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BIM-integrated Indoor Aerosol Modeling Based On Outdoor Particles In Germany

Jan Drzymalla, MEng
Student Member ASHRAE

Jannick Höper, MEng

Sven Eckers, MEng

Sebastian Theißen, MEng

Michaela Lambertz, DrIng

Andreas Henne, DrIng

ABSTRACT

Indoor air quality (IAQ) plays an intrinsic role in occupant comfort, and should be evaluated as a key building performance indicator of early design phases. However, IAQ is very complex due to a plethora of chemical compounds in the indoor air and also depends on the activities in the building. Therefore, IAQ assessment is often not comprehensively considered, or applied only during late project phases. This study reviewed how Building Information Modeling (BIM) could be applied for IAQ performance analysis, to provide a more holistic design process. Accordingly, the integrability of Indoor Aerosol Modeling (IAM) into the open BIM data format Industry Foundation Classes was analyzed. The goal was to enable automated BIM-integrated IAM based on particle concentrations in Germany's outdoor air. For this IAM, a Material Balance Model was chosen which is based on the principle of mass conversation and applies to a single zone. The analysis showed that eight Exchange Requirements (ERs), two Property Sets (Psets) and two Quantity Sets (Qsets) are required for the presented BIM-integrated IAM of naturally ventilated single-zone buildings, which form the basis for an Information Delivery Manual, a Model View Definition and a BIM application case. One of the two required Psets ("Pfd_IndoorAerosolModeling") was redefined as part of this study, since the associated attributes for an IAM have not yet been standardized. Finally, the developed BIM-integrated IAM was validated on an example building located in Cologne-Mülheim Germany, where a constant PM10 outdoor concentration of $C_O = 61.00\ \mu g/m^3$ *were assumed. Based on this, it was possible to automatically calculate the occurring indoor concentrations and the time histories of the airborne particle mass concentrations over a selected period of seven minutes (*$t = 420s$*) for the fractions PM10 (*$C_{m,PM10}(t) = 1.72\ \mu g/m^3$*), PM2.5 (*$C_{m,PM2.5}(t) = 1.40\ \mu g/m^3$*), thoracic (*$C_{m,thoracic}(t) = 1.66\ \mu g/m^3$*) and high risk respirable (*$C_{m,hrr}(t) = 1.31\ \mu g/m^3$*).*

INTRODUCTION

The holistic and cooperative working method Building Information Modeling (BIM) will fundamentally change the processes from planning to operating buildings in all areas. One potential area where BIM can provide optimization through its consistent exchange of information and data through the entire building life cycle is Indoor Environmental Quality Performance (IEQP). IEQP is of enormous importance for the construction and building sector, as average Europeans spend about 80 to 90% of their life indoors (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit 2005). The IEQP consists of six different subareas: Energy Efficiency, Thermal Comfort, Lighting Comfort, Humidity Comfort, Acoustic Comfort and Indoor Air Quality (IAQ) (Kirkegaard and Kamari 2017). The IAQ refers in particular to the air quality inside buildings, as this has an impact on the health and comfort of building occupants. In order to prevent negative health and comfort impacts, the IAQ should be considered as a key indicator for building performance in early project phases. However, its planning is very complex due to the large number of chemical compounds and pollutants in indoor air, as these usually cannot be fully taken into account. Both in the indoor air and in

Jan Drzymalla, Jannick Höper and **Sebastian Theißen** are research associates at the Institute of Building Services Engineering, University of Applied Sciences (TH Köln), Cologne, Germany. **Sven Eckers** is a project engineer at Weber & Partner Ingenieurgesellschaft für technische Gesamtplanung mbH, Cologne, Germany. **Michaela Lambertz** and **Andreas Henne** are professors at the Institute of Building Services Engineering, University of Applied Sciences (TH Köln), Cologne, Germany.

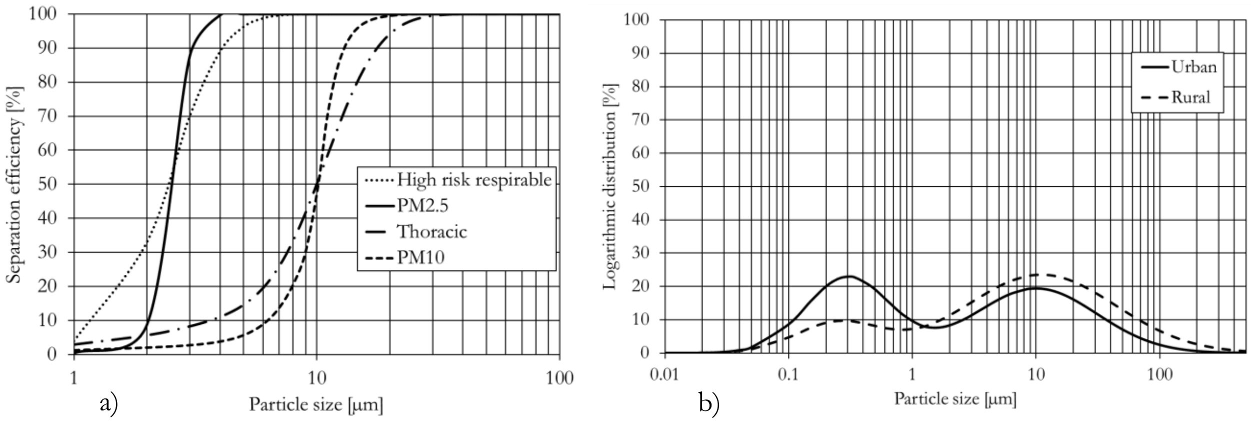
the environment as a whole, a heterogeneous mixture of solid and liquid suspended particles is usually found, which is called an aerosol (Hinds 1999). Aerosols can also occur in different ways as dust, smoke, mist or smog. In addition, fungi, bacteria, viruses or pollen, among other things, can adhere to the particles suspended in the aerosol (bioaerosols) and have negative effects on air quality. Due to the apparent complexity and the associated influencing variables, IAQ assessment is often not considered comprehensively enough or is only applied in late project phases. This study presents a possible approach as to how the BIM method can be used for IAQ assessment to enable an efficient and more holistic design process. The goal is to enable automated BIM-integrated Indoor Aerosol Modeling (IAM) based on particle concentrations in Germany's outdoor air. For this purpose, the integration of a Material Balance Model into the openBIM Format Industry Foundation Classes (IFC) is analyzed below. The resulting target values are Exchange Requirements (ERs), Property Ses (Psets) and Quantity Sets (Qsets), which form the basis for an Information Delivery Manual (IDM), Model View Definition (MVD) and a BIM application case. For validation purposes, the developed BIM-integrated IAM is performed and tested in the context of a use case on an example building.

METHOD AND MATERIALS

This section explains the method and materials required to implement an IAM of naturally ventilated single-zone buildings using the BIM method. The type and size fractions of the aerosol to be modeled are explained. Subsequently, the applied Material Balance Model and its linking to BIM are presented.

Particulate Matter and Size Fractions

Aerosols are often referred to as suspended particulate matter (SPM), aerocolloidal systems and disperse systems (Hinds 1999). The term SPM occurs particularly frequently in occupational safety and environmental protection regulations, where different classifications are defined either according to the main deposition region in the respiratory tract or according to the sampling cut-off size. The categorization according to the sampling cut-off size comes primarily from atmospheric research, where different fractions are measured and indicated in the form of *PMx* (Winkel et al. 2014; Mattenklott and Höfert 2009). This abbreviation describes SPM in the air that passes through a size-selective air inlet or sample inlet, which has a separation efficiency of 50% at an aerodynamic diameter of *x* μm (Deutsches Institut für Normung e. V. [DIN] 2014). German legislation and DIN EN 12341 usually differentiate between the two fractions *PM10* and *PM2.5*. In parallel, DIN EN 481 and DIN ISO 7708 define *PM10* as *thoracic* and *PM2.5* as *high risk respirable* (DIN 1993, 1996). Accordingly, this study will focus primarily on the fractions mentioned above. Although *PM10* and *thoracic* at approx. 10.00 μm and *PM2.5* and *high risk respirable* at approx. 2.50 μm have a separation efficiency of 50%, the corresponding separation curves differ enormously (see Figure 1a). These separation curves thus define the separation efficiency (impactor efficiency) of different particle size fractions. Ideally, a separation curve for the cut-off size corresponds to a straight line from 0% to 100% (Lamminen 2015). However, this is not possible in reality, which is why there is always an S-shaped separation curve.



a) b)

Figure 1 (a) Separation curves and (b) typical particle size distributions.

