



OSLO METROPOLITAN UNIVERSITY
STORBYUNIVERSITETET

Department of Built Environment
Postal address: P.O.box 4 St. Olavs plass, N-0130 Oslo, Norway
Visiting address: Pilestredet 35, Oslo
Website: www.oslomet.no

MASTER'S THESIS

TITLE: A BIM-oriented tool to evaluate indoor TVOC-concentration compliance	SUBMISSION DATE: 25.05.2023
	NO OF PAGES & APPENDICES: 53/2
AUTHOR: Morten Riksfjord	SUPERVISORS: Peter G. Schild

DONE IN COLLABORATION WITH: -	CONTACT PERSON: Peter G. Schild
----------------------------------	------------------------------------

ABSTRACT:
The average human spends about 90 % of their life indoors. This has led to an increased focus on IAQ including TVOC concentrations, as the latter can be up to ten times higher indoors than outdoors. Sources of TVOC must be identified and measured so that measures can be taken to ensure good IAQ. This study has researched the use of BIM for calculation of the indoor TVOC concentrations and developed an add-in in Autodesk Revit for this purpose. There are few earlier studies that have used BIM to assess TVOC concentration despite the number of analytical models developed for determining emissions and concentrations. Environmental building standards and labelling schemes have requirements for emission levels which give the manufacturers an incentive to perform tests and provide documentation. The add-in used static TVOC concentration calculation and emission data from building materials to perform a calculation in the Revit environment. This has shown to be a simple method, but there is also a need for further development of the program to make this calculation manageable and simple to use for architects and engineers.

KEYWORDS (separate with comma):
TVOC, Emission, BIM, BREEAM-NOR, Indoor Climate, Revit, IAQ

Preface

I completed my degree as a Bachelor of Science in Electrical Engineering in 2021 and started the same year on this master's course. This became the transition from the electrical world to the HVAC world and I do not regret this choice. The journey has been inspiring and exciting with this project as the final part of the master's study. It was an instructive and interesting period with a deep dive into fields I have not worked with before. I hope this thesis can be a valuable supply to the HVAC field

I would like to thank my supervisor Peter G. Schild for all his guidance, support and help during the research and writing period of this theses. His help has been invaluable.

I wish to thank my colleagues for flexibility and professional advice, and especially Lars for cooperation and conversations throughout this whole study.

I also want to thank Sebastian for always being there to support me no matter what. I really look forward to spending more time with you and Rita in the future.

Finally, I wish to thank all my friends and family supporting me though this period, especially my family in MV331, my friends visiting me every Monday, my hairdresser, Joachim, and of course my little brother Ørjan.

I look forward to a time to prioritize BUK, friends, and family.

Morten Riksfjord

25.05.2023

Summary

Due to the amount of time modern humans spend indoors, indoor air quality is an important topic as TVOC concentration indoors can be as high as ten times higher than outdoors. Sources of TVOC must therefore be identified and measures must be taken to ensure good indoor air quality for the occupants. This study consisted of two main goals where the first goal is to perform research for use of BIM for performing TVOC concentration calculation, and the second being to develop an add-in for assessing compliance with environmental standards.

To meet the first goal, a literature review was performed that revealed that little research was done on the use of BIM to perform this type of calculations despite all the analytical models developed for both static and dynamic conditions. There are however some programs available that can perform TVOC concentration calculation, but they are not all BIM-oriented and do not comply with the definition of BIM later defined in this study.

Research conducted in this study about environmental building and certification standards, revealed thresholds for both material TVOC emissions and airborne TVOC concentration. Multiple ecolabelling schemes were evaluated and summarized. These schemes give manufacturers an incentive to perform emission tests and contribute to increased documentation on material emission which will give entrepreneurs, architects, and engineers the necessary data to make decisions on what materials to choose, and data to perform TVOC concentration calculations. The testing method required for measuring material emissions is a chamber test performed according to ISO 16000-9 or EN 16516, where the latter is based on the former.

To meet the second goal, calculation methods for both TVOC emissions and TVOC air concentration were evaluated. Dynamic and static equations were developed and simplified for use in an add-in for Autodesk Revit developed with the use of Revit API. This add-in has provided a simple way of adding information to the model and using this information to perform calculation on the TVOC concentrations. Further development of the add-in is required to make the add-in easy to use for architects and engineers.

Summary in Norwegian

Moderne mennesker tilbringer mye av tiden innendørs, og dette har ført til at innendørs luftkvalitet har blitt et viktig tema ettersom TVOC konsentrasjonene innendørs kan være opp til ti ganger høyere enn de er utendørs. Kilder til TVOC må derfor bli identifisert og målt slik at tiltak kan gjøres for å sikre god innendørs luftkvalitet for brukerne. Dette studiet besto av to hovedmål hvor det først målet var å utføre et litteratursøk for bruk av BIM for å utføre beregning på TVOC konsentrasjon, og det andre målet var å utvikle en add-in for å kontrollere samsvar med miljøstandarder.

For å nå det første målet, har et litteratursøk blitt gjennomført og vist at det er lite forskning som er gjort på bruken av BIM for å utføre denne type beregning på tross av antallet analytiske modeller som er utviklet for beregning av både statiske og dynamiske forhold. Det er derimot noen programmer tilgjengelig som kan utføre beregning av TVOC konsentrasjon, men de er ikke alle BIM-orientert og samsvarer ikke med definisjonen av BIM senere definert i dette studiet.

Det er i forbindelse med dette studiet gjennomført undersøkelser på miljøstandarder for bygninger og sertifisering, som har vist terskelverdier for både TVOC emisjoner fra material, samt. TVOC konsentrasjon i luften. Flere merkeordninger for miljøvennlige produkter har blitt evaluert og oppsummert. Disse ordningene gir produsenter et insentiv til å utføre emisjonstester og bidrar til økt dokumentasjon på materialeemisjoner som igjen vil gi entreprenører, arkitekter og ingeniører nødvendige data for å foreta materialvalg og gjøre beregninger på TVOC konsentrasjon. Den nødvendige testmetoden for å måle emisjoner er en kammertest som er gjennomført i henhold til ISO 16000-9 eller EN 16516, hvor sistnevnte er basert på førstnevnte.

For å nå det andre målet, så er beregningsmetodene evaluert for både TVOC emisjoner og TVOC konsentrasjoner i luften. Dynamiske og statiske formler ble utviklet og forenklet for bruk i en add-in for Autodesk Revit utviklet i Revit API-miljøet. Denne add-in har gitt en enkel metode for å legge inn informasjonen i modellen, samt. bruke denne informasjonen til å gjennomføre beregninger på TVOC konsentrasjonene. Videre utvikling av add-in er nødvendig for å gjøre den enklere å bruke for arkitekter og ingeniører.

Contents

Preface	2
Summary.....	3
Summary in Norwegian	4
Contents	5
Glossary.....	6
1 Introduction	7
1.1 Overview and background.....	7
1.2 Research questions	7
1.3 Study limitations.....	8
1.4 Structure of the study	8
2 Earlier studies	10
2.1 Documentation of the literature review	10
2.2 Research findings	10
3 VOC & material thresholds.....	13
3.1 Health based TVOC concentration thresholds.....	13
3.2 Certification schemes and related thresholds	14
3.3 Material testing.....	17
3.4 Material labelling and certifications.....	18
4 Overview of emission calculation methods.....	22
4.1 Material domain – Emission rate	22
4.2 Air domain – Airbourne TVOC concentration.....	24
4.3 Conclusion	26
5 Development and description of the BIM tool	28
5.1 Motivation for an add-in.....	28
5.2 The needed functions and capabilities	28
5.3 User interface	28
5.4 Available functions.....	29
5.5 Details about the add-in.....	35
6 Application on case building - Results and discussion	36
6.1 Case building	36
6.2 Calculation of concentration	36
6.3 Change of ventilation rate in rooms.....	36
6.4 Verification of the add-in.....	38
7 Conclusions.....	40
7.1 Main findings.....	40
7.2 Suggested further work	41
8 References.....	42
9 APPENDICES	46
9.1 Appendix A – Further details about the add-in.....	47
9.2 Appendix B – The reviewed studies with their calculation methods.....	53

Glossary

ASHRAE - American Society of Heating Refrigerating and Air-Conditioning Engineers

BIM – Building Information Modelling

IAQ – Indoor Air Quality

LCI – Lowest Concentration of Interest

LOI – Level Of Information

OSHA - Occupational Safety and Health Administration

PM – Particulate Matter

SER – Specific Emission Rate

TVOC – Total Volatile Organic Compound

U.S. EPA – United States Environmental Protection Agency

UI – User Interface

VOC –Volatile Organic Compound

WHO – World Health Organization

1 Introduction

1.1 Overview and background

The average human spends about 90 % of their life indoors [1]. Indoor Air Quality (IAQ) is therefore important for our health. IAQ refers to the degree to which indoor air is conducive to the health and well-being of occupants. It is influenced by the presence of gaseous and particulate pollutants like volatile organic compounds (VOC), radon, carbon monoxide, dust, mold, allergens, pathogens, and other airborne contaminants. Approximately 6,7 million people die every year from exposure to ambient and household air pollution according to World Health Organization (WHO) and 99 % of the world's population live in places where the air pollution levels exceed WHO guideline limits [2]. Polluted air may not however be the main reason in all cases, but it can be a contributing factor and is therefore a valid argument for why further research about air pollution should be done.

Some of these air pollutions mentioned are VOCs. These are gases that over time are emitted from solids and liquids found in most of the materials that are used in building materials, furniture, perfumes, plastics, and cleaning products [3]. These gases can be of different densities and volatilities, but can be summed up and referred to as total volatile organic compounds (TVOC). The United States Environmental Protection Agency (U.S. EPA) states that TVOC levels indoors might be up to ten times higher indoors than what they are outdoors [4]. Some VOCs have negative health effects and its severity depends on the different VOC [3]. The building certification standards BREEAM-NOR, WELL and LEED are some of the many standards that have requirements for the materials used in buildings and for the air pollution concentration. They have their own set of parameters that must be satisfied to get points or the certificate of approval [5]–[7].

Calculation of TVOC concentrations in the indoor air can be performed already in the design phase of a construction process. By integrating this calculation in a Building Information Modelling-environment (BIM), it can be done with the model geometry in the BIM-model as a part of the design process. Material testing and assessment of the emission rates will be a critical factor for the validity of the calculation performed in the design phase. A great barrier for BIM compatibility is presented by Kirkegaard et. al [8] in their studies where the problem emerges as soon as information about the model is exported out from the original model and into another software like e.g. Excel for transformation. Calculations and changes made in Excel will not automatically update back to the model, and this will downgrade the BIM compatibility. Maintaining BIM compatibility is the main reason why creating an add-in will be interesting to do in this study. This might also make the evaluation of indoor climate a more seamless and quicker operation as the add-in will handle the information and calculation, and use the most recent geometries from the model.

This study will look at how to utilize a BIM-oriented tool to evaluate indoor TVOC-concentration compliance and seek to answer the research questions raised in the next section. The term “BIM-oriented” is further described in Section 2.2.4.

