for increased awareness among technicians and manufacturers. Complete and transparent emission data are vital for effective design towards Healthy Buildings.

4.3. Use of CFD Simulation of TVOC Concentration

CFD simulations provide a realistic 3D representation of indoor VOC concentration dynamics, offering insights into diffusion processes. Unsteady simulations demonstrate concentration stabilization after a few hours, reaching asymptotic values around 10^{-1} μg/m³. CFD proves valuable in spatially visualizing ventilation's role in contaminant distribution.
Despite the advantages, CFD comes with drawbacks, including high computation times and costs, especially

for unsteady simulations. Interoperability with building design tools like BIM remains a challenge. The study's convergence between box modeling and CFD results reaffirms the applicability of box models, offering a pragmatic approach for IAQ assessment and comparison with IAGVs.

4.4. Limitations and Future Research Directions

The study acknowledges limitations, particularly the constrained sampling protocol during the Covid-19 pandemic. Future research should extend sampling durations, consider different seasons, and simultaneously measure outdoor and indoor VOCs. Detailed CFD simulations incorporating various factors like furnishings, external VOCs, and filtration systems could enhance accuracy.
Limitations include the focus on TVOCs due to data availability, and future studies should specify major VOCs. Simplifications, such as simulating emissions from a single material type, should be refined in future work. Despite these limitations, the study provides insights into the relationship between IAQ and building material contributions. In conclusion, the research lays a foundation for understanding the intricate factors influencing indoor VOC concentrations. Future studies can build on these findings, exploring residential, commercial, and workplace environments, considering diverse contributors to pollutant concentrations. The growing importance of IAQ underscores the need for continued interdisciplinary research and collaboration between building design, environmental science, and public health.

5. Conclusion

The significant qualitative transformations occurring in indoor air, coupled with a notable increase in pollutants, have drawn heightened attention to the well-being and health of individuals spending over 90% of their time in confined spaces. In response to these concerns, salutogenic design has gained traction, offering an approach that focuses on the potential positive impacts of design on health. By applying health-building principles, salutogenic design aims to create buildings that actively promote health and well-being.
Scientific scrutiny of these issues has spurred evidence-based research, investigating construction performance aspects most pertinent to user health. The intricate nature of Indoor Air Quality (IAQ), with its nuances in environmental hygiene and material chemistry, places architectural designers in a challenging position. Existing rules and regulations primarily emphasize material emissivity rather than concentrations of indoor pollutants. As revealed in the results, merely meeting emissivity limits for materials does not guarantee acceptable Total Volatile Organic Compounds (TVOC) concentrations in indoor environments.
The lack of comprehensive performance specifications in regulatory frameworks necessitates reference to Indoor Air Guide Values (IAGVs), adding complexity to their application in projects, and making adherence non-mandatory. The method introduced serves as an initial tool for building designers to assess IAQ performance, focusing specifically on the building box's performance. This allows for the evaluation of design choices in isolation.
The presented methodology marks the initial phase of the "BIM4H&W: BIM for Health and Wellbeing" research project (POR FESR LAZIO 2014/2020–Integrated projects). In another contribution by the authors, discussed in this special issue, the VOC prediction model is further developed by integration with digital design systems such as Building Information Modelling (BIM). This integration enhances the practical application of the model within the broader context of digital design and construction practices.

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