The separation curves for the *thoracic* and *high risk respirable* fractions can be determined using Equation 1 below (DIN 1993, 1996):

$$thoracic = high\, risk\, respirable = 100 - \frac{\left(50\,(1+e^{-0.06\, d_{ae}})\right)}{100} E_{TR} \qquad (1)$$

where the numerator corresponds to the convention of the inhalable fraction E_I and is defined as the target value for sampling devices if the mass fraction of all suspended particles inhaled through the mouth and nose is to be determined. Moreover d_{ae} is the aerodynamic particle diameter (μm) and E_{TR} is the sampling curve percentage for thoracic or high risk respirable fraction sampling devices (%). The numerical approximations to the cumulative log normal distributions are calculated according to Equations 2 to 4 (DIN 1993, 1996):

$$G = 0.5\,(1 + 0.14112821y + 0.08864027y^2 + 0.02743349y^3 - 0.00039446y^4 + 0.00328975y^5)^{-8} \qquad (2)$$

$$E_{TR_1} = 100\,(1 - G)\,, \quad d_{ae} \leq M \text{ and } y = y_1 \quad \text{and} \quad E_{TR_2} = 100\,G\,, \quad d_{ae} \geq M \text{ and } y = y_2 \qquad (3)$$

$$y_1 = -\left(\frac{Ln\left(\frac{d_{ae}}{M}\right)}{\sqrt{2}\,Ln(1.5)}\right), \quad d_{ae} \leq M \text{ and } y = y_1 \quad \text{and} \quad y_2 = \frac{Ln\left(\frac{d_{ae}}{M}\right)}{\sqrt{2}\,Ln(1.5)}\,, \quad d_{ae} \geq M \text{ and } y = y_2 \qquad (4)$$

where G is an error curve or approximation function (dimensionless) dependent on the absolute value y (dimensionless) of the function in Equation 4. M represents the median value (μm) of the associated cumulative log normal distribution and can be taken from Table 1. Since there are no standardized numerical calculation equations for the fractions *PM10* and *PM2.5*, approximate functions were derived from the impactor efficiencies specified in DIN EN 12341. For *PM10* the separation curves can be calculated according to Equations 5 and 6:

$$PM10_1 = \frac{100 - 1.7005d_{ae} + 0.4788{d_{ae}}^2 - 0.0736{d_{ae}}^3}{100}\,, \quad d_{ae} < M \qquad (5)$$

$$PM10_2 = 0.5\,(1 + 0.4y_2 + 0.3{y_2}^2 + 0.01{y_2}^3 - 0.2{y_2}^4 + 0.1{y_2}^5)^{-8}\,, \quad d_{ae} \geq M \text{ and } y = y_2 \qquad (6)$$

For *PM2.5*, the separation curves can be approximated using Equations 7 and 8:

$$PM2.5_1 = 100 - \frac{100\left(1 - \left(0.5\,(1+0.3y_1+0.9{y_1}^2+0.1{y_1}^3-0.04{y_1}^4+0.003{y_1}^5)^{-8}\right)\right) 50\,(1+e^{-0.01\, d_{ae}})}{100}\,, \quad d_{ae} \leq M \text{ and } y = y_1 \qquad (7)$$

$$PM2.5_2 = 100 - \frac{100\left(0.5\,(1+0.3y_2+0.9{y_2}^2+0.1{y_2}^3-0.04{y_2}^4+0.003{y_2}^5)^{-8}\right) 50\,(1+e^{-0.01\, d_{ae}})}{100}\,, \quad d_{ae} \geq M \text{ and } y = y_2 \qquad (8)$$

Table 1. Median value M(Fraction)

M(thoracic)	*M(hrr)**	*M(PM10)*	*M(PM2.5)*
11.64 μm	2.50 μm	10.16 μm	2.50 μm

* hrr = high risk respirable.

For IAM, the 24h moving average value of *PM10* (μg/m³) is defined as the simulation start value. In Germany, for example, the Federal Environment Agency offers a suitable measuring network for all federal states, from which the site-specific *PM10* outdoor concentrations can be read out. Since IAM has to be carried out particle size dependent, among other things because of the deposition effect, the pure *PM10* concentration value is useless for the time being. For further calculations, the corresponding particle size distribution (PSD) is therefore required, which is usually not recorded by official measuring stations. Accordingly, the typical particle size distribution according to DIN EN ISO 16890 is used (Figure 1b). A distinction must be made between urban and rural bimodal size distributions, which are given by the combination of logarithmic normal distributions for the coarse and fine mode. The typical urban particle size distribution q_{3u} (dimensionless) can be calculated according to Equation 9 as follows (DIN 2017):

$$q_{3u} = 0.45\left(\frac{1}{\sqrt{2\pi}\,Ln(2.2)}\right) e^{\left(-\frac{(Ln(d_{ae})-Ln(0.3))^2}{2\,Ln(2.2)^2}\right)} + (1 - 0.45)\left(\frac{1}{\sqrt{2\pi}\,Ln(3.1)}\right) e^{\left(-\frac{(Ln(d_{ae})-Ln(10))^2}{2\,Ln(3.1)^2}\right)} \qquad (9)$$

This size distribution has its fine modal value at a particle diameter of 0.30 µm and its coarse modal value at 10.00 µm. The associated standard deviations are 2.20 and 3.10. These modes are weighted over a mixing ratio of 0.45. In the rural particle size distribution, however, the fine mode is 0.25 µm and the coarse mode 11.00 µm. From the mixing ratio of 0.18 and the standard deviations of 2.20 and 4.00 the rural distribution is calculated as Equation 10 (DIN 2017):

$$q_{3r} = 0.18\left(\frac{1}{\sqrt{2\pi}\,Ln(2.2)}\right)e^{\left(-\frac{(Ln(d_{ae})-Ln(0.25))^2}{2\,Ln(2.2)^2}\right)} + (1-0.18)\left(\frac{1}{\sqrt{2\pi}\,Ln(4)}\right)e^{\left(-\frac{(Ln(d_{ae})-Ln(11))^2}{2\,Ln(4)^2}\right)} \tag{10}$$

With the help of the particle size distribution and the separation curves, the particle size specific mass concentrations required for IAM can be determined from the *PM10* mass concentration. This also allows conclusions to be drawn about the *SPM* mass concentration. Based on the *SPM* concentration, the initial concentration of the other three fractions can be derived. Thus, the *PM10* concentration can be used for IAM for the fractions *PM10*, *PM2.5*, *thoracic* and *high risk respirable.*

Material Balance Model

Material Balance Models are based on the principle of particle number or mass conservation. These models can apply to a single zone or multiple zones, where a zone is defined as a single room within a building or describes only a part of a single room. The parameter to be determined using a Material Balance Model is given a single uniform value in this zone. If a room is regarded as a zone and a *PM10* concentration calculation is carried out for it, only one concentration value per time interval results for the room. IAM aims at predicting the particle mass or number concentration in indoor rooms. This indoor particle concentration is influenced by both particle sources (e.g. natural infiltration, resuspension and generation) and sinks (e.g. natural exfiltration and deposition) (Chao, Wan, and Cheng 2003), which can be represented by the mass balance for naturally ventilated buildings from Equation 11 (Drzymalla and Henne 2019; Nazaroff 2004):

$$V\frac{dC_m}{dt} = PQkC_O - QkC_m(t) - Q_dC_m(t) + E(t) + R(t) \tag{11}$$

Here, V corresponds to the room volume (m³), which is the result of the clear dimensions of the room. Natural infiltration is one of the particle sources and is described by the product of penetration coefficient P (dimensionless), air flow rate Q (m³/s), mixing factor k (dimensionless) and the outdoor aerosol concentration C_O (µg/m³). In contrast, the term consisting of $QkC_m(t)$ stands for the natural exfiltration of particles and has a negative sign as particle sink. $C_m(t)$ describes the indoor aerosol concentration (µg/m³) at time t. The deposition also corresponds to a particle sink and is described by the product of the volumetric flow rate Q_d (µg/m³) and $C_m(t)$. Q_d in turn, corresponds to the product of the deposition surface area A of the zone under consideration (m²) and the particulate deposition velocity V_d (m/s) (Tung, Chao, and Burnett 1999). V_d is usually determined by Brownian diffusion, thermophoresis and gravitational forces. Gravitational forces have the greatest influence on V_d, which is why in this study V_d is equated with the gravitational settling V_g (m/s) (Hinds 1999). Also $R(t)$ represents the particle resuspension rate (µg/s) and $E(t)$ the particle generation rate (µg/s). Since this study assumes that there are no occupants in the rooms or buildings to be simulated, aerosol whirling and generation is unlikely. Accordingly, the terms $R(t)$ and $E(t)$ can be neglected. Furthermore, it is assumed that $C_m(t)$ at time $t = 0$ corresponds to the initial indoor concentration C_i (µg/m³). It should be noted, that Equation 11 is only valid if indoor and outdoor temperatures are equal, otherwise, entering air flow rate is not equal to outgoing volume air flow rate. Moreover, the mass balance only includes the fundamental effects in naturally ventilated buildings (natural infiltration/exfiltration, particle deposition/resuspension and generation) and neglects e.g. particle nucleation, coagulation, deactivation or effects in association with ventilation systems (filter efficiencies, supply or recirculation air flow rates). Taking A and V_g into account and integrating the differential Equation 11 gives (Morawska & Salthammer 2003):

$$C_m = \left(C_i - \frac{PQkC_0}{Qk+A\frac{\rho_0 d_{ae}{}^2 g}{18\eta}}\right)e^{-\left(\frac{Qk+A\frac{\rho_0 d_{ae}{}^2 g}{18\eta}}{V}\right)t} + \frac{PQkC_0}{Qk+A\frac{\rho_0 d_{ae}{}^2 g}{18\eta}} \tag{12}$$

where ρ_0 corresponds to the unit density (1000.00 kg/m³), g to the gravity (9.81 m/s²) and η to the viscosity of air (1.81E-05 kg/ms).

Linking Building Information Modeling with Indoor Aerosol Modeling

To link the IAM described above with the open BIM method, a possible workflow is presented, which is shown in Figure 2. In the first step, the ERs for the IAM of naturally ventilated single-zone buildings have to be identified and documented. The ERs describe a defined amount of information that should be exchanged at a certain point in time during an information transfer between processes of different stakeholders (DIN 2018). These ERs ultimately serve to meet predefined operational requirements of certain process phases and usually result in a tabular breakdown. Within these ERs, attributes are defined for a defined use case to attach arbitrary characteristics to BIM model elements (Klempin 2019). A Pset is therefore a collection of similar attributes. These Psets are structured according to a certain schema, whose attributes may differ depending on the IFC version. Before defining individual Psets, they should be compared with the standardized and predefined Psets of the buildingSMART organization. The IFC, in turn, are an interoperable data exchange format based on the standard for the exchange of product model data, STEP for short, which structures geometric and alphanumeric information according to the EXPRESS schema (Schatz and Westphal 2020). In the second step, the architecture of the building to be considered must be modeled. In this study, Autodesk Revit is used as a BIM modeling tool. If new, non-standard features or attributes need to be defined (Psets), they can be manually added to the BIM model as project parameters within Revit in the third step. For further use of BIM, an IFC export is necessary in the fourth step. This IFC export is done using the integrated export function within Revit. The IFC version that influences the IFC schema and the Model View Definition (MVD) must be selected. An MVD is used to filter domain-specific information from the BIM model during the data export. Since the MVDs available in Revit cannot be easily modified, the information added manually in step three would be lost during the export. To avoid this data loss, a mapping table must be created to correctly locate the new Revit information in the IFC schema. This mapping table must be in the form of a text file (*.txt) and should be imported during the export process (Autodesk GmbH 2018). Afterwards, all information required for IAM can be exported into the IFC format without loss. Alternatively, the location table mentioned above can be omitted. However, the incomplete IFC file must be manually extended with the missing information or attributes, taking into account the EXPRESS schema. As soon as a reusable IFC file is available, the fifth step is to import the IFC file into an information management tool. Such a tool is not used to model geometric objects, but to process semantic information. In this study, DESITE BIM is used as an information management tool to enable advanced editing and referencing of the data in the BIM model. In the sixth step, a script for IAM is programmed using an interface available in DESITE BIM. The programming is primarily done using JavaScript and HTML. In the seventh and last step, automated IAM is performed.

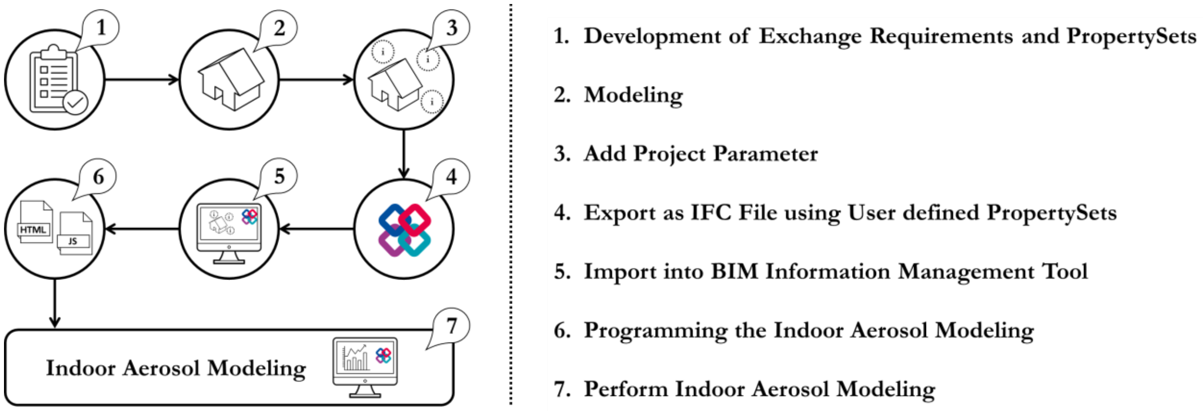


Figure 2 Schematic workflow for linking BIM and IAM.

CASE STUDY

The BIM-integrated IAM is tested on a naturally ventilated single-zone building whose walls are adjacent to the outside air. The chosen residential building is a fictitious example building in 51065 Cologne-Mülheim Germany, whose geometry is modeled in Autodesk Revit. A net floor area of 40.00 m² (length = 8.00 m and width = 5.00 m) and a clear height of 2.80 m are assumed for the building, resulting in a net room volume of 112.00 m³. According to the fact, that the zone is empty (unfurnished) and only the effect of particle settling to the floor is considered, the net floor area corresponds to the particle deposition surface area. Additionally, a typical total required ventilation rate of 46.80 m³/h can be selected as the air flow rate for the described zone, generating an air exchange rate of 0.42 h^{-1} (ANSI/ASHRAE 2019). The IAM is carried out for a selected time period of seven minutes on 01-01-2020, where all boundary conditions from Table 2 have to be considered. This includes the constant *PM10* outdoor concentration of 61.00 µg/m³ which is based on the daily mean value of the official measuring station DENW211, located at the Clevischer Ring in Cologne-Mülheim (Umweltbundesamt 2020). Since DENW211 has a *PM10* sample inlet standardized according to DIN EN 12341 (see Figure 1a) and an urban PSD (see Figure 1b) is assumend, Equations 5, 6 and 9 can be used to calculate back to an SPM concentration of 71.71 µg/m³. Subsequently, using Equations 1 to 4 and 7 to 9, the outdoor concentration values for the fractions *thoracic*, *high risk respirable* and *PM2.5* can be calculated. The resulting PSDs are shown in Figure 3a. In addition, an unoccupied and unpolluted zone is assumed, which is why an initial indoor concentration of 0.00 µg/m³ is assumed for all mentioned fractions. Furthermore, a penetration coefficient must be selected. This coefficient ranges between 0 and 1, where 1 means that 100% of the particles can infiltrate through the building envelope. Also, this coefficient varies greatly depending on the particle size. Since particle diameters between 0.005 and 500.00 µm are considered for the IAM, it is almost impossible to define an individual penetration coefficient for each particle diameter. For this reason, a uniform value of 0.60 is used for all aerodynamic particle diameters, which is normally typical for particles with a diameter of 1.00 to 5.00 µm (Emmerich & Nabinger 2001). In addition, a homogeneously well-mixed indoor air is assumed.

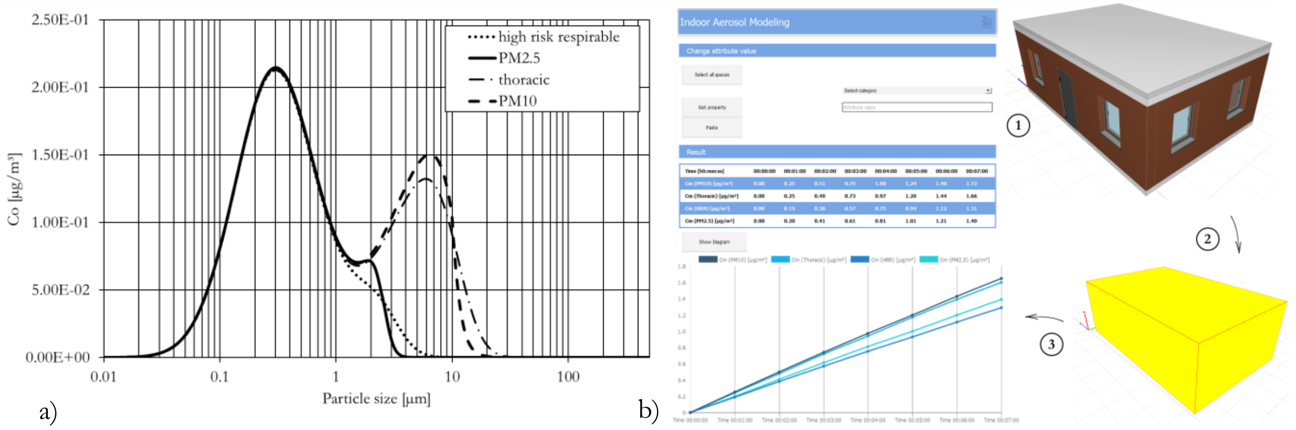
Table 2. Boundary conditions for the IAM

V	n	$Q = V n$	A	C_O *(PM10)**	C_i *(Fraction)*	P	k	d_{ae}	*PSD*
112.00 m³	0.42 h^{-1}	46.80 m³/h	40.00 m²	61.00 µg/m³	0.00 µg/m³	0.60	1.00	Figure 3a	urban

* The PM10 outdoor concentration taken from the Umweltbundesamt (Umweltbundesamt 2020). The other outdoor concentrations are C_O *(thoracic) = 59.12 µg/m³*, C_O *(PM2.5) = 48.97 µg/m³ and* C_O *(hrr) = 45.64 µg/m³* based on SPM = 71.71 µg/m³.

RESULTS AND DISCUSSION

To implement the IAM of naturally ventilated single-zone buildings, a total of eight attributes were defined, which are shown in Table 3 in the Appendix. Three of these attributes were used, which are standardized by buildingSMART (buildingSMART International Ltd. 2020). The remaining five attributes had to be redefined in line with the buildingSMART, as these have not been standardized up to now. Accordingly, these specific ERs were located under the Pset "Pfd_IndoorAerosolModeling". The ERs were then mapped in the IFC data model. By following the method described above and integrating the ERs, an automated IAM could be performed within DESITE BIM. Figure 3b shows a screenshot of the automated calculation for the building described in the case study. Point 1 of Figure 3b shows the example building and the user interface developed in DESITE BIM. Under the section "Change attribute value", the button "Select all spaces" must be pressed at the beginning of the simulation, which selects the room volume of the building, highlights it in yellow and performs the IAM automatically. The calculation results for the fractions *PM10*, *thoracic*, *PM2.5* and *high risk respirable* are then displayed within the user interface as absolute values in µg/m³. According to the case study described and a simulation time of 420 seconds, the following concentrations occur in the indoor air: $C_{m,PM10}$(t = 420 s) = 1.72 µg/m³, $C_{m,PM2.5}$(t = 420 s) = 1.40 µg/m³), $C_{m,thoracic}$(t = 420 s) = 1.66 µg/m³ and $C_{m,hrr}$(t = 420 s) = 1.31 µg/m³. Additionally, it is possible to display the calculated time history of the airborne particle mass concentrations in a diagram. Thereby, the aerosol concentrations in the building can be visualized and evaluated. For example, the *PM2.5* concentration can be compared with the assessment values according to VDI 6022-3 and thus a classification of the indoor air quality can be made (Verein Deutscher Ingenieure e. V. 2011). Based on this, measures can be taken in advance to prevent the assessment values from being exceeded. With the button "Select category" it is possible to vary the penetration coefficient, the mixing factor and the initial *PM10* indoor concentration to represent different scenarios. If the building geometry changes during the numerous project phases, it can be easily updated using the IFC data format. The results show that BIM-integrated IAM is possible. The method presented in this study follows a big open BIM approach. This means that, on the one hand, there is model-based communication between the project participants and, on the other hand, vendor-neutral data formats are used. In this study this is implemented by exchanging models from Revit to DESITE BIM in the IFC data format. Proprietary BIM tools were used, but only because there is currently no standardized solution or MVD for IAM of naturally ventilated single-zone buildings.



Time [hh:mm:ss]	00:00:00	00:01:00	00:02:00	00:03:00	00:04:00	00:05:00	00:06:00	00:07:00
Cn (PM10) [µg/m³]	0.00	0.25	0.51	0.75	1.00	1.24	1.48	1.72
Cn (Thoracic) [µg/m³]	0.00	0.25	0.49	0.73	0.97	1.20	1.44	1.66
Cn (HRR) [µg/m³]	0.00	0.19	0.38	0.57	0.75	0.94	1.12	1.31
Cn (PM2.5) [µg/m³]	0.00	0.20	0.41	0.61	0.81	1.01	1.21	1.40

a) b)

Figure 3 (a) Urban outdoor PSDs of the four fractions and (b) BIM-integrated IAM within DESITE BIM.

CONCLUSION

The goal of this study was to enable automated BIM-integrated IAM based on particle concentrations in Germany's outdoor air. A suitable method was successfully developed and presented for this purpose. Among other things, separation functions for the fractions *PM10* and *PM2.5* were presented for the first time, which conform to DIN EN 12341. The results of the case study illustrate that the IAM can be implemented to the BIM-process very well with suitable BIM tools, but that there is no full standardization. As a general rule, linking IAM to BIM requires a deeper understanding of the IFC hierarchy. However, once the link has been made, a successful BIM-integration can make workflows more efficient, which results in an early and more holistic process between the development of project designs and indoor air quality. Finally, in order for IAM using BIM to become practicable, the results obtained should be used in the next step to define an IDM, an MVD and a BIM application case according to VDI 2552, in which the process participants are identified and their tasks are named.

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APPENDIX

Table 3. Exchange Requirements

Category	Element	Attribute	Unit	Entity	Pset / Qset*	Property / Quantity*	PropertyType / QuantityType*	Value Type
Air Quality	Site Plan	PSD	-	IfcSpace	Pfd_IndoorAerosolModeling	ParticleSizeDistribution	P_SINGLEVALUE	IfcLabel
Air Quality	Umweltbundesamt	Co (PM10)	$\mu g/m^3$	IfcSpace	Pfd_IndoorAerosolModeling	OutdoorConcentrationPm10	P_SINGLEVALUE	IfcReal
Air Quality	Measurement/ Estimation	Ci (PM10)	$\mu g/m^3$	IfcSpace	Pfd_IndoorAerosolModeling	InitialConcentrationPm10	P_SINGLEVALUE	IfcReal
Air Quality	Measurement/ Estimation	P	-	IfcSpace	Pfd_IndoorAerosolModeling	PenetrationCoefficient	P_SINGLEVALUE	IfcReal
Air Quality	Measurement/ Estimation	k	-	IfcSpace	Pfd_IndoorAerosolModeling	MixingFactor	P_SINGLEVALUE	IfcReal
HVAC	Air Conditioning Systems	n	h^{-1}	IfcSpace	Pset_SpaceThermalRequirements	NaturalVentilationRate	P_SINGLEVALUE	IfcCountMeasure
Architecture	Building Model	A	m^2	IfcSpace	*Qto_BuildingElementProxyQuantities	*NetSurfaceArea	*Q_COUNT	IfcAreaMeasure
Architecture	Building Model	V	m^3	IfcSpace	*Qto_SpaceBaseQuantities	*NetVolume	*Q_VOLUME	IfcVolumeMeasure