1.2 Research questions

1. Is BIM used today to evaluate TVOC concentration indoors?
 - How far have researchers and developers come in this field, and is there any available BIM-oriented programs that can do this evaluation?
 - A literature review will be performed to assess this and what research that has been done.
2. What requirements do the standards set for materials and IAQ?
 - What thresholds do the environmental standards set for materials and for IAQ?
 - A review of environmental standards will be performed, and the different thresholds will be presented.
3. How are materials tested for TVOC, and is this documentation available?
 - How is the testing process performed and is this material testing documentation available for customers and engineers for use in TVOC calculations?
 - Are there different methods for how the materials can be tested?

- A review of some of the methods referred to in the environmental standards will be carried out.
- 4. How can the TVOC concentration be calculated?
 - Is this calculation a computational demanding process?
 - Can this calculation be done dynamically?
 - Is there any program that already performs this task?
 - A review of the available methods will be performed.
- 5. How can the calculation be implemented in a BIM-oriented program?
 - Is the calculation of TVOC concentration possible to implement in a BIM-oriented program and how can it be done?
 - Can the calculation be performed in a simple way?
 - A proof of concept of implementation of TVOC calculation in a BIM-oriented program will be performed.

1.3 Study limitations

It was important to set study limitations to focus on what was the object for this study. These narrowing factors and limitations are listed below.

This study does not:

1. Explain the technical and chemical details regarding measurement methods of TVOC.
2. Explain the difference between SVOC, VVOC, etc., and the compositions of the different VOC categories.
3. Explain the health risk with high TVOC levels.
4. Investigate the validity of the testing methods performed by standards and certifications.
5. Investigate other means of calculation than analytical methods.
6. Investigate the rate of adsorption or absorption of TVOC to materials.

1.4 Structure of the study

Section 2 - Earlier studies

A literature review for studies using a BIM-oriented program to calculate concentrations of TVOC. Documentation of the review with its research findings will be presented.

Section 3 - TVOC & material thresholds

Investigating environmental standards and certification schemes with their TVOC concentration & emission thresholds. The thresholds found will be presented. How materials are tested with labelling schemes is also a topic in this section.

Section 4 - Overview of emission calculation methods

Calculation of TVOC material emission and TVOC airborne concentration from a literature review will be presented.

Section 5 - Development and description of the BIM tool

Description of the need for a BIM-tool for calculating TVOC concentration and requirements for this tool. Presentation of the functions in the developed add-in with the user interface.

Section 6 - Application on case building - Results and discussion

Proof of concept of the developed add-in on a case building. Testing the calculations and verification of the validity of the methods used

Section 7 - Conclusions

Concluding the study with main findings, important topics to mention and suggested further work for both the study and the add-in.

Section 8 - References

Section 9 - APPENDICES

Appendix A – Further details about the add-in

Appendix B – The reviewed studies with their calculation methods

2 Earlier studies

A literature review was performed to discover earlier studies and research that focuses on the use of BIM to evaluate TVOC. This section will present a summary of the research results.

2.1 Documentation of the literature review

The selected search engine for the literature review was Google Scholar as it searches in a broad amount of literature libraries. The number of search results with the iterations and selected keywords are presented in Table 1.

Table 1 - Search results literature review

Search iteration	Search words	Number of results	Search engine
1	bim voc	6690	Google scholar
2	bim voc building	4220	Google scholar
3	bim voc building emission	2100	Google scholar
Reviewed	Selected based on title	13	Google scholar

The search results were many, but the relevance of the articles became smaller and smaller for each article reviewed. Most articles got discarded by their title, and many promising articles got discarded due to their summary presenting another approach than what was sought. The “snowballing”-method was used on the relevant articles and has revealed studies that were used in Section 4.

2.2 Research findings

Of the 2100 articles in the result, 13 articles were investigated further. Selection of these articles was based on titles and abstracts of the articles. The key information and characteristics of the articles will be presented in the next sections.

2.2.1 Software used

Table 2 shows a short overview of the software used for either calculation, simulation, or modeling of IAQ. Autodesk Revit and VICO Constructor were used to retrieve geometry from the building program. CONTAM and IAQx were used to run an IAQ simulation of the indoor environment.

Table 2 - The software used in the articles from the literature review

Software	Studies	Description
Autodesk Revit	[11]	3D modelling tool for designing, construction and documentation [12]
VICO Constructor	[9], [10]	The 3D design component of the 5D package the VICO presents [13]
CONTAM	[14]	“Multizone indoor air quality and ventilation analysis program” [15]
IAQx	[16]	IAQ multizone simulation tool for indoor pollution [17]

2.2.2 Calculation methods

The one thing all the 13 studies have in common, is that they have a method for estimating the pollution levels from building materials to the air in a room. The number of studies for each method is shown in Figure 1.

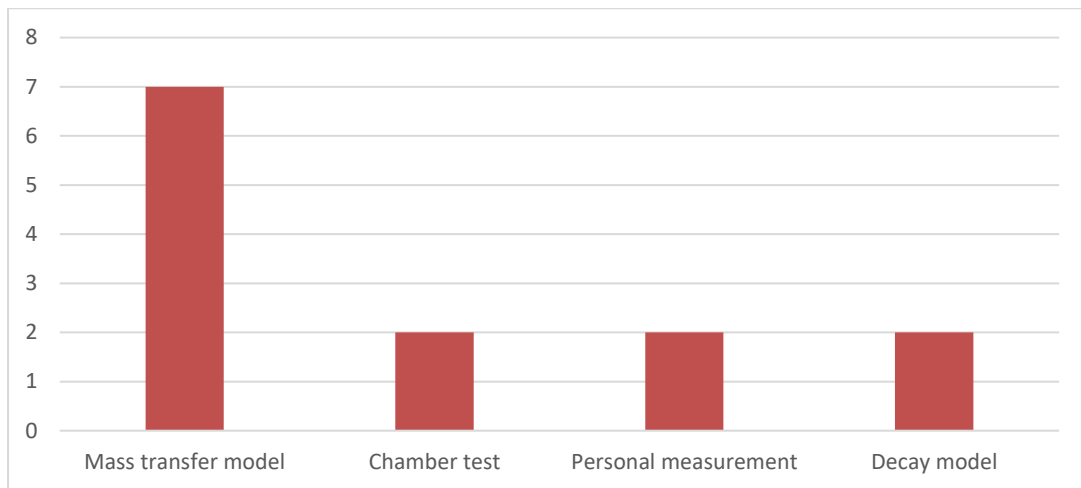


Figure 1 - Pollution estimation method

This figure shows four ways for how emissions from materials were determined for the studies:

- Mass transfer model
 - Model that estimates the mass transfer with diffusion of TVOC through the material and emission to the air. [18]–[24]
- Chamber test
 - Empirical chamber test of materials to test their emission rates. [11], [14]
- Personal measurement
 - Wearable measuring equipment was worn during polluting work to measure the amount of pollution. [9], [10]
- Decay model
 - An approximate decay model for different materials, typical diffusion, and surface treatment. [16], [25]

The methods, with exception of “Personal measurement”, will be presented further in Section 4. Only five of the studies perform a pollution calculation to find the concentration in the room.

2.2.3 Summary of the studies

Only five of the 13 studies reviewed calculate pollution concentrations in the indoor environment, whereas two studies use software that only have their focus on IAQ and the others being more BIM-oriented.

One of the five articles from the literature review performed its study with the same intent and tool as this study. This is the study by D’Amico et al. [11] “*BIM for Healthy Buildings: An Integrated Approach of Architectural Design based on IAQ Prediction*”. It has described the process on how to calculate the TVOC concentration based on the material emissions, ventilation rate and area of the surfaces with the use of BIM. The BIM tool selected for this study was Autodesk Revit. The main way the study achieved to do the calculation in the model, was by creating a set of parameters for different TVOC contributions and the summation of TVOC. It has used several free Revit add-ins to create parameters, assign values, calculate, and perform the final evaluation of the TVOC concentrations. The study uses a static analytical model for calculating concentration and is the same as the one presented in section 9 in EN 16516. A more detailed description of this formula will be presented in Section 3.3.2 as it will be used for the calculation in the developed Revit add-in.

The study performed by Kirkegaard et. al [16] focuses on the use of BIM tools to evaluate performance analysis of the IAQ. The tool presented for estimating the TVOC concentration in this study was IAQX. IAQX is a simulation program for simulating pollution. It specializes in TVOCs, particulate matter (PM) and gases [17]. It is not explicitly connected to BIM-software like Autodesk Revit. Geometry, however, can be extracted from a CAD file for calculation with the surface areas from a model.

The study “*Integrating Occupational Indoor Air Quality with Building Information Modeling (BIM)*” [10] targets the use of BIM to determine the pollution concentration during construction and

indoor treatment of the construction elements such as painting, sanding and dusting. PM is the main pollution source that is evaluated. However, the static calculation method with a mass balance model for calculation of PM is the same as the one used for TVOC. The study used VICO Constructor and VICO Estimator as programs to retrieve geometry and to assign pollution during the different working processes for each worker.

As an average, the other eight studies focus on improved methods for determining TVOC emissions from materials with dynamic methods. They lay the foundation for the dynamic calculation method described in Section 0. The studies have developed analytical methods and performed simulations and on-site measurements to compare the quality of the analytical method.

A short summary of the articles reviewed can be found in Table 22 in Appendix B. A detailed overview of TVOC with measurement methods was developed in the review article by Salthammer [26].

2.2.4 Defining BIM and a “BIM-oriented” software

BIM is defined by the “US National Building Information Modelling Standard” as a digital representation of a physical building [27]. The ISO 19650 standard series describes and defines BIM with requirements for information, information flow, project cycle and more. Autodesk presents a “BIM Process” on its website that is divided into four parts as seen in Figure 2. Their definition is not 100 % to what is described in ISO 19650.

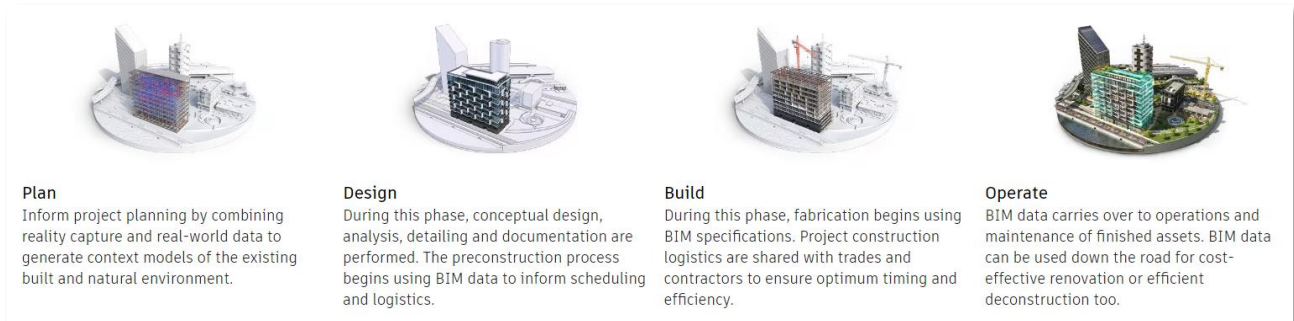


Figure 2 – Why use BIM? [28]

The use of BIM can also be divided into five levels (0-4) of collaboration and complexity [29], [30]. Level 2 of this collaboration introduces 3D as a working environment and sharing of the 3D model with the use of an open file format. For further work in this study, it is chosen to define BIM according to this description of level 2 together with the description given by Autodesk.

The five levels of BIM collaboration are [29], [30]:

0. Paper-based drawing with zero collaboration.
1. 2D construction drawings with some 3D modelling.
2. Teams work in their own 3D models.
3. Teams work with a shared 3D model.
4. Adding scheduling, cost, & sustainability information.

As a summary, a BIM-oriented software includes the use of 3D in the four phases of the building process as well as sharing and importing the 3D model with an open file format.

3 VOC & material thresholds

In this section, information about how materials are tested and labelled will be presented. A few environmental standards will also be presented with their thresholds for TVOC emission from materials and concentration in indoor air.

3.1 Health based TVOC concentration thresholds

WHO has released IAQ guidelines for Europe which define classes with thresholds for health hazards for different TVOC concentrations. Table 3 shows the classes.

Table 3 - Thresholds by WHO [33]

Level	Recommendation	TVOC [mg/m^3]	TVOC [ppm]
1	Target value	> 0,25	0 - 0,05
3	Slightly increased (harmless)	0,5 - 1,0	0,10 - 0,20
4	Significantly increased (only temporary exposure)	1,0 - 3,0	0,20 - 0,61
Outside quality classes	Greatly increased (not acceptable)	> 3,0	> 0,61

All the standards reviewed in this study have their concentration threshold below what is considered harmless according to WHO with exception of LEED. This is presented further in Section 3.2.3.

The German Environment Agency has presented its own list with thresholds for hygienic classes as shown in Table 4:

Table 4- German Environment Agency [31]

Stage	Hygienic assessment	TVOC Threshold [mg/m^3]
1	Hygienically safe	$\leq 0,3$
2	Hygienically still safe, if indoor air guide values are not exceeded for single substances or substance groups	0,3 - 1,0
3	Hygienically noticeable	1,0 - 3,0
4	Hygienically alarming	3,0 - 10,0
5	Hygienically unacceptable	>10,0

It is important to mention that different VOCs have their own emission thresholds. A full list of these thresholds can be found in Table 1 from the "German AgBB Testing and Evaluation Scheme (2015)" [32].

The European Union (EU) presented in 1992 a TVOC threshold at $300 \mu\text{g}/\text{m}^3$ and no compound concentration should exceed 50 % of their compound class threshold nor more than 10 % of the TVOC limit [33]. EU also has a list with lowest concentration of interest (LCI) with thresholds for individual VOC compounds [34].

The U.S. EPA does not present thresholds for neither TVOC concentration in the air or LCI-values.

American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE) presents concentration of interest for individual compounds in its ANSI/ASHRAE Standard 62.1-2022.

Occupational Safety and Health Administration (OSHA) does not evaluate TVOC, but it present a list of permissible exposure limits [35].

3.2 Certification schemes and related thresholds

The core differences in the building standards presented in this section are shown in Table 5. The table assesses the general differences and the method for how the standards evaluate emissions.

Table 5 - Core differences in environmental building standards

Certification	Type of certification	System	Country	Targets	Method
BREEAM	“Green building”	Points, class	Global	Materials used in building	Material testing in chamber
WELL	“Green building”	Points	Global	TVOC concentration in air	VOC measurement in air
LEED	“Green building”	Points, class	Global	Materials used in building	Material testing in chamber
FiSIAQ	IAQ	Class	Finland	TVOC concentration in air	VOC measurement in air
Nordic Swan Ecolabel	IAQ	Pass/Fail	Northern countries	Materials used in building	Material testing in chamber

3.2.1 BREEAM-NOR 2016

BREEAM is a point-based rating system where there are multiple available certification levels a building can achieve as shown in Figure 3 [36].

GOOD	VERY GOOD	EXCELLENT	OUTSTANDING
≥ 45% score	≥ 55% score	≥ 70% score	≥ 85% score

Figure 3 - BREEAM certification levels [36]

A BREEAM assessor with team decides which certification level the building will aim to accomplish and which points that the building shall achieve to reach the score needed for the certification level. There are nine categories with different number of points and weighing, and multiple stages for the building process [36]. The standard provides multiple available choices in the categories, but there are also some base requirements that must be met to get BREEAM certified.

Table Hea 02-01 in BREEAM-NOR sets a TVOC emission limit of $\leq 0,3 \text{ mg/m}^3$ for every material that is used in the building if points in the Hea 02 class are to be reached. The material emission rate is a result from a chamber test according to ISO 16000-9, EN 16516, EN 16402 or CDPH Standard Method, and is applicable for wood-based products, flooring materials, ceiling, wall, acoustic and thermal insulation, adhesives, and sealants [7].

3.2.2 WELL v2. Q4 2022

“The WELL Building standard is a vehicle for buildings and organizations to deliver more thoughtful and intentional spaces that enhance human health and well-being” it says on the website for WELL [5]. The standard has multiple preconditions that must be met and many available optimizations.

Many of the preconditions provide two or more choices for the user to choose from. Section A01 Air Quality Part 2 provide two methods for meeting thresholds for organic gases:

1. Laboratory-based TVOC tests with the results criteria as shown in Figure 4.

Option 1: Laboratory-based VOC tests

The following thresholds are met in occupiable spaces:

- a. Benzene (CAS 71-43-2): 10 µg/m³ or lower.¹¹
- b. Formaldehyde (CAS 50-00-0): 50 µg/m³ or lower.¹²
- c. Toluene (CAS 108-88-3): 300 µg/m³ or lower.¹³

Verified by: Performance Test

Figure 4 - WELL Option 1 [5]

2. TVOC continuous monitoring with the criteria shown in Figure 5.

Option 2: TVOC continuous monitoring

The following threshold is met in occupiable spaces:

- a. Total VOC: 500 µg/m³ or lower.

Verified by: Sensor Data

Figure 5 - WELL Option 2 [5]

To verify that the actual concentrations are below the thresholds presented by WELL, on-side measurements with air samplings according to ISO 16000-3 or 16000-6 must be performed. Sampling has to be done on multiple locations in the building [37].

3.2.3 LEED v4.1

LEED is a rating system that claims to be the most widely used green building rating system in the world [38]. It is a point-based system where the building gets a score based on how many measures are taken in the different categories.

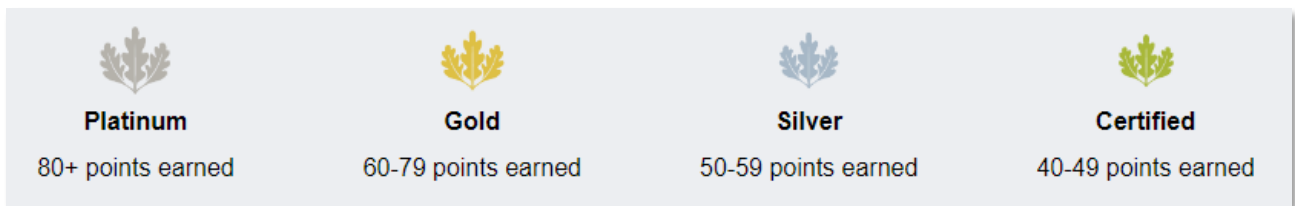


Figure 6 - LEED certification rating system [39]

The number of points available in the LEED standard for the choice of low emitting materials is shown in Table 6.

Table 6 - LEED emission points [6]

Available points for low emitting materials	
2 product categories	1 point
3 product categories	2 point
4 product categories	3 point
5 product categories	3 point + exemplary performance
Reach 90 % threshold in at least three product categories	Exemplary performance or 1 additional point if only 1 or 2 points achieved above

The categories are as follows:

- Paints and coatings
- Adhesives and sealants
- Flooring
- Ceilings
- Insulation
- Furniture
- Composite wood

All these categories require that 75 % or more materials of that category meet the TVOC emissions evaluation and two also require that 100 % meet the TVOC content evaluation. The whole list can be found in the LEED manual [6].

The TVOC emissions evaluation requires evaluation in one of two ways where the last way is chamber testing of materials according to EN 16516. There are thresholds for the separate VOCs that must be satisfied. These VOCs must be compliant with the LCI-values from Table 1 of the “German AgBB Testing and Evaluation Scheme (2015)” [32]. Additionally, the amount of TVOCs after 28 days measured according to EN 16516 must be reported to be in between one of the following limits:

- Below 0,5 mg/m³
- Between 0,5 and 5 mg/m³
- Above 5 mg/m³

Neither the LEED manual nor the LCI-values explicitly set a threshold for the TVOC concentration.

3.2.4 Finnish Society of IAQ and Climate (2018)

This standard is a voluntary classification standard guided by the National Building Code in Finland. The standard target indoor climate and presents three grades of certification as presented in Table 7 [40], [41].

Table 7 - Certification grade Finnish Society of IAQ and Climate [40], [41]

Grade	Grade Assessment	Description	TVOC Threshold [µg/m ³]
M1	Individual Indoor Climate	Very good air quality in space. Comfortable thermal conditions in summer and winter. The user may individually control the ventilation	< 200
M2	Good Indoor Climate	Good air quality. No draughts. Temperature rises above comfortable levels during the hottest days of summer	< 400
M3	Satisfactory Indoor Climate	The air quality and thermal conditions fulfill the requirements set by the building codes. Temperature usually rises above comfort levels on hot day	> 400

To fulfill the criteria for concentration limits presented in Table 7, on-site measurement must be performed. At least 70 % of the VOCs shall be identified and the individual VOC must not be higher than the given thresholds. The measurements must be performed according to the measurement method described in the National Report of Switzerland [42]. This report is a part of an European research initiated across multiple countries to assess the indoor climates in European buildings.

The measurement method describes the use of an adsorption tube (Tenax) to sample the TVOC levels. Description about the tube and the function can be found in the study by Jia et. al [43].

3.2.5 Chosen thresholds

A third-party software for calculation emission and testing compliance, must have several thresholds to test compliance according to. These thresholds must be for TVOC concentration in the air. Good candidates for this purpose are presented in Table 8.

Table 8 - TVOC Concentration thresholds

Pollutant	Certification	Score	Concentration limit [$\mu\text{g}/\text{m}^3$]	Reference
TVOC	FiSIAQ	M1	200	[41]
TVOC	FiSIAQ	M2	400	[41]
TVOC	WELL A01 Part 2	-	500	[5]

3.3 Material testing

3.3.1 ISO 16000-9 – Chamber test

The ISO 16000-9 testing standard uses a chamber test for determining the emissions and lays the foundation for the EN 16516 testing standard as EN 16516 is built upon ISO 16000-9 [44]. The content of ISO 16000-9 was not evaluated further in this study. See Table 9 in Section 3.3.2 for more information about the parameters regarding the chamber test in ISO 16000-9.

3.3.2 EN 16516 – Chamber test

The article “New European VOC emissions testing method CEN/TS 16516 and CE marking of construction products” writes the following about EN 16516:

“It is based on ISO 16000 standard series, but it contains additional refinements for improving reability and has gone through extensive validations” [44]

The standard utilizes a chamber test to perform testing for emission levels for materials. The test is performed to measure only the emissions from the material tested, and converts the results to an equivalent concentration if the material was used in a hypothetical reference room with set dimensions. The parameters and dimensions for the reference rooms in EN 16516 and ISO 16000-9 are as shown in Table 9.

Table 9 - Reference room [44]

	CEN/TS 16516	ISO 16000-9
Temperature [$^{\circ}\text{C}$]	23	23
Relative humidity [%]	50	50
Ventilation rate [/h]	0,5	0,5
Dimensions	3 m x 4 m x 2,5 m 1 door, 1 window	not specified
Volume [m^3]	30	17,4
Loading factors [m^2/m^3]		
Walls	1,0	1,4
Floor or ceiling	0,4	0,4
Small surface, e.g., door or window	0,05	not specified
Very small surfaces	0,007	0,011

The loading factor in Table 9 describes the surface area pr room volume for different surface elements. E.g., a wall with loading factor of $1 \text{ m}^2/\text{m}^3$ in a 30 m^3 room will have 30 m^2 surface area of walls. The loading factors with their equivalent areas for a reference room is presented in Table 10.

Table 10 - Loading factors and areas

		EN 16516		ISO 16000-9	
Volume [m ³]		30		17,4	
		Loading factors in [m ² /m ³]	Area [m ²]	Loading factors in [m ² /m ³]	Area [m ²]
	Walls	1,0	30,0	1,4	24,4
	Floors and ceiling	0,4	12,0	0,4	7,0
	Small surface, e.g., door or window	0,05	1,5	not specified	-
	Very small surfaces	0,007	0,21	0,011	0,191

The output result from the chamber test is a concentration of pollution in the air given with the unit $\mu\text{g}/\text{m}^3$. This concentration is highly theoretical since it only accounts for one material and there is more than one material and pollution source in most rooms. The concentration can be evaluated as the materials contribution to the total concentration in the room. This method is suitable for setting requirements for the pollution from individual materials.

EN 16516 section 9 describes how Specific Emission Rate (SER) for each material can be calculated from the chamber test concentration results like presented in Equation (3-1):

$$SER_A = \frac{C_a AER_t}{L_{At}} \quad (3-1)$$

where

SER_A is the area specific emission rate [$\mu\text{g}/\text{m}^2\text{h}$];

C_a is the mass concentration of compound a in the sampled air [$\mu\text{g}/\text{m}^3$];

AER_t is the air exchange rate of the test chamber [air changes/h];

L_{At} is the loading factor in the test chamber [$\text{m}^2 \text{ sample}/\text{m}^3$].

A more detailed description of how the chamber test is performed and Equation (3-1) is presented by Reinhard Oppl in [44]. The SER calculated can be used as an emission rate in further calculations in combination with other emission rates from ceilings, floors, and other surfaces.

The study performed by Marć [45] “Problems and challenges associated with estimating the emissions of organic compounds from indoor materials” states that the dataset acquired from this testing method is valid and accurate, and gives a probable estimation of the emissions for the compounds under the specific conditions for the test.

3.4 Material labelling and certifications

3.4.1 RTS Emission Classification

RTS Emission Classification is a material labelling classification owned by The Building Information Foundation RTS which is a Finnish foundation with focus on good planning and building methods [46]. Testing for the M1 or M2 label is done as a chamber test according to their own testing standard, ISO 16000-9 or EN 16516. Emission testing results shall be reported as SER and model room concentration [47]. The M1 emission label is as shown in Figure 7.



Figure 7 - M1 RTS Emission label [21]

The SER thresholds to acquire M1 and M2 labelling are shown in Table 11.

Table 11 - M1 and M2 label emission thresholds [48]

Parameter	Emission class M1 [$\mu\text{g}/\text{m}^2\text{h}$]	Emission class M2 [$\mu\text{g}/\text{m}^2\text{h}$]
TVOC emissions	≤ 200	≤ 400

3.4.2 EN 15251 – Points to chamber test

Table 12 shows thresholds from the Norwegian ratified version of EN 15251. The table gives two thresholds for TVOC emission rates to determine three emission classes. Low emitting materials pointing to this standard must have emission levels below $200 \mu\text{g}/\text{m}^2\text{h}$ and must be tested according to the testing method described in ISO 16000-9 or 16000-10. The original table also states that undocumented materials count as non-low emitting materials [49].

Table 12 - Translated version of parts of Table NA.12 from NS-EN 15251:2007+NA:2014 [16]

Compound	Testing method	Emission factor after 28 days		
		Class I Very low emitting materials	Class II Low emitting materials	Class III Non-low emitting materials
		[$\mu\text{g}/\text{m}^2\text{h}$]	[$\mu\text{g}/\text{m}^2\text{h}$]	[$\mu\text{g}/\text{m}^2\text{h}$]
TVOC	EN ISO 16000-9 or ISO 16000-10 in combination with ISO 16000-6	≤ 75	≤ 200	≥ 200

3.4.3 GEV-EMICODE

GEV-EMICODE is a German labelling certification standard which has its outspring from EN 16516 [50]. The standard uses three labels as shown in Figure 8 to certificate the materials. The label thresholds for the different labels are as shown in Table 13.



Products that are **low in emissions** are awarded the **EMICODE® EC2** label. This class fulfils the basic requirements for being granted the **EMICODE®** label.



The highest class **EMICODE® EC1** has proven itself over many years as a standard for products that are **very low in emissions**. The materials awarded this label comply with very stringent health and environmental requirements.



The premium class **EMICODE® EC1^{PLUS}** defines the limit of what is technically feasible today. Introduced in 2010, it sets even higher and stricter limit values than category EC1.

Figure 8 - Certification labels for GEV-EMICODE [51]

Table 13 - GEV-EMICODE label thresholds with conversion to SER in parenthesis [51]

$\mu\text{g}/\text{m}^3$ ($\mu\text{g}/\text{m}^2\text{h}$)	EC1 ^{PLUS}	EC1	EC2
Flooring and construction products: TVOC after 28 days. Loading factor = 0,4	≤ 60 (≤ 75)	≤ 100 (≤ 125)	≤ 300 (≤ 375)
Surface treatment products: Sum of TVOC+TSVOC after 28 days Loading factor = 1	≤ 100 thereof max. 40 SVOC (≤ 50 thereof max. 20 SVOC)	≤ 150 thereof max. 50 SVOC (≤ 75 thereof max. 20 SVOC)	≤ 400 thereof max. 100 SVOC (≤ 200 thereof max. 50 SVOC)

3.4.4 The Nordic Swan Ecolabel v4.0

The Nordic Swan Ecolabel is a labelling scheme with environmental requirements in 59 different product categories. It sets requirements for product life cycle, use of chemicals and sustainable development [52]. It is developed by Nordic Ecolabelling which is one of the founders of Global Ecolabelling Network (GEN). GEN has members in nearly 60 countries and territories around the world [53]. The Nordic Swan Ecolabel can only be assigned to residential and educational buildings. It has a point-based system with multiple categories with minimum requirements. Nordic Ecolabelling must also conduct an inspection of the building site. The labelling does not consist of degrees of compliance, but there is pass or fail [54].

For building materials and paints, limit values for emissions for material categories are given as a concentration calculated from its equivalent emission value from chamber testing according to EN 16516, ISO 16000-9 or others. The concentration threshold for building materials is $100 \mu\text{g}/\text{m}^3$ [55],[56]. Conversion to SER with loading factor 1 gives $50 \mu\text{g}/\text{m}^2\text{h}$. The Nordic Swan Ecolabel is shown in Figure 9 [57].



Figure 9 - Nordic Swan Ecolabel

3.4.5 Comparison of the ecolabels

Labelling schemes for materials with their grades and thresholds for labelling are shown in Table 14.

Table 14 - Summation of the ecolabels with their emission limits

Labelling scheme	Grade	Emission rate $[\mu\text{g}/\text{m}^2\text{h}]$	Testing standard
RTS Emission Classification	M1	≤ 200	EN 16516/ISO 16000-9, other
RTS Emission Classification	M2	≤ 400	EN 16516/ISO 16000-9, other
EN 15251	Class I	≤ 75	ISO 16000-9
EN 15251	Class II	≤ 200	ISO 16000-9
EN 15251	Class II	≥ 200	ISO 16000-9
GEV-EMICODE	EC1 Plus	≤ 75	EN 16516
GEV-EMICODE	EC1	≤ 125	EN 16516
GEV-EMICODE	EC2	≤ 375	EN 16516

Nordic Swan Ecolabel	-	≤ 50	EN 16516/ISO 16000-9, other
----------------------	---	------	-----------------------------

4 Overview of emission calculation methods

In this section, calculation methods discovered in a literature review for similar studies and from the standards, will be presented. The calculation methods can be divided into two categories:

1. Material domain – Emission rate.
 - Calculation of rate of TVOC from the material to the air.
 - Can also consider the rate of diffusion through the layers in the material.
2. Air domain – TVOC concentration.
 - Calculation of the concentration of TVOC in the room.

4.1 Material domain – Emission rate

Emissions from the materials can be divided into categories as shown in Figure 10.

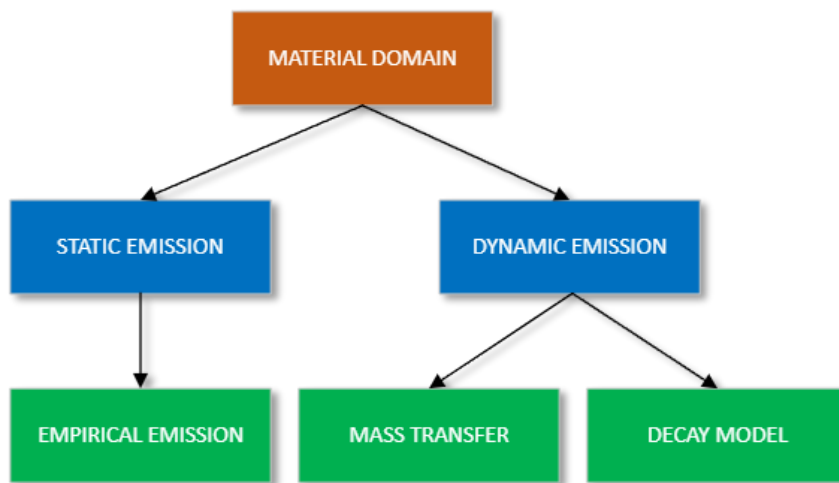


Figure 10 - Categories in the material domain

The result from each of these categories is a total emission rate given that can be calculated to a value in $\mu\text{g}/\text{h}$. This rate can be static or dynamic depending on the method used and the simplifications made.

4.1.1 Empirical emission

The calculation of the SER from a material is described in Section 3.3.2. The emission rate and area for each surface in a room can be multiplied and added up as shown in Equation (4-1). This method is static and does not vary over time.

$$E = \sum_{i=1}^N (SER_i A_i) \quad (4-1)$$

where

- E is the total emission from materials in the room [$\mu\text{g}/\text{h}$];
 SER_i is the area specific emission rate for material i [$\mu\text{g}/\text{m}^2\text{h}$];
 A_i is the area surface of the material i in the room [m^2];

4.1.2 Mass transfer

The mass transfer method is a complex method and consists of an analytical model of the behavior of the emissions from the walls. It considers emissions through multi-layered materials with diffusion through the materials and level of exposure to the air. The study performed by Little et. al [58], “*Modeling emissions of volatile organic compounds from new carpets*”, is one of the pioneering studies in this research field. The model they developed is shown in Equation (4-2). How to convert the result from this equation to emission rate, and the variables, indexes and units of this equation can be found in the study mentioned.

$$C(x, t) = 2C_0 \sum_{n=1}^{\infty} \left\{ \frac{\exp(-Dq_n^2 t) (h - kq_n^2) \cos(q_n x)}{[L(h - kq_n^2)^2 + q_n^2(L + k) + h] \cos(q_n L)} \right\} \quad (4-2)$$

This method relies on detailed data on the initial concentration of the TVOC in the material, the diffusion rate through the material, and the emission rate from the material to the air. These three parameters are defined by Little et. al [58]:

- C_0 [$\mu\text{g}/\text{m}^3$] – Initial emittable concentration
- D [m^2/s] - Diffusion coefficient in material
- K [-] – Material/air partition coefficient

The study performed by Deng et al. [24] “*Numerical modeling of volatile organic compound emissions from multi-layer dry building materials*” creates a numerical model for multi-layered emissions of TVOC. The study shows good comparisons between simulated data and on-site measurements. The numerical model is complex, but it is valid for both single and multi-layered materials. It also considers diffusion through the different layers, which is an interesting topic because low diffusion on the layer exposed to air will lead to a lower emission rate to the air and thus a lower concentration of TVOC.

A similar study was performed by Hu et al. [59] in “*An analytical mass transfer model for predicting VOC emissions from multilayered building materials with convective surfaces on both sides*” where they used a mass transfer model to predict the TVOC emissions through materials and from two sides of the wall. This method shows good results when compared with experimental data. The model is however most precise with the long-term emissions from the materials since a small error in the model shows to be significant in the early stage [59].

Xu et al. [18] performed another study on this topic in “*An improved mass transfer based model for analyzing VOC emissions from building materials*”. Use of this model with the correct information can calculate the TVOC emissions with a maximum relative error of 5 % [18].

4.1.3 Decay model

The literature review performed by Guo [25] presents a number of decay models for different materials. The models are derived from emissive characteristics for multiple materials. The simplest decay model is a first-order decay model which gives reduction in TVOC concentration in a material as a function of time. The first order decay model as given in Equation (4-3) assumes that the emission rate is proportional to the remaining pollution in the source. The decay model can also be of a higher order and complexity.

$$E = E_0 e^{-kt} \quad (4-3)$$

where

- E is the emission factor of the material [$\mu\text{g}/\text{m}^2\text{h}$];
- E_0 is the initial emission factor of the material [$\mu\text{g}/\text{m}^2\text{h}$];
- k is the decay rate constant of the material [$1/\text{h}$];
- t is time [h];

4.2 Air domain – Airborne TVOC concentration

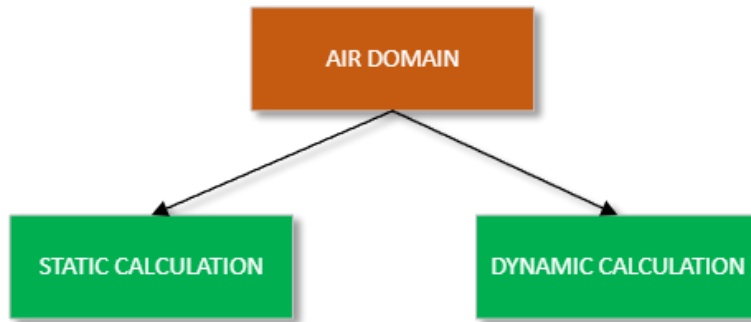


Figure 11 – Airborne TVOC calculation

To calculate the TVOC concentration in the air, it can be done statically or dynamically with a mass balance model. Both methods are based on Equation (4-4).

$$V \frac{dC_{ind}}{dt} = E(t) + Q(t)[fC_{out}(t) - C_{ind}(t)] - S(t) \quad (4-4)$$

where

- V is the volume of the air [m^3];
- C_{ind} is the concentration of TVOC in the indoor air [$\mu g/m^3$];
- C_{out} is the concentration of TVOC in the outdoor air [$\mu g/m^3$];
- E is the emission rate [$\mu g/h$];
- Q is the ventilation rate [m^3/h];
- f is the filtration rate of the supply air [-];
- S is the rate of TVOC adsorption to materials [$\mu g/h$];

The equation is merged from equations from the studies performed by Haghghat and Huang [60] and Guo [25]. Flow of air between rooms is not considered in the equation. An iterative equation for this can be formed as shown in Equation (4-5).

$$C_{ind,(i+1)} - C_{ind,i} = \left\{ AER_i(fC_{out,i} - C_{ind,i}) + \frac{E_i - S_i}{V} \right\} \Delta t \quad (4-5)$$

where

- V is the volume of the air [m^3];
- $C_{ind,i}$ is the concentration of TVOC in the indoor air at the timestep i [$\mu g/m^3$];
- $C_{out,i}$ is the concentration of TVOC in the outdoor air at the timestep i [$\mu g/m^3$];
- E_i is the emission rate at the timestep i [$\mu g/h$];
- AER_i is the air change rate at the timestep i [m^3/h];
- f is the filtration rate of the supply air [-];
- S_i is the rate of TVOC adsorption to materials at the timestep i [$\mu g/h$];
- Δt is the length of the timestep [h];

These equations ignore the effects of indoor chemical and photolytic reactions with e.g. sunlight and compounds in the air.

4.2.1 Static calculation

In a static calculation, all time-varying variables are set to be static. By also assuming outdoor air free from pollution and no adsorption of TVOC to materials, Equation (4-5) can be rewritten as:

$$C_{ind} = \frac{E}{VR} \quad (4-6)$$

where

- C_{ind} , is the concentration of TVOC in the indoor air [$\mu\text{g}/\text{m}^3$];
- E is the emission rate [$\mu\text{g}/\text{h}$];
- VR is the ventilation rate of the room [m^3/h];

By combining this equation with Equation (4-1) for static emission, we get the following equation:

$$C_{ind} = \frac{\sum_{i=1}^N (SER_i A_i)}{VR} \quad (4-7)$$

where

- C_{ind} , is the concentration of TVOC in the indoor air [$\mu\text{g}/\text{m}^3$];
- SER_i is the area specific emission rate for material i [$\mu\text{g}/\text{m}^2\text{h}$];
- A_i is the area surface of the material i in the room [m^2];
- VR is the ventilation rate of the room [m^3/h];

This static calculation takes into account multiple materials with different areas and emission rates, and also requires a few amount of variables to be used. An illustration for this is shown in Figure 12. This method was used in the study by D'Amico et. al [11] and in the study by Altaf [10] to calculate concentration of indoor pollution.

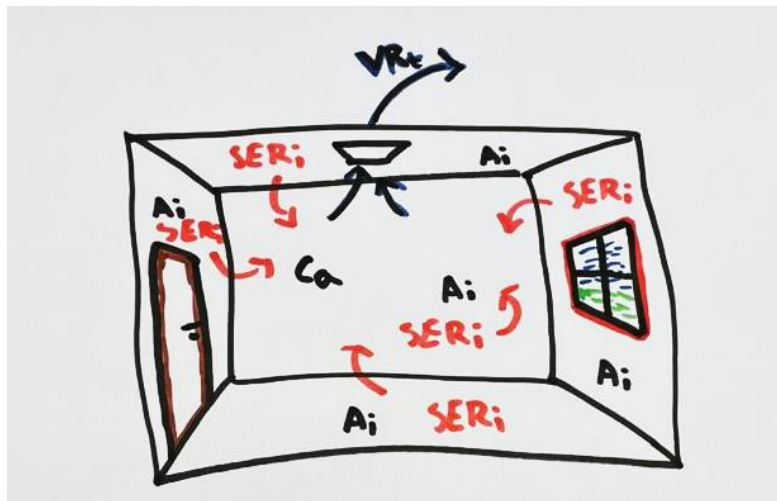


Figure 12 - Illustration of the emissions

4.2.2 Dynamic calculation

To calculate the TVOC concentration dynamically, Equation (4-5) must be used. The equation should be used with a dynamic method for emission rate like the decay model or the mass transfer method. This will replace the emission rate E_i in Equation (4-5).

Multi zone air flow model

In addition to presenting a numerical model for stationary conditions, the study by D’Amico et. al [14] also presents the use of CONTAM which calculates concentration as a multi-zone model. This software calculates the TVOC concentration dynamically. COMIS is also a program that works in the same way as CONTAM [61]. These multi-zone models can calculate flow from one room to another and treat every room as a single cell, whereas a CFD-model divides a room into millions of cells. No studies were found where use of CFD was the calculation method. This is a computational consuming method, but it allows for dynamic results, flow visualization and visualization of concentration hotspots [62].

4.3 Conclusion

The empirical emission method presented in Section 4.1.1 relies on the use of empirical data from chamber testing of the materials to determine emission rates. These data are required by environmental certification such as BREEAM-NOR, WELL, LEED, The Nordic Swan Ecolabelling, and others. This gives manufacturers an incentive to perform this type of testing and include environmental documentation for their products. If all material data is given for test results after 28 days, the calculation of concentration with empirical testing data will be valid for concentration after 28 days. This is by standard considered to be the long-term emissions and the longest test duration [44].

Since the mass transfer method relies on three parameters to calculate the concentration and diffusion through the materials, it is important that these parameters are available for each of the different materials in the building. This is also pointed out as a limitation in the study by Liu et. al [63]. This material data was not discovered in any of the environmental product declarations for the materials used in this study. The study also mentions that the traditional method described does not distinguish between emission rates in the early or transition stage of the emission for a material. The rate of emission from the materials to the air is strongly determined by the diffusion of the emission through the material as mentioned by Holøs et. al [64] in their study “*VOC emission rates in newly built and renovated buildings, and the influence of ventilation – a review and meta-analysis*”. This is something the mass transfer method can consider unlike the empirical method.

The decay model as presented in the review by Guo [25], shows multiple equations for decay rates of TVOC in different types of materials and applications.

These three methods assess TVOC and not the individual compound which can be of a higher toxicity. Calculation of the individual compound was not evaluated further in this study. The main differences between the methods are presented in Table 15.

Table 15 - Comparison between calculation methods

	Advantages	Disadvantages
Empirical emission with static concentration	Easy to use. Material data is available. Simple calculation.	Static. Does not take layered materials into account.
Mass transfer with dynamic concentration	Dynamic. Takes layered materials into account.	Complex calculation. Material data is not available. Use of software recommended.
Decay model with dynamic concentration	Dynamic. Different formula for different types of materials and applications.	Complex calculation. Different formula for different types of materials and applications. Use of software recommended.

Zhang and Shaw [65] have performed a literature review on the modelling methods for emissions and describes a great number of methods that will not be presented in this study.

Table 22 in Appendix B list the 13 studies reviewed from the literature review from Section 2 with their calculation method.

4.3.1 R-number and Hazard Index

R-number is a new and improved way of measuring TVOC as it accounts for the individual VOCs toxicity with the use of LCI-values for each VOC. The Equation for R-number is given in Equation (4-8) [44]. The method is described in EN 16516:2017.

$$R = \sum_{i=1}^N \left(\frac{C_i}{LCI_i} \right) \quad (4-8)$$

where

R is the R-value of TVOC the room [-];

C_i is the concentration of compound i in the indoor air [$\mu\text{g}/\text{m}^3$];

LCI_i is the LCI-value for the compound i [$\mu\text{g}/\text{m}^3$];

In the review by Salthammer [26], Hazard Index (HI) is presented. It represents the same as the R-number and the calculation method works in the same way. HI is defined by the European Commission by its scientific committees [66].

5 Development and description of the BIM tool

An add-in was created to seamlessly perform calculations on TVOC concentrations directly inside the Revit model. The programming language used was C# in the Revit API environment. This section will describe the add-in with its capabilities and functions.

5.1 Motivation for an add-in

The literature review performed for use of BIM to determine TVOC concentration revealed that there was only one study by D'Amico et. al [67] that did this. However, some of the steps in the calculation in the study were performed with multiple other add-ins, and outside the Revit environment with Excel. Kirkegaard et. al [16] stated in their study that use of Excel or other programs than the BIM program itself contributes to downgrading of the BIM operability.

In the study by Brown et. al [68] "*Estimating indoor air quality using integrated 3D CAD building models*", they point out that a program for calculation concentration based on material choice, surface area and types of furniture can be used to give the designers insight in what parameters and materials affect the final IAQ and what measures that can be made.

By having all the information in a BIM-environment with surface areas together with the emission rate for materials, the BIM-model and TVOC concentration will always be updated if ventilation rates, material assignments and room dimensions are correct. This will reduce the need for manual export of data from the model to perform calculations and a need to maintain an Excel sheet. Although software is not needed to perform a static calculation of TVOC concentration, a room can consist of multiple surfaces and different materials which will make the static calculation more demanding. By having this information in the model, the level of information (LOI) will increase.

5.2 The needed functions and capabilities

To meet the requirements for the add-in and to secure the development of an add-in that fulfils its purpose and is easy to use, some design criteria were decided. The add in should work in the following way:

1. Quick to initialize and to use for testing and designing.
2. Able to choose what material to use for the surfaces.
3. Give necessary details on the surfaces in a room and their emissions.
4. Give the total emission and concentration for each room.
5. Give a visual overview of certification results.

5.3 User interface

The User Interface (UI) for the add-in in Revit is made up of buttons on panels in the ribbon as shown in Figure 13. The function of each button will be explained in the next sections. All buttons have their own tooltip with short information on how to use the button and what it does.

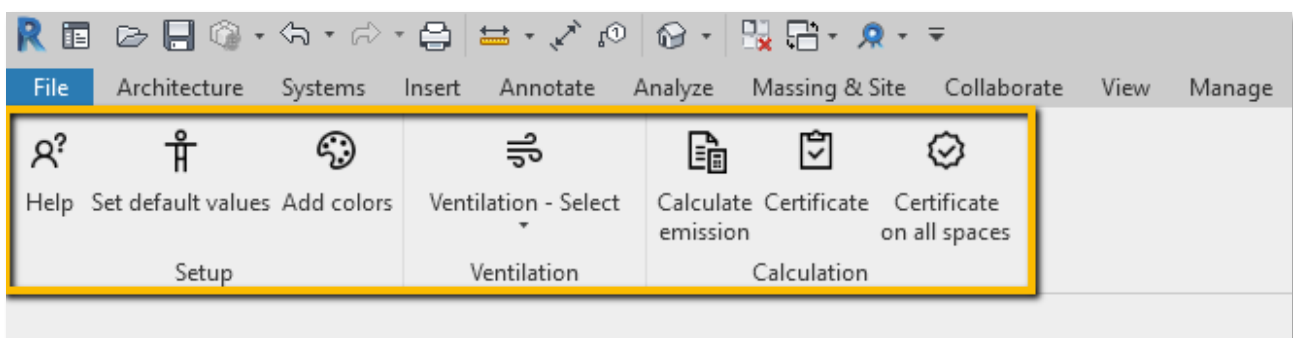


Figure 13- UI of the Revit Add-in

5.4 Available functions

5.4.1 Help



Figure 14 - Revit UI Help

The purpose of this button is to give the user a short introduction of how to use the add-in. The button will display a short informative message. It also creates parameters that are needed for the TVOC calculation process. The help message is shown in Figure 15.

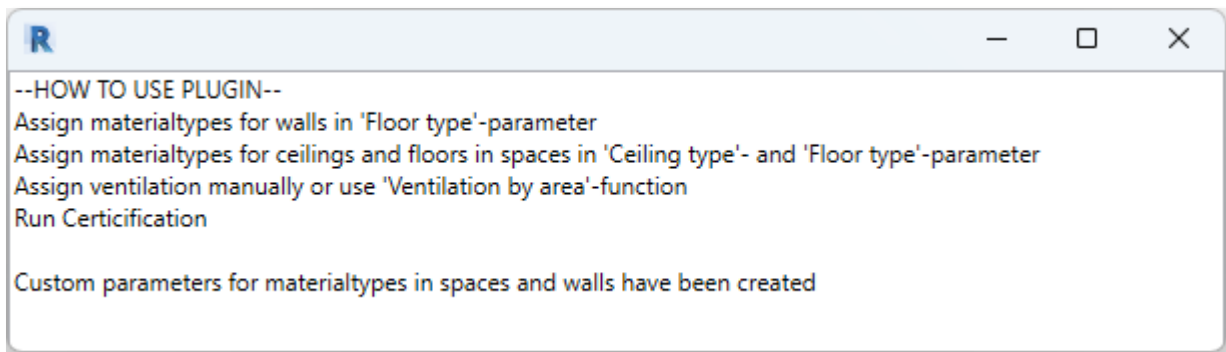


Figure 15 - Help message from add-in

5.4.2 Set default values



Figure 16 - Revit UI Set default values

The first goal set in Section 5.2 is to make the add-in quick to use and make the initializing process as short as possible. This button creates all necessary parameters for the add-in to work and fills in default values in all the places needed where there are no current values. These parameters help to fulfil the second and third goal in Section 5.2.

The parameters created for spaces and walls are shown with a yellow square in Figure 17 and Figure 18 respectively. These will also get a default value along with ventilation rate marked in green in Figure 17.

Mechanical - Flow	
Specified Supply Airflow	0.00 L/s
Calculated Supply Airflow	Not Computed
Actual Supply Airflow	0.00 L/s
Return Airflow	Specified
Specified Return Airflow	50.46 L/s
Actual Return Airflow	0.00 L/s
Specified Exhaust Airflow	0.00 L/s
Actual Exhaust Airflow	0.00 L/s
Outdoor Airflow	3.49 L/s
Identity Data	
Number	1
Name	Space
Room Number	Unoccupied
Room Name	Unoccupied
Image	
Comments	
Floor type	1
Ceiling type	1
Certificate state	0

Figure 17 - Creating parameters for spaces

Identity Data	
Image	
Comments	
Mark	
Surface type	1

Figure 18 - Creating parameter for walls

The custom created parameters for spaces and walls with their default values are shown in Table 16. The “*Certificate state*”-parameter will be reset to 0 when the button is pressed unlike other parameters which will keep their values.

Table 16 - Parameters and default values

Parameter name	Element type/Family	Default value	Data type	Custom parameter	Purpose
<i>Specified Return Airflow</i>	<i>Space</i>	<i>5,56 l/s*m² (Calculated)</i>	<i>HVACAir flow</i>	<i>No</i>	<i>Holds ventilation rate for a space element</i>
<i>Floor type</i>	<i>Space</i>	<i>1</i>	<i>Integer</i>	<i>Yes</i>	<i>ID for the chosen floor material</i>
<i>Ceiling type</i>	<i>Space</i>	<i>1</i>	<i>Integer</i>	<i>Yes</i>	<i>ID for the chosen ceiling material</i>
<i>Surface type</i>	<i>Wall</i>	<i>1</i>	<i>Integer</i>	<i>Yes</i>	<i>ID for the chosen wall material</i>
<i>Certificate state</i>	<i>Space</i>	<i>0</i>	<i>Integer</i>	<i>Yes</i>	<i>Gets a 1 for passed certification and a 2 for failed. Will be reset to 0 when “Set default values”-button is pressed</i>

5.4.3 Add colors



Figure 19 - Revit UI Add colors

To achieve the fifth goal set in Section 5.2, coloring based on certification results is added. The button creates a color scheme that colors the spaces based on the value in the parameter “*Certification state*” in a space. The value is determined for whether the certification passed or not. Default value of 0 in the parameter makes the space white. Passed or failed certification for a space will give the value 1 or 2 respectively which will make the space green or red as shown in Figure 20.

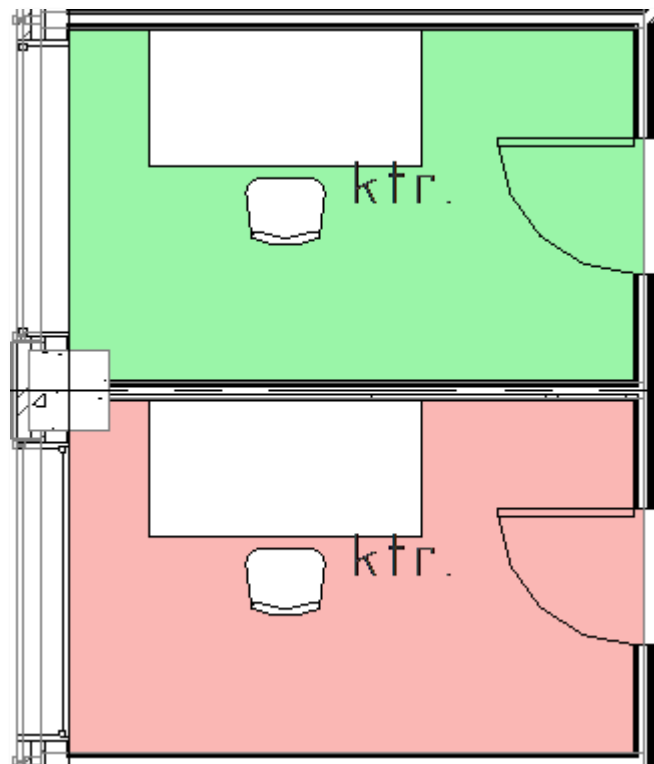


Figure 20 - Added colors

5.4.4 Ventilation

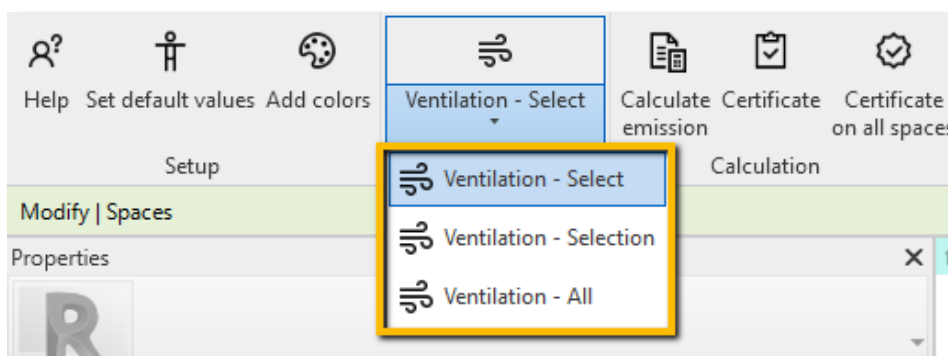


Figure 21 - Revit UI Ventilation

Revit already has parameters for ventilation rate, but calculating and setting the necessary ventilation rate can be a more tedious task since different rooms require different ventilation rates based on their

area. These three ventilation buttons marked in Figure 21 serve to assist this operation and fulfils the first goal in Section 5.2. The buttons have one set of functions in common:

1. Get a space area from the area parameter in the space.
2. Multiply the area with area specific ventilation rate set to be $20 \text{ m}^3/(\text{h}\cdot\text{m}^2)$.
3. Write the result to "Specific Return Airflow" parameter in the space.

The three variants of the button work like presented in Table 17. The operation will override the value in the parameter.

Table 17 - Function of "Ventilation"-buttons

Ventilation - Select	Prompts the user to select which spaces that will get an updated ventilation rate. Exit the command with ESC
Ventilation - Selection	Updates ventilation rate on all already selected spaces. Filters out other non-space components if selected
Ventilation - All	Updates ventilation rate on all spaces

5.4.5 Calculate emission



Figure 22 - Revit UI Calculate emission

One of the key features of the add-in is calculation of the emissions in a room. This feature fulfils the first part of the fourth goal in Section 5.2. Calculation of the emission is done according to Equation (4-1). Retrieving data from the model and iteration through the materials is performed as shown in Figure 23.

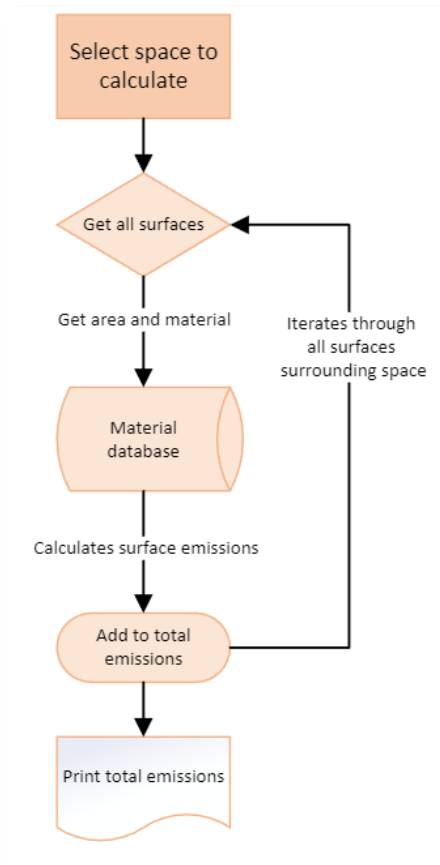


Figure 23 – Calculating the emissions

Length around windows is automatically measured with 5 mm of glue or sealant around the window. Surface area of windows and door are subtracted from the wall to account for less wall surface area. The material database contains surfaces with emissions from both the building material and the paint. The information collected from the TVOC calculation is divided into six parts for presentation:

1. Identification of the space
 - Name
2. Floor emissions
 - Selected floor material, area, and emissions
3. Ceiling emissions
 - Selected ceiling material, area, and emissions
4. Glue emissions
 - Selected glue, length, and emissions
5. Wall emissions
 - For each wall: Selected wall material, wall family, area, and emissions
 - Total wall emissions
6. Total emission
 - Summation of all the emissions

The result box with this information is shown in Figure 24. It is possible to copy text from this box. Export of a file with the results was not implemented.

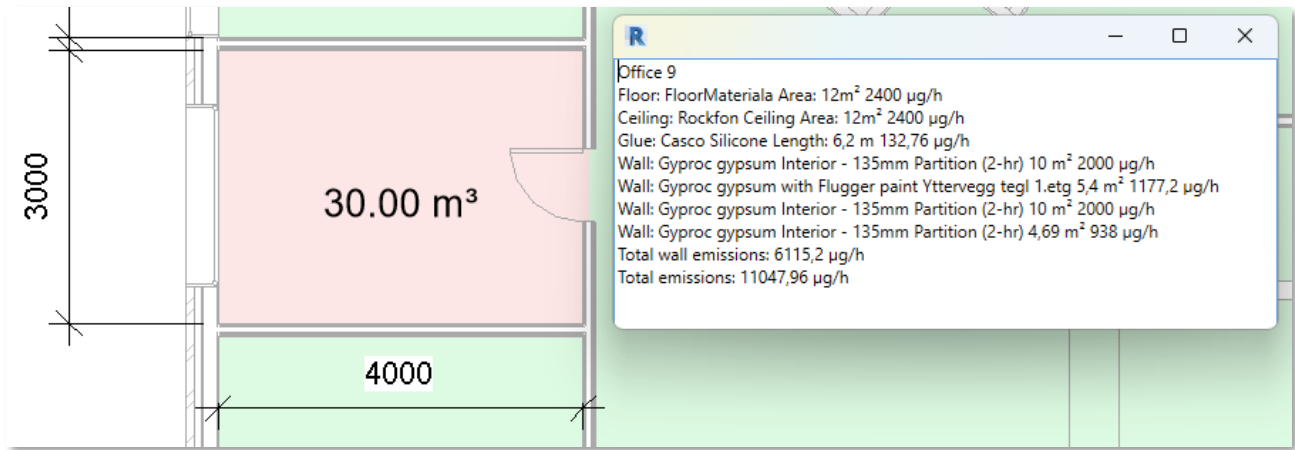


Figure 24 - Results from TVOC calculation

5.4.6 Certificate



Figure 25 - Revit UI Certificate

This button fulfils the fourth goal in Section 5.2 and calculates TVOC concentration and compares the concentration with thresholds in a small number of certifications. It utilizes the same method to summarize the emissions in the room as described in Section 5.4.5, but also takes into account the ventilation rate to calculate the concentration in the room according to Equation (4-7). In addition to that, the button also compares the calculated concentration with some certifications. The certifications and their thresholds implemented in the add-in are shown in Table 8.

If the concentration is below all environmental standard concentration thresholds, the "Certificate state"-parameter will get the value of 1 according to the description for values and colors in Section 5.4.3. Failed certification will set the parameter value to 2. The information collected from the certification of a space is divided into six parts for presentation:

1. General information about the room
 - Space name, area, and volume
2. Ventilation rate
3. Total emissions
 - Calculated as presented in Section 5.4.5
4. Calculated concentration
5. Certifications passed or failed
6. Checks compliance with the concentration thresholds in multiple standards

The result box with this information is shown in Figure 26. It is possible to copy text from this box. Export of a file with the results was not implemented.

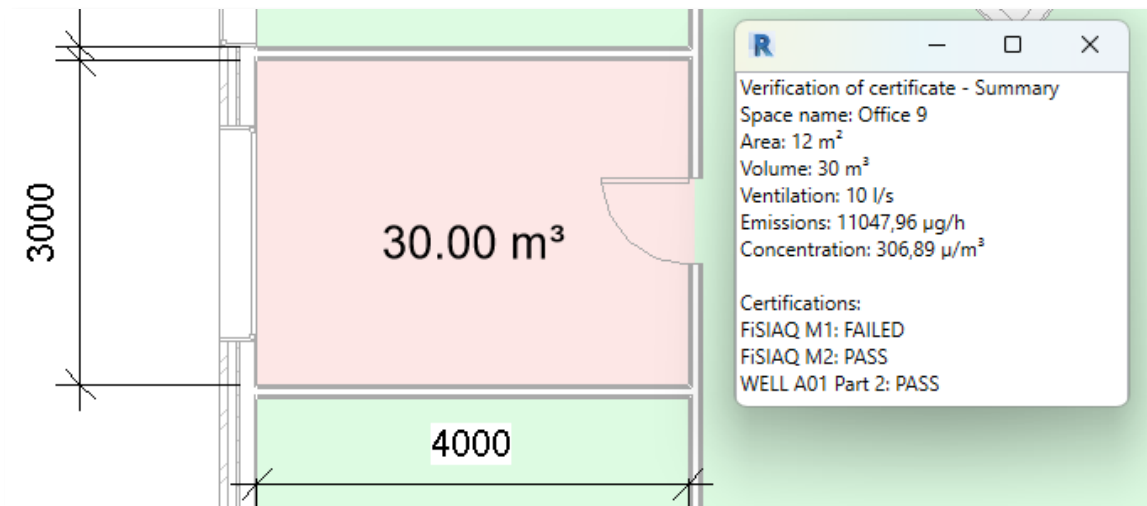


Figure 26 - Results from certification

It is important to consider the three assumptions that were taken for this calculation. The result will only be valid in the same degree the assumptions are valid:

1. The certification does not account for flow of air from one room to another.
2. All air added is considered clean of VOCs. This gives only valid certification in primary rooms that receive fresh air.
3. The certification assumes complete mix of the TVOC in the air with no “hot spots”.

5.4.7 Certificate on all spaces



Figure 27 - Revit UI Certificate on all spaces

This button is an extended version of “Certificate” described in the previous section. It certifies and outputs a summary for all spaces in the same way as shown in Figure 26.

5.5 Details about the add-in

Further details about the add-in are presented in Appendix A and Appendix B.

6 Application on case building - Results and discussion

Application on a case building was a major part of the development of the add-in where data retrieval and programming were continuously tested in the project for both testing the code and checking whether the results were valid or not.

6.1 Case building

The case building for this study is a model of Mustads vei 1, Oslo, reworked by OsloMet to a two-story building. The model is built in the Revit Architecture template. Walls and construction elements are not linked in, but are modelled in the same file as the rest of the model. A 3D-view of the model is shown in Figure 28. The building consists mostly of areas for offices and meetings. Having both the construction and the calculation environment in the same Revit model was a major simplification as Revit links are often used in interdisciplinary projects.



Figure 28 - Case study building

6.2 Calculation of concentration

Calculation of the TVOC concentration of the rooms in the Revit model with the static method was a simple way. The validity of the results from the calculation depends on the validity of the testing methods that are used to determine the individual material TVOC. The timestamp for the TVOC concentration date will be on day 28 as most materials document their emissions for day 28.

If the calculation is performed in a model that receives the latest updated version of the building, the calculation will always be up to date with the latest geometry and components. Creating and maintaining a small library with often used materials in the model will not be a tedious task if the add-in is developed a bit further to contain this feature. Only a few clicks are needed to set up the use of the add-in if the Revit model is set up correctly with the use of spaces.

6.3 Change of ventilation rate in rooms

Calculations were performed on some of the rooms in the Revit model to test the add-in. The dimensions of the rooms are shown in Figure 29. The height of all the rooms is set to be at 2,5 m. All the rooms have one door and one window with glue around it.

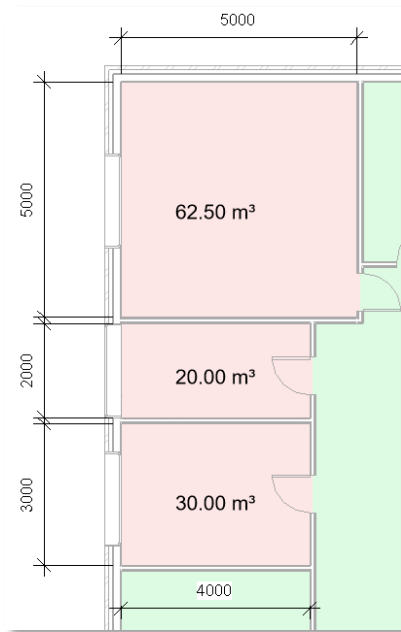


Figure 29 - Dimensions of the rooms

The choice of materials for all the selected surfaces in these rooms are shown in Table 18.

Table 18 - Surfaces selected for TVOC calculation in the rooms

Surface	Surface type	Material name	Surface emission [$\mu\text{g}/\text{m}^2\text{h}$]
Wall	5	Gyproc gypsum with Nordsjø paint	219
Glue	1	Casco silicone	4286
Ceiling	1	Rockfon ceiling	200
Floor	1	Placeholder product	200

To check the difference between TVOC concentrations for varying room sizes and ventilation rates, TVOC calculations were performed four times with different air change rates. The results were plotted in Figure 30.

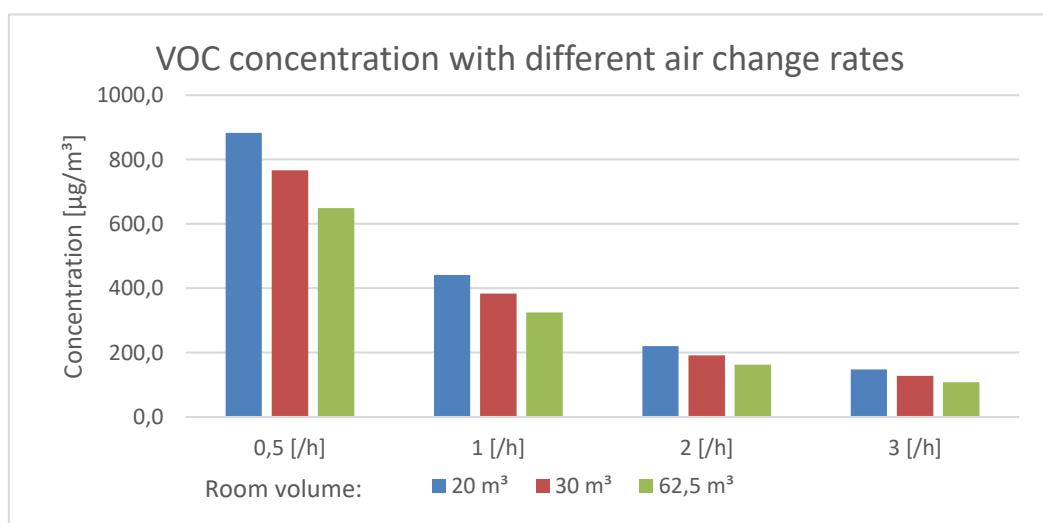


Figure 30 - Calculation of VOC concentration with different air change rates and room volumes

The figure shows that the smallest room has the highest TVOC concentration. Further investigation of this discovery shows that as a general observation, small rooms have a higher surface-to-volume-ratio leading to a higher surface area of pollution sources to the room. This investigation was performed in Excel by calculating ratios with different room dimensions. Change in ventilation rate does not affect the emission rate from materials to a noticeable grade [64].

6.4 Verification of the add-in

To verify the calculation method for TVOC concentration in the add-in, the method for calculating SER given in Equation (3-1) was used. A hypothetical paint with emission value at the threshold of approved paint according to BREEAM was applied to the walls for the reference room shown in Figure 31. The threshold is $300 \mu\text{g}/\text{m}^3$ tested according to EN 16516. Characteristics of the reference room is given in Table 9. The final concentration of TVOC has shown to be according to the threshold specified by BREEAM as shown in the results in Figure 31. The deviance of $1,5 \mu\text{g}/\text{m}^3$ is due to measuring error of area of windows and doors. This is further described in Appendix A.

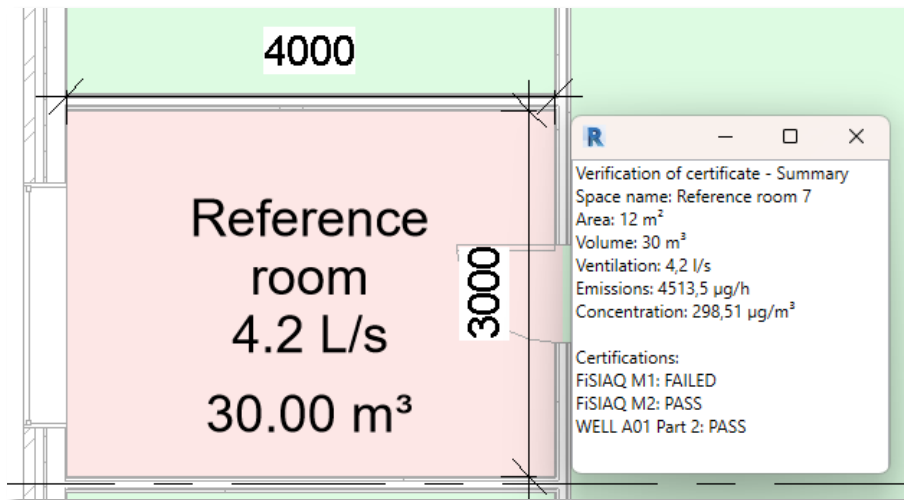


Figure 31 - Verification of the add-in

Another verification of the calculation of TVOC emission and concentration with floor, ceiling, glue, and walls was performed in Excel as shown in Figure 32. This data can be compared to the results from the same calculations performed in the add-in as shown in Figure 33 and Figure 34.

Material	Material Emission [$\mu\text{g}/\text{m}^2\text{h}$]	Area [m^2]	Contributing emission [$\mu\text{g}/\text{h}$]	Comment/marks
Walls	-	35	-	Room dim: LxWxH = 4 m x 3 m x 2,5 m
Window	-	2	-	1 m * 2 m
Door	-	1,6	-	2 m * 0,8 m
Total walls	218	31,4	6845,2	Total wall minus windows and doors. Type 4 wall. Gyproc gypsum with Fluggler paint
Ceiling	200	12	2400	Type 1 ceiling. Rockfon Ceiling
Floor	300	12	3600	Type 2 floor. Material placeholder
Glue, sealant (5mm wide)	4285,7	0,03	128,571	Circumference around window. Type 1 glue. Casco Silicone
Total emission [$\mu\text{g}/\text{m}^2\text{h}$]			12973,771	
Ventilation rate [m^3/h]			241,9	
Concentration [$\mu\text{g}/\text{m}^3$]			53,6	

Figure 32 - Verification of calculation in Excel

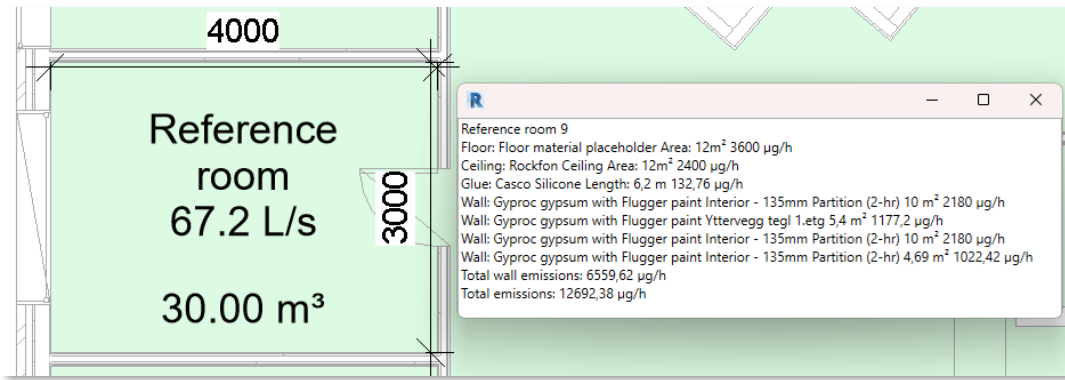


Figure 33 - Verification of calculation of emission in add-in

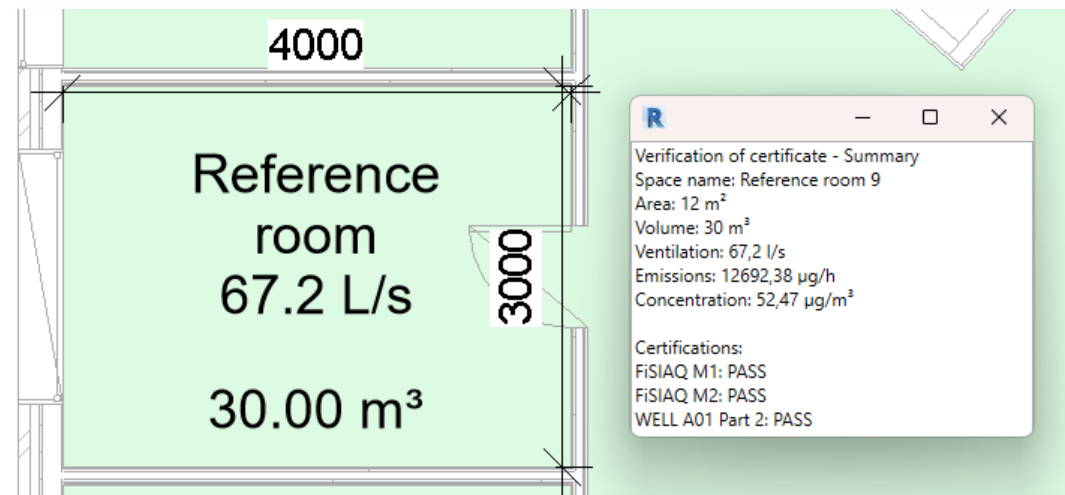


Figure 34 - Verification of calculation of concentration in add-in

These data verifies that the add-in can calculate the TVOC emission and concentration according to Equation (4-1) and Equation (4-7) with emission data for materials according to the testing method in EN 16516.

The calculation error for this verification was 2,2 %. This is due to a measuring error of windows and doors further described in Appendix A. The materials chosen for the verification in Excel and the add-in is shown in Table 19.

Table 19 - Surfaces selected for verification of calculation

Surface	Surface type	Material name	Surface emission [µg/m²h]
Wall	4	Gyproc gypsum with Flugger paint	218
Glue	1	Casco silicone	4286
Ceiling	1	Rockfon ceiling	200
Floor	1	Placeholder product	200

7 Conclusions

7.1 Main findings

7.1.1 Answering research questions

1. Is BIM used today to evaluate TVOC concentration indoors?
 - Only three of the studies reviewed have used BIM-oriented software to perform concentration calculation of indoor pollution such as PM and TVOC, whereas only one study has calculated the concentration of TVOC. This is the study by D'Amico et. al [11] where Autodesk Revit was used. The other BIM-oriented software was VICO Constructor. Other software has however been used for calculating concentrations of TVOC such as CONTAM, COMIS and IAQX, but those programs do not fit the description of BIM defined in Section 2.2.4. The review reveals that there are very few studies that use BIM for assessing indoor TVOC concentration.
2. What requirements do the standards set for materials and IAQ?
 - Environmