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BIM FOR HEALTHY BUILDINGS:
INTEGRATING VOC REQUIREMENTS FOR ASSESSING IAQ

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Research

The research “**BIM4H&W: BIM for Health and Wellbeing**” is developed in partnership of effective collaboration between RI.EL.CO S.R.L. and the University of Rome “Sapienza”.

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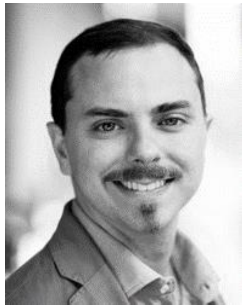

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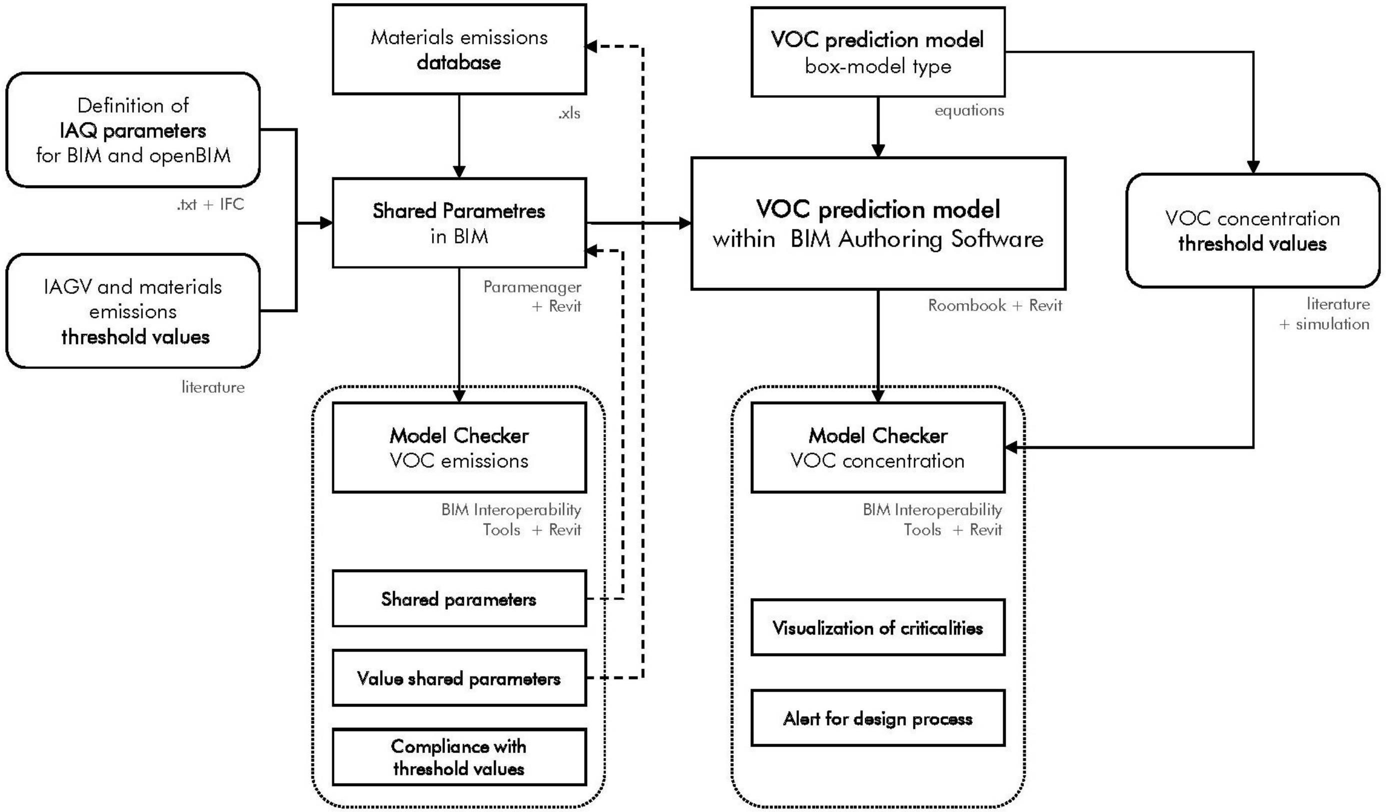
Aim and Methodology

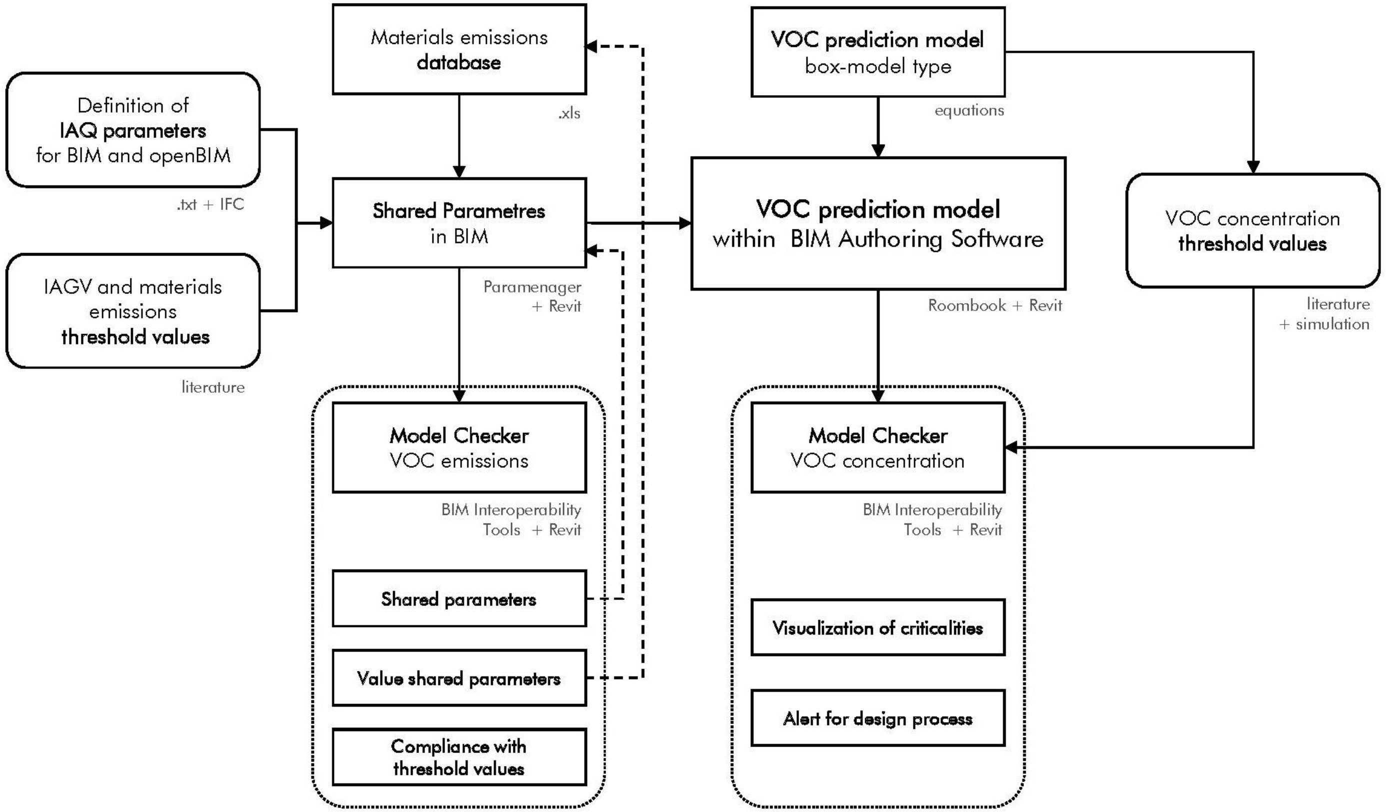
The aim of the research was the development of a verification tool for the designer on the IAQ performance of the building organism.



The result is an **applicative workflow** and a **tool integrated into the BIM process** for the check and control of VOC emissions from building materials and their concentration in confined environments, referred to national and international standards, and to guide values for IAQ (IAGVs).

Aim and Methodology

This tool focuses on the performance of the building box, precisely to allow the evaluation of design choices, and the proposed threshold value is precautionary because the contributions of users, furnishings, and cleaning systems must be considered in the real situation, in addition to the ones of the construction elements. All these other contributions are more complex simulation in the early stages of the project.

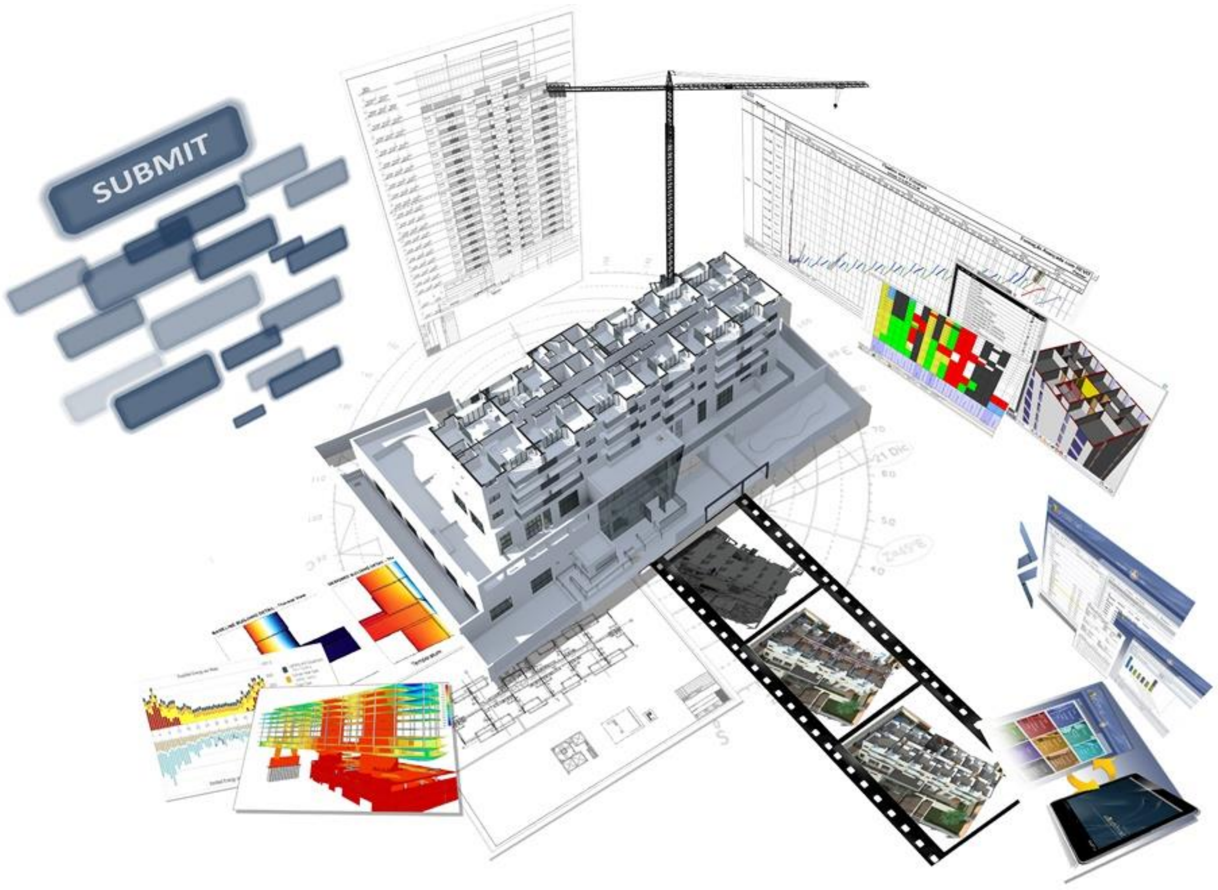


The main research question was: **how to switch from the VOC emission values of the materials to the concentration values in an indoor environment in order to control the IAQ in the design phase?**

To reach this result we developed of a numerical box-model predicting VOC concentration in the indoor environment and the proposal of a guide value for environments with low-emissivity building materials.

What is BIM

Building Information Modeling (BIM) is an intelligent 3D model-based process that gives architecture, engineering, and construction (AEC) professionals the insight and tools to more efficiently plan, design, construct, and manage buildings and infrastructure.



With BIM, designers create digital 3D models that include data associated with physical and functional characteristics.

The data in a model defines the design elements and establishes behavior and relationships between model components.

The data can be used in powerful analyses and simulations and to include realistic visualizations.

The power of BIM is how it allows architects, engineers and contractors to collaborate on coordinated models.

Autodesk definitions.

Voc prediction model

Estimating the concentration of pollutants in a confined environment can be achieved with different types of numerical models generically capable of considering the sources of the pollutant and the fluid dynamic conditions of the environment.

Our work considers and integrates a box-model using a mass balance approach within the BIM process.

This type of model, often used for indoor environments, can calculate the concentration of a pollutant in the volume represented by the room under examination starting from a hypothesis of complete mixing (box-model), namely assuming a homogeneous distribution of the concentration in the volume itself.
It calculates the temporal variation of VOC concentration as a function of ventilation conditions.

The developed numerical model estimates the concentration of VOC in the indoor environment through Equation:

$$V \frac{dC_{ind}}{dt} = AER \cdot V \cdot C_{vent} - AER \cdot V \cdot C_{ind} + S$$

where:

- V [m^3] represents the volume of the room considered,
- C_{ind} [g/m^3] represents the VOC concentrations in the indoor environment,
- AER [h^{-1}] represents the air exchange rate,
- C_{vent} [g/m^3] represents the VOC concentration in the ventilation air
- S [g/h] represents the hourly VOC flow rate of the sources inside the room.

Voc prediction model

Wanting to estimate only the contribution to the concentration due to the materials and considering the emissions due to them to be constant over time, a hypothesis that can be considered plausible for materials laid for more than 28 days. The asymptotic value of the concentration that is reached in the indoor environment for certain ventilation conditions

$$C_{ind} = \frac{S}{V \cdot AER}$$

The hourly flow thus considered is equivalent to the emission capacity of the material over time (ER).
The method for estimating the emissions of the various materials following tests carried out in the “chamber test”, defined by the EN16516 standard.

$$ER[\mu g/h] = C_{CH}\left[\mu g/m^3\right] \cdot 1\left[m^3\right] \cdot 0.5\,[1/h] \qquad SER\left[\mu g/\left(m^2\,h\right)\right] = ER\,[\mu g/h]/1\left[m^2\right]$$

- the emissive capacity of the material, the emission rate (ER) [g/h], is expressed as a function of the concentration, C_{CH} [mg/m_3], that is established in the air inside the “chamber” with a volume equal to 1 m_3 with an Air Exchange Rate, AER [1/h] equal to 0.5 considering 1 m_2 of material surface.
- the area-specific emission capacity or area-specific emission rate, SER.

Voc prediction model

Applying what is defined in the EN 16516 standard relating to ideal reference room, to a real room, in which it is considered a loading factor, L_a, defined by the ratio between the m^2 on which the material is present and the m^3 of the volume of the room considered

$$C_a = \frac{SER_a \cdot A_s}{AER_a \cdot V_a} \qquad L_a = \frac{A_s}{V_a}$$

The last equation was defined as capable of estimating the concentration of VOC, C_a, which is reached in a room volume V_a, under steady ventilation conditions determined by the AER_a, due to the emissions of an internal source of VOC, consisting of a material, characterised by SER_a, and distributed over the surface area A_s:

$$C_a = \frac{SER_a \cdot L_a}{AER_a} \longrightarrow C_a\left[\mu g/m^3\right] = \frac{\left(C_{CH}\left[\mu g/m^3\right] \cdot 1\left[m^3\right] \cdot 0.5\left[1/h\right]/1\left[m^2\right]\right) \cdot A_s\left[m^2\right]}{AER_a[1/h] \cdot V_a[m^3]}$$

where:

- SER_a: area-specific emission rate of the considered material.
- A_s: areal extension of the source characterised by the specific SER.
- V_a: volume of the room.
- AER_a: air exchange rate.

VOC prediction model in BIM process

$$C_a\left[\mu g/m^3\right] = \frac{\left(C_{CH}\left[\mu g/m^3\right]\cdot 1\left[m^3\right]\cdot 0.5\left[1/h\right]/1\left[m^2\right]\right)\cdot A_s\left[m^2\right]}{AER_a\left[1/h\right]\cdot V_a\left[m^3\right]}$$

This last relationship allows us to calculate the concentration in the room, with defined ventilation, with the emission data of the material as estimated in the test chamber available.

The numerical model thus developed was implemented within the BIM model, and applied to all the finishes of the rooms/spaces. All the parameters used in the Equation can be obtained from a BIM modelling developed for this purpose.

$$WallCoveringVOCs = \frac{WallCoveringVOCsTestChamber\cdot 0.5\cdot NetWallArea}{MechanicalVentilationRate\cdot NetVolume}$$

$$FloorCoveringVOCs = \frac{FloorCoveringVOCsTestChamber\cdot 0.5\cdot NetFloorArea}{MechanicalVentilationRate\cdot NetVolume}$$

$$CeilingCoveringVOCs = \frac{CeilingCoveringVOCsTestChamber\cdot 0.5\cdot NetCeilingArea}{MechanicalVentilationRate\cdot NetVolume}$$

$$SpaceVOCs = WallCoveringVOCs + FloorCoveringVOCs + CeilingCoveringVOCs$$

where SpaceVOCs (C_a) represents VOC concentration that is reached in the room due to the contribution of all the present finishes.

VOC prediction model in BIM process

Once the parameters necessary for the implementation of the analysis of VOC emission workflow have been elaborated, we proceeded with their implementation in the BIM environment, within the model developed with BIM Authoring Autodesk Revit.

Table 2. "Pset_IndoorAirQualityRequirements" and the parameters that compose it.

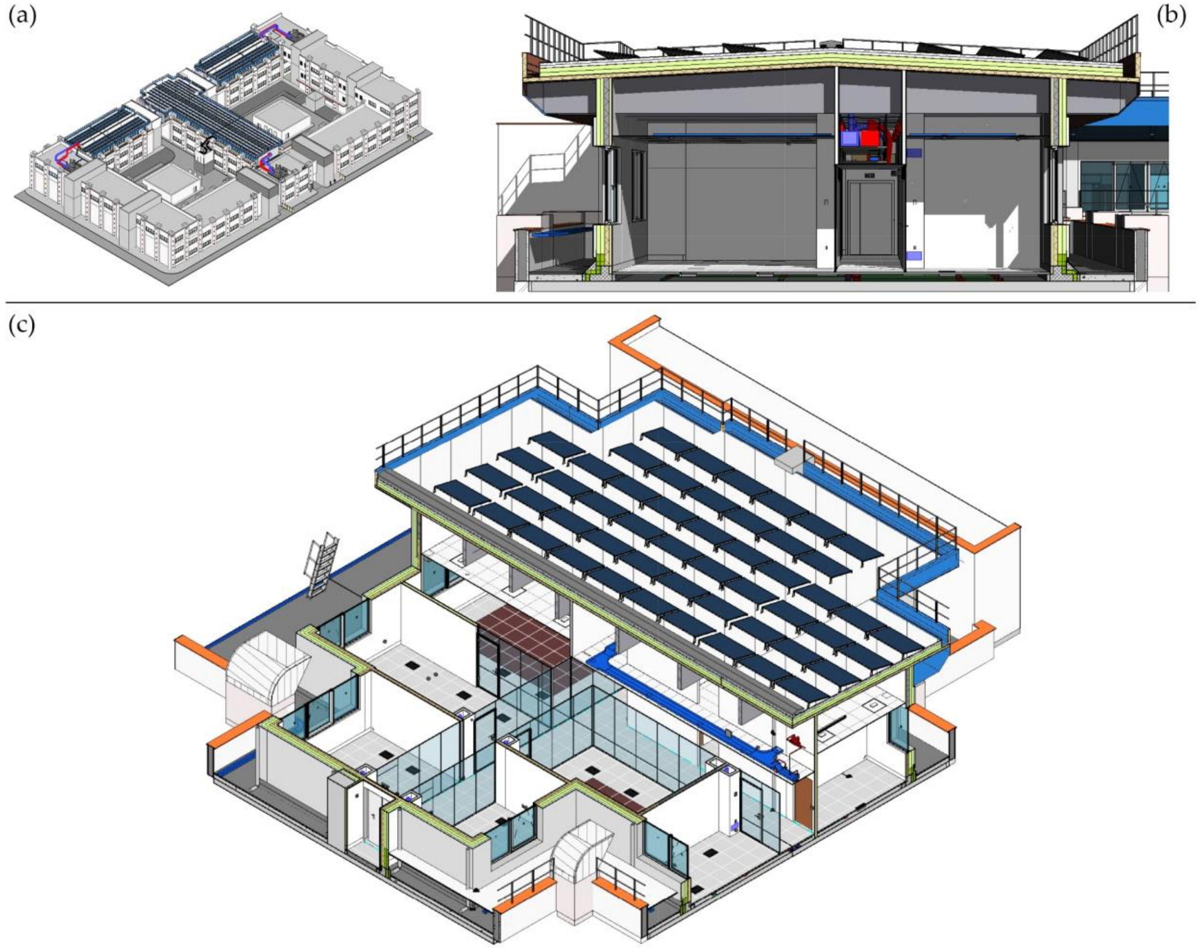
Parameter Name	Parameter Description	Entities to Which It Is Assigned
VOCsEmission	Quantity of VOCs emissions for elements. Unit of measure $\mu g/m^3$	IfcMaterial, IfcWall, IfcSlab, IfcCeiling
VOCsEmissionCAM	CAM limit of the quantity of VOCs emissions for elements. Unit of measure $\mu g/m^3$	IfcMaterial, IfcWall, IfcSlab, IfcCeiling

Table 3. "Pset_SpaceIndoorAirQualityRequirements" and the parameters that compose it.

Parameter Name	Parameter Description	Entities
SpaceVOCs	VOCs presence inside the space. Unit of measure $\mu g/m^3$	IfcSpace
WallCoveringVOCsTestChamber	VOCs Test Chamber Concentration of wall finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace
FloorCoveringVOCsTestChamber	VOCs Test Chamber Concentration of floor finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace
CeilingCoveringVOCsTestChamber	VOCs Test Chamber Concentration of ceiling finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace
WallCoveringVOCs	VOCs Concentration of wall finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace
FloorCoveringVOCs	VOCs Concentration of floor finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace
CeilingCoveringVOCs	VOCs Concentration of ceiling finish inside the space. Unit of measure $\mu g/m^3$	IfcSpace

Case study

The case study selected to develop the proposed workflow and the integration between IAQ and BIM is a recent project by RI.EL.CO IMPIANTI SRL, the main partner of the research project.



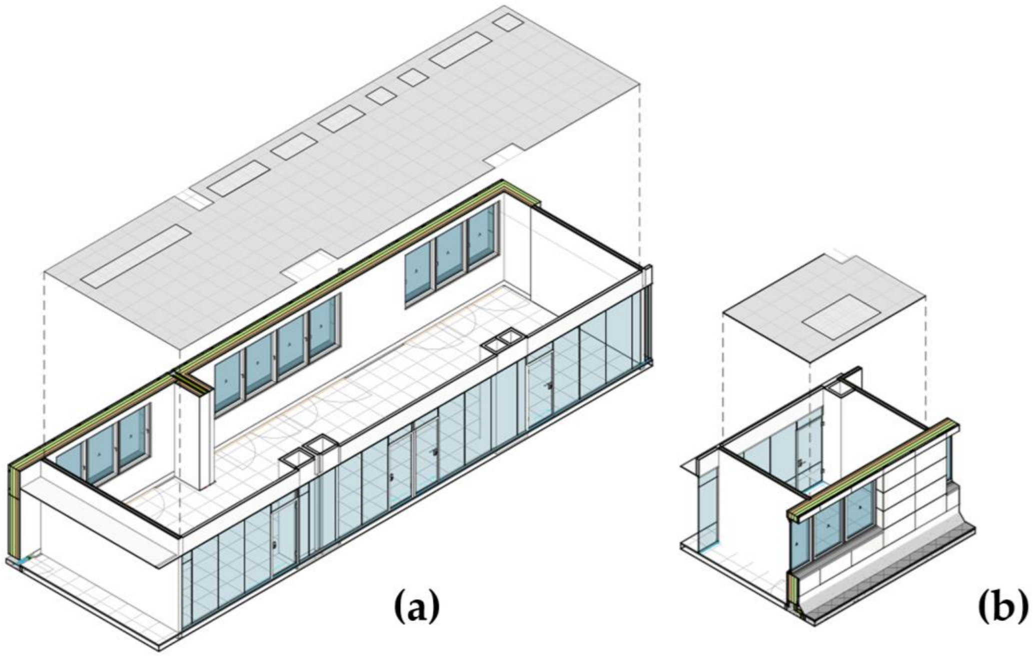
The building chosen is the new headquarters of the Institute of Informatics and Telematics (IIT), which is part of the Research Area of the C.N.R., in Pisa (IT).

Construction of the building was completed in 2020, and it was inaugurated in February of last year. The preliminary design of the building is by Eng. Ottavio Zirilli (CNR), the executive project was handled by RIELCO Srl (Project Leader Eng. Carmine Rinaldi).

Case study

Two types of sampling were collected to set the box model: continuous environmental sampling through instruments integrated into the ventilation management system (SIEMENS system) and data measured with mobile samplers, positioned in the center of each room and 1 m from the floor.

The environmental parameters measured by the sensors installed in the ventilation system are: indoor air temperature [°C], ventilation rate [m^3/h], airspeed [m/s], and CO_2 concentration [ppm]; these data were acquired with variable frequency.



The mobile acquisition tools used in the sampling campaign are:

- Photo-Ionization Detector (PID), TIGER—VOC detector (isobutylene calibration) 1 ppm resolution;
- Laser Particle Counter, AIRY TECHNOLOGY P311 (0.5 μm–2,5 μm–5 μm);
- Multisensor 8-Channel IAQ Monitor, YESAIR.

The data measured with these mobile samplers are VOC concentration [ppm], temperature [°C], and relative humidity [%] with an acquisition frequency of 5 min.

Indoor Air Guide Values (IAGVs)

The values deriving from the sampling will be compared with the IAGVs.

The WHO and France, and Germany, usually particularly attentive to the regulatory aspects of indoor pollutants, have not released guide values referred to TVOC.

While Belgium and Holland define a value of 200 $\mu g/m^3$, but with very different and contrasting evaluation periods.

It was, therefore, decided to choose as the reference guide value the one expressed by Portugal, equal to 600 $\mu g/m^3$ over an evaluation period of 24 and 8 h.

Pollutant [$\mu g/m^3$]	Average Period *	WHO	France	Germany	Netherlands	Belgium	Portugal
TVOC	1 year	-	-	-	200	-	-
	24 h	-	-	-	-	200	600
	8 h	-	-	-	-	-	600

* period of time used to calculate the pollutant average concentration.

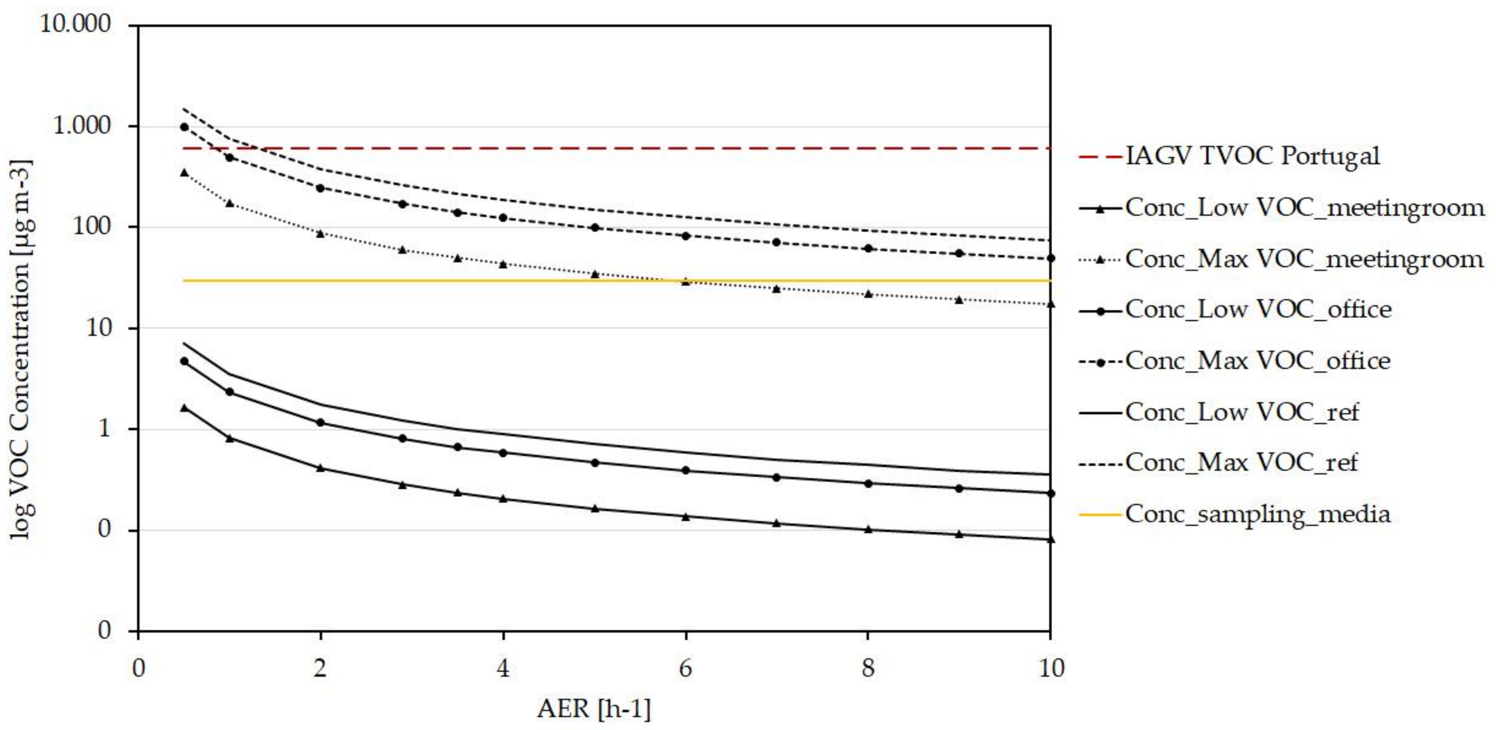
In Italy, a specific standard that incorporates WHO guidelines has not been drawn up, while Ministerial Decree of 11 October 2017 dictates the minimum environmental criteria (CAM) for construction and exclusively defines the limits of emissions from materials, but not those to concentrations in the indoor environment.

(CAM) TVOC emission = 1500 $\mu g/m^3$

The HVAC systems role in IAQ

A fundamental role in the evaluation of IAQ is, therefore, linked to air changes and the design of the HVAC system. The greater the ventilation rate the system is designed with, the greater the dilution of the substances present in the air and, therefore, the lowering of their concentration.

The considerations set out here take into account the minimum air change, i.e. a value of 0.5, for two main reasons:



- it is not always possible to know the air changes of the HVAC system, in the early stages of the development of the architectural project, or it is not certain that there are air changes higher than the minimum in the absence of mechanized ventilation (i.e. in residential construction);
- in the case of the HVAC system with ventilation rates higher than 0.5, a malfunction could occur, which would lead to an accumulation of VOCs in an indoor environment.

Automatic VOC calculation within BIM

To set up an automatic calculation within the BIM authoring Autodesk Revit, a schedule was set up of all the BIM elements in the Rooms category with a succession of “calculated parameters” also called “calculated values”.

Legenda

- Parameters to be filled in by the designer.
- Parameters provided in the material data sheets
- Dimensional parameters calculated by the BIM model
- Mass balance model parameters in which to insert the respective formulas

$$SpaceVOCs = WallCoveringVOCs + FloorCoveringVOCs + CeilingCoveringVOCs$$

$$CeilingCoveringVOCs = \frac{CeilingCoveringVOCsTestChamber \times 0{,}5 \times NetCeilingArea}{NetVolume \times MechanicalVentilationRate}$$

$$FloorCoveringVOCs = \frac{FloorCoveringVOCsTestChamber \times 0{,}5 \times NetFloorArea}{NetVolume \times MechanicalVentilationRate}$$

$$WallCoveringVOCs = \frac{WallCoveringVOCsTestChamber \times 0{,}5 \times NetWallArea}{NetVolume \times MechanicalVentilationRate}$$

BIM4H&W_RoomVOCsConcentr... ✕

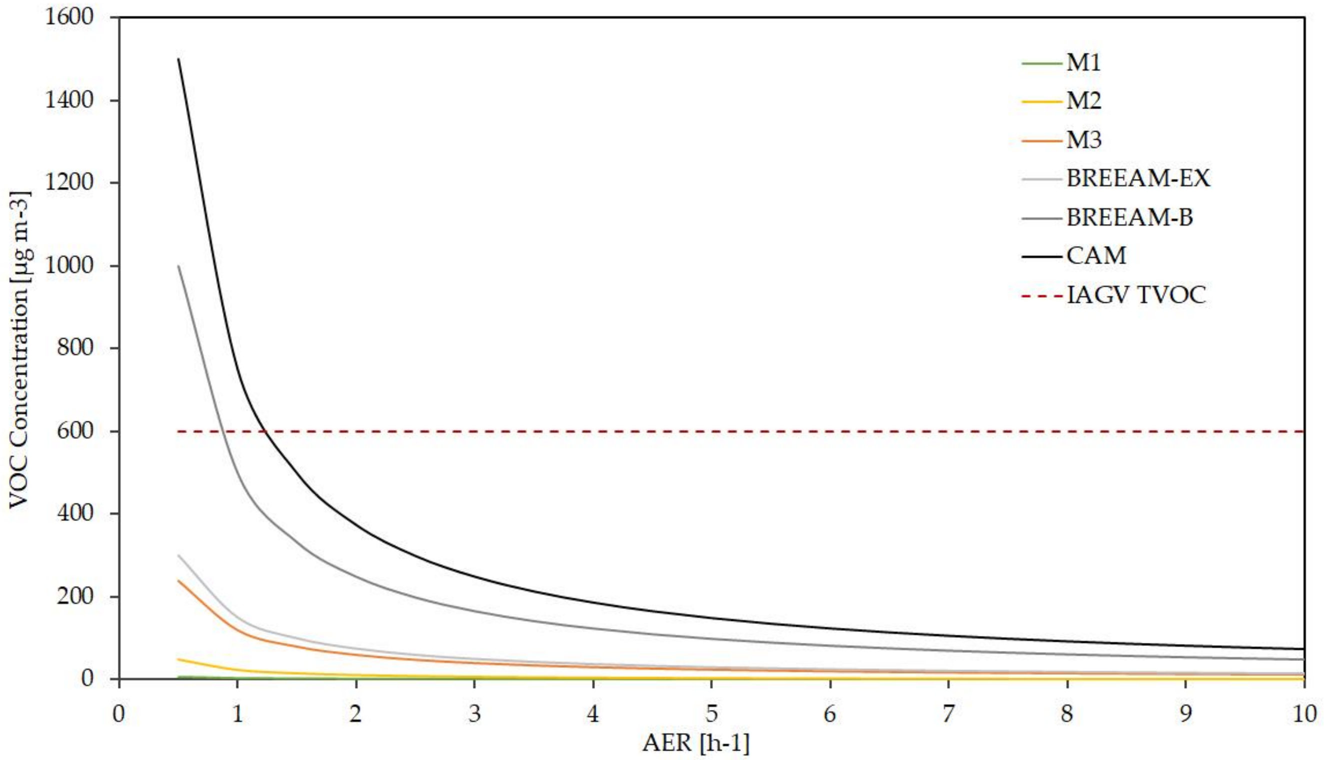
<BIM4H&W_RoomVOCsConcentration>

A	B	C	D	E	F	G	H	I	J	K	L	M
Room	MechanicalVentilationRate [1/h]	NetWallArea [m2]	WallCoveringVOCsTestChamber [µg/m3]	NetFloorArea [m2]	FloorCoveringVOCsTestChamber [µg/m3]	NetCeilingArea [m2]	CeilingCoveringVOCsTestChamber [µg/m3	NetVolume [m3]	WallCoveringVOCs [µg/m3]	FloorCoveringVOCs [µg/m3]	CeilingCoveringVOCs [µg/m3]	SpaceVOCs [µg/m3]
B2A2-1 UFFICIO	3.4	40.76 m²	7.1	19.14 m²	0	19.14 m²	0	60.097	0.708155	0	0	0.708155
B2A2-2 ARCHIVIO	3.6	97.29 m²	7.1	88.05 m²	0	88.05 m²	0	276.426	0.347069	0	0	0.347069
B2A2-3 RIPOSTIGLIO	4.3	25.41 m²	7.1	4.53 m²	0	4.53 m²	0	14.245	1.47268	0	0	1.47268
B2A2-4 UFFICIO	4	28.61 m²	7.1	9.03 m²	0	9.03 m²	0	28.390	0.894365	0	0	0.894365
B2A2-5 UFFICIO	4.3	33.60 m²	7.1	13.40 m²	0	13.40 m²	0	42.156	0.658017	0	0	0.658017
B2A2-6 UFFICIO	3.4	30.19 m²	7.1	10.35 m²	0	10.35 m²	0	32.548	0.968483	0	0	0.968483
B2A2-7 UFFICIO	3.9	40.98 m²	7.1	22.52 m²	0	22.52 m²	0	70.843	0.526552	0	0	0.526552
B2A2-8 UFFICIO	3.9	31.07 m²	7.1	11.07 m²	0	11.07 m²	0	34.828	0.81204	0	0	0.81204
B2A2-9 UFFICIO	3.5	34.70 m²	7.1	14.25 m²	0	14.25 m²	0	44.811	0.785434	0	0	0.785434
B2A2-10 ARCHIVIO	3.8	25.91 m²	7.1	4.76 m²	0	4.76 m²	0	14.969	1.616995	0	0	1.616995
BAGNO 1	6	19.35 m²	7.1	6.34 m²	0	6.34 m²	0	19.926	0.574557	0	0	0.574557
BAGNO 2	6	3.91 m²	7.1	1.27 m²	0	1.27 m²	0	3.980	0.581208	0	0	0.581208
BAGNO 3	6	0.00 m²	7.1	1.26 m²	0	1.26 m²	0	3.970	0	0	0	0
BAGNO 4	6	3.99 m²	7.1	1.32 m²	0	1.32 m²	0	4.138	0.570565	0	0	0.570565
BAGNO 5	6	0.00 m²	7.1	1.26 m²	0	1.26 m²	0	3.967	0	0	0	0
BAGNO 6	6	2.65 m²	7.1	6.48 m²	0	6.48 m²	0	20.394	0.076881	0	0	0.076881
BAGNO 7	6	0.00 m²	7.1	3.27 m²	0	3.27 m²	0	10.279	0	0	0	0
CORRIDOIO	3.2	51.71 m²	7.1	56.39 m²	0	56.39 m²	0	140.690	0.407746	0	0	0.407746

BIM Model Checker to verify indoor TVOC Concentration

For the verification of the threshold values of the VOC concentrations due to the materials for every single room/space of the BIM model, a threshold value has been defined.

This limit value was set based on simulations carried out with the box-model using three types of low-emissivity materials: One used in the case study and two others selected from scientific literature.
The emission values of these materials are, respectively: 7.1 μg/m^3; 50 μg/m^3; 240 μg/m^3.



These values were compared with the threshold values established by the environmental sustainability certification protocol BREEAM (Basic level 1000 μg/m^3; Exemplary Level 300 μg/m^3) and with the limit value defined by the Italian CAM (1500 μg/m^3).

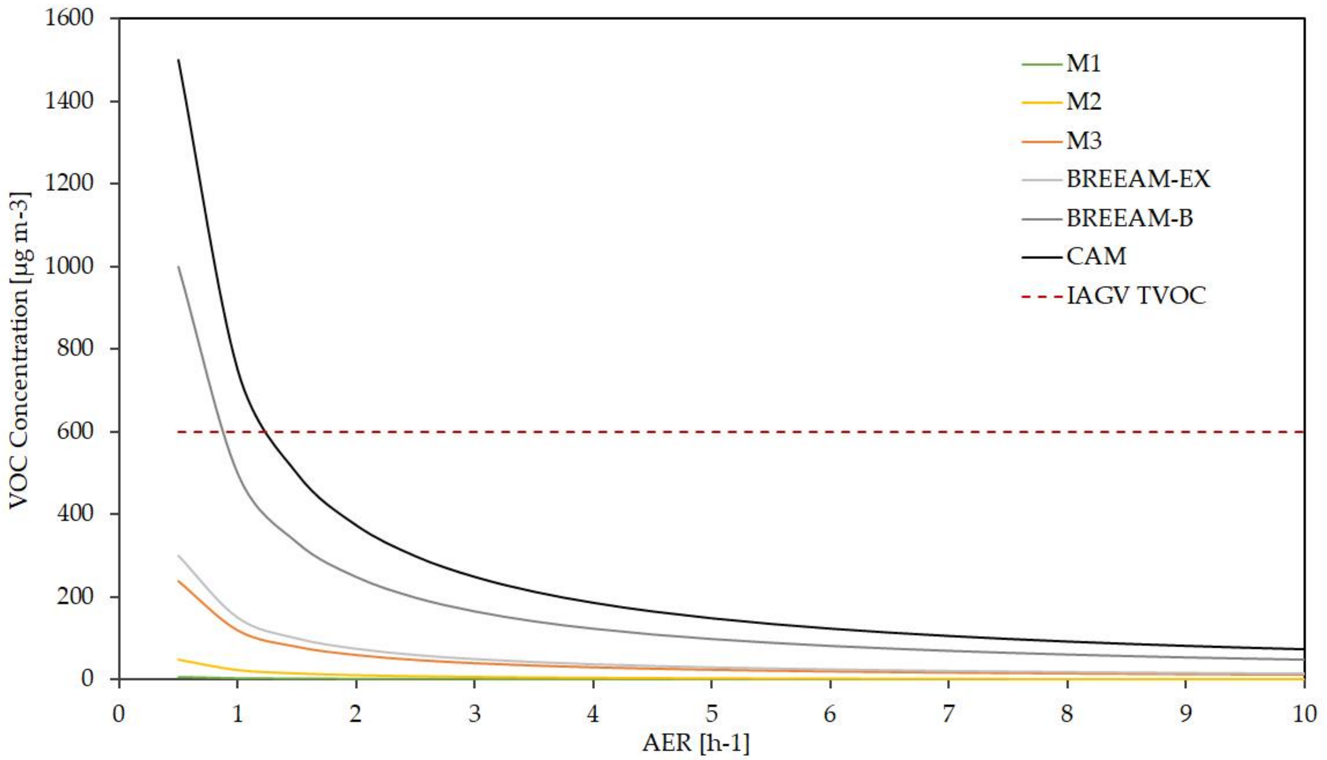
These emission values were applied in the numerical mass balance model developed and considering the reference room defined by the EN 16516 standard to evaluate the concertation of TVOC.

BIM Model Checker to verify indoor TVOC Concentration

The concentration values thus obtained were compared with the IAGVs defined by Portugal, equal to the value of 600 μg/m3.

In light of the results obtained, it was decided to set the limit on the value of 50 μg/m3 as a precautionary threshold.

$$SpaceVOCs < 50\ \mu g/m^3$$



This reasoning is because this threshold only considers the concentration of TVOC due to building materials and therefore useful for design purposes, to which the contributions of outdoor air, people, furniture, and cleaning products are added.

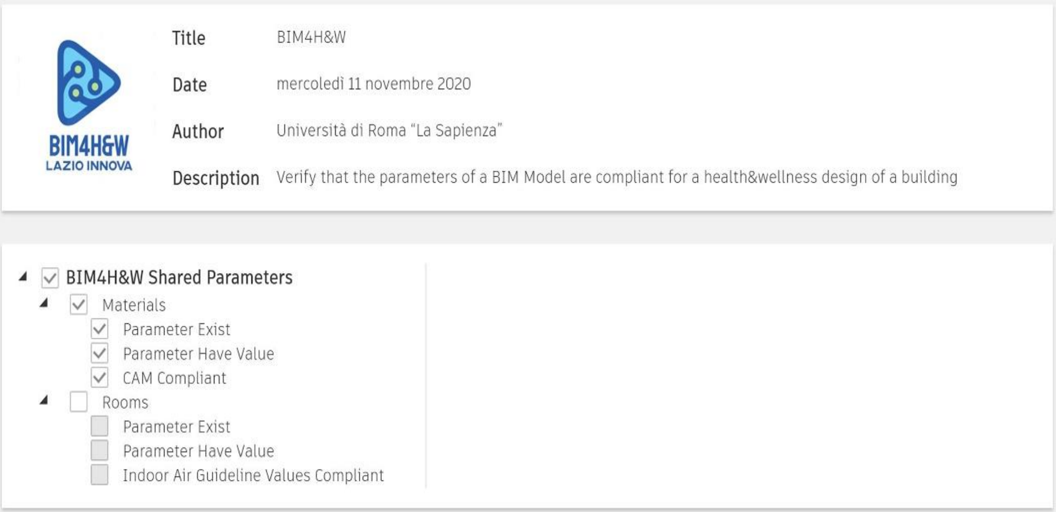
It was therefore decided to settle on a value of approximately 10% of the considered IAGV.

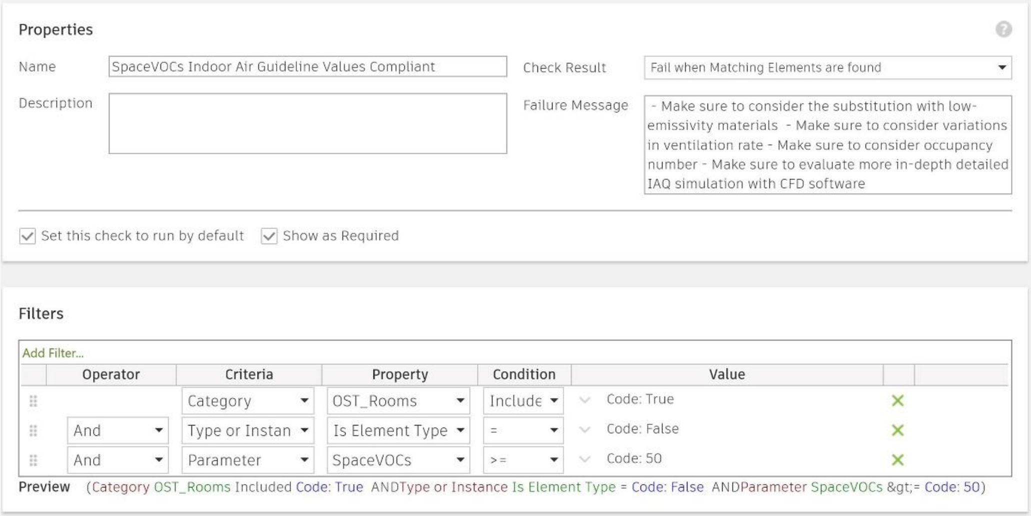
BIM Model Checker to verify indoor TVOC Concentration

A “Checkset” for appropriate presence, filling, and value in parameters has been created in .xml format, a set of control rules, specific for the VOC emission analysis workflow.

The “BIM4H&W.xml” file contains Checksets that can be used in all BIM models developed in Autodesk Revit and that have previously entered the shared parameters of the “Shared Parameters-BIM4H&W.txt” file.

Containing all the necessary rules for the BIM4H&W workflow, the Checkset is organised in sections, so the user can activate the controls step by step.





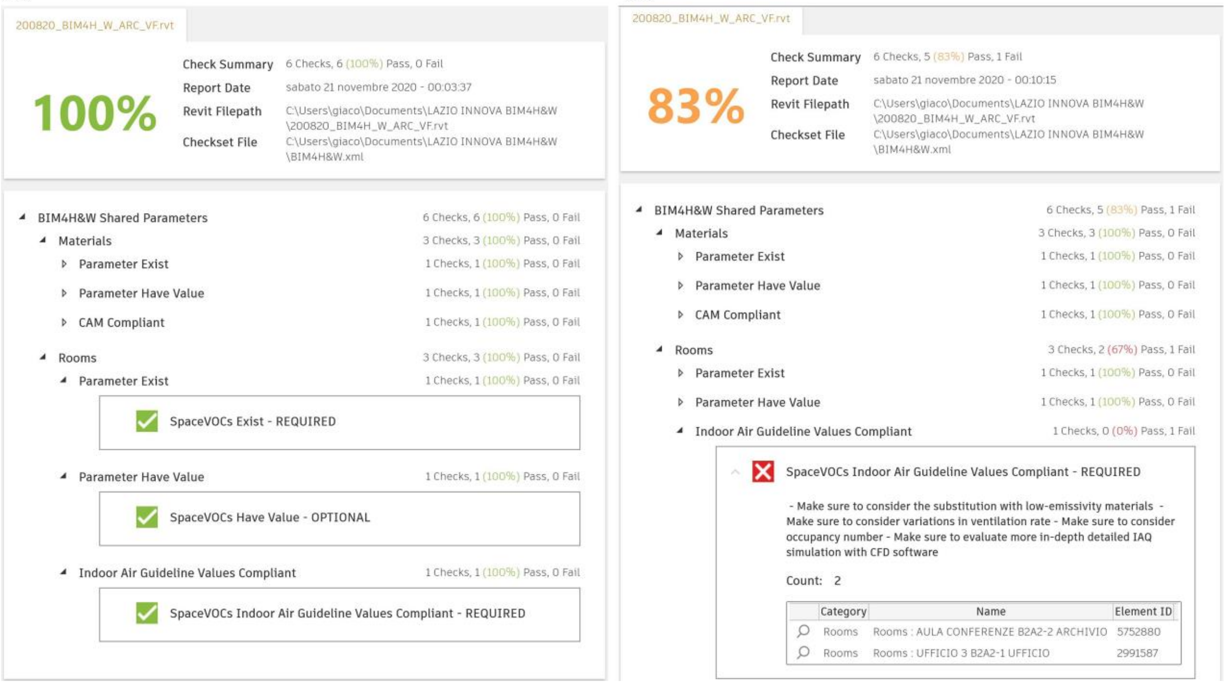
BIM Model Checker to verify indoor TVOC Concentration

The verification that the parameter SpaceVOCs is $< 50\ \mu g/m^3$ is implemented, through the code of a check rule with "Autodesk Model Checker".

Figure shows the "Autodesk Model Checker" screen if the value of the SpaceVOCs parameter exceeds the pre-established threshold. In this case, more in-depth checks are suggested to the designer and possible alternative solutions proposed are:

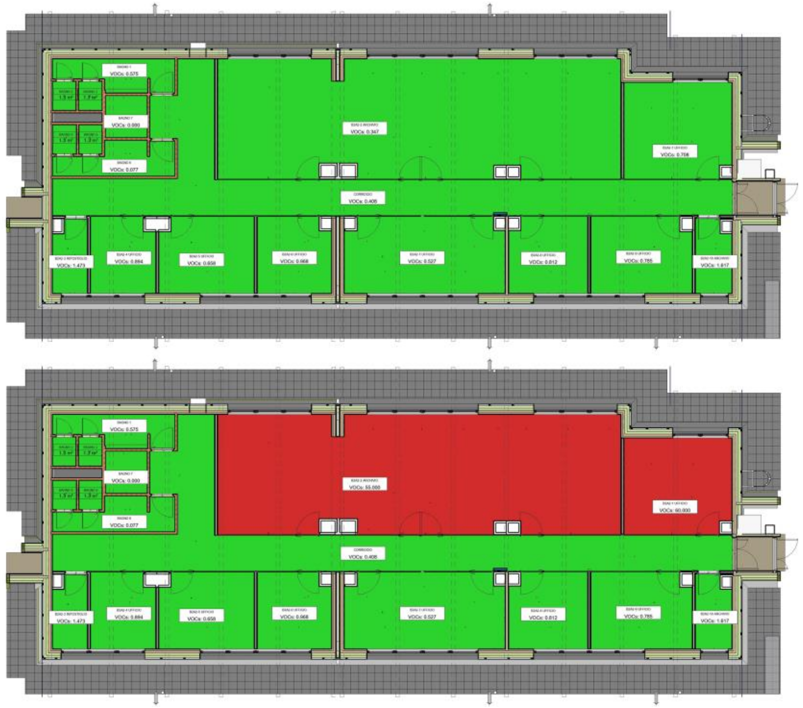
- Make sure to consider the substitution with low-emissivity materials.
- Make sure to consider variations in ventilation rate.
- Make sure to consider occupancy number.
- Make sure to evaluate more in-depth detailed IAQ simulation with CFD software.

(a) (b)



(a)

(b)



Limitations and critical issues

A critical issue that emerged during the development of the research project relates to **the topic knowledge by the technicians and manufacturers of building materials**.

Although to date the majority of construction products are certified and report emission data, these data still appear to be incomplete or not correctly disseminated. The issues can be summarised in:

- Materials with technical data sheets containing incomplete emission data: Not always all the main indoor pollutants are present (i.e. Formaldehyde, VOC, Benzene);
- Unclear understanding of the VOC emission data: When the data are present, it is often not specified with which procedures and tests the value was obtained, how many days after application it refers to, and whether the declared data refer to the VOCs contained in internal material or those emitted.

In most cases, when present, the VOC emission data referred to the TVOCs and not to a specification, at least to the main ones. However, it should be noted that there were also manufacturers who provided complete data of certifications and indications on the methods of testing the emissivity of materials, and which allowed the analyses carried out.

These considerations have directed the project to focus **on the TVOC data**, <u>which therefore appears to be the one actually easier to find even for architectural designers</u>.

Limitations and critical issues

Unfortunately**, the period of the Covid-19 pandemic has severely limited the availability of access to the case study**. Despite this, the sampling was carried out for 3 days in a row, showing a complete history of the indoor environments both during the day and at night. In particular, the absence of users made it possible to concentrate the reading of the results on the building materials data only, avoiding further confounding factors.

Finally, some simplifying conditions were necessary. In particular, it was decided to simulate the emission of VOCs in the rooms as coming from a **single type of material**: the internal finishing paint applied to the walls.

It was decided to carry out this simplification as it is known from the literature that the emissions from multilayer materials are comparable with those of the outermost top-layer material.

At the same time, because over the years the phenomena of diffusion within multilayer materials have been extensively investigated, the integration of this modelling into the BIM process represents a field of sure interest and possible future development.

Conclusions

The results of the analyses showed that the satisfaction of the emission threshold values (i.e. for the LEED and BREEAM protocols) and the regulatory limits (CAM) do not have a direct correspondence with high indoor air quality.

Indeed, the upper limit imposed by the CAM (1500 $\mu g/m^3$) should first be contextualized compared to the actual air changes in the environment under analysis. Considering a minimum exchange of 0.5 volumes/h as described by the regulations for the evaluation of individual materials, the result is an indoor concentration value far superior to the IAGVs elaborated in the scientific literature.

The method presented here is intended to be **a first verification tool for the designer on the IAQ performance** of the building organism.

This tool focuses on the performance of the building box alone, precisely to allow the evaluation of design choices, and the proposed guide value is precautionary because the contributions of users, furnishings, and cleaning systems must be considered in the real situation, in addition to the ones of the construction elements. All these other contributions require a more complex simulation in the early stages of the building design.

It is certainly necessary **to work for greater awareness of the IAQ theme** and for an increase in the technical knowledge of both the designers, who must request the information, and the manufacturers, who must provide it; this work could make the design towards Healthy Buildings and the simulation of significative performances more effective.

Published papers

sustainability

MDPI

Article

BIM for Healthy Buildings: An Integrated Approach of Architectural Design Based on IAQ Prediction

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Abstract: The relationship between users and the built environment represents a fundamental aspect of health. The factors that define the properties linked to health and well-being are increasingly becoming part of building design. In these terms, building information modelling (BIM) and BIM-based performance simulation take on a priority role. Among the key features for the design of Healthy Buildings, indoor air quality (IAQ) plays a central role. There are numerous indoor pollutants with significant health effects; volatile organic compounds (VOCs) are to be mentioned among these. The paper presents the proposal of an integrated workflow in the BIM process for the check and control of VOC emissions from building materials and their concentration in confined environments. The workflow is developed through the systematisation of IAQ parameters for the open BIM standard, the integration in the BIM process of a numerical model for the prediction of the VOCs concentration in the indoor environment, and the development of model checkers for performance verification. The results show a good adhesion between the numerical model and the implementation in BIM, providing the designer with a rapid control instrument of IAQ in the various phases of the building design. The present study is the first development focused on TVOC, but implementable concerning other aspects of IAQ, as needed for the effectiveness of performance building-based design for health and wellness issues.

Keywords: design and health; BIM; materials; interior design; salutogenesis; wellbeing; VOC emission; IAQ; building design

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Modelling VOC Emissions from Building Materials for Healthy Building Design

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Abstract: The profound qualitative changes of indoor air and the progressive increase in the absolute number of pollutants, combined with the scientific awareness of the health impacts deriving from spending more than 90% of one's time inside confined spaces, have increased the attention onto the needs of well-being, hygiene, and the health of users. This scientific attention has produced studies and analyses useful for evidence-based insights into building performance. Among the main pollutants in the indoor environment, Volatile Organic Compounds (VOCs) play a central role, and the use of box-models using the mass balance approach and Computational Fluid Dynamics (CFD) models are now consolidated to study their concentrations in an indoor environment. This paper presents the use of both types of modelling for the prediction of the VOC concentration in the indoor environment and the proposal of a guide value for the Indoor Air Quality (IAQ)-oriented building design, specifically related to the indoor VOC concentration due to building materials. Methodologically, the topic is addressed through environmental sampling, the definition of the parameters necessary for the numerical models, the simulations with the box-model and the CFD, and the comparison between the results. They show a good correspondence between the modelling tools used, highlighting the central role of ventilation and allowing a discussion of the relationship between regulatory limits of emissivity of materials and Indoor Air Guide Values for the concentration of pollutants.

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

Thanks for you attention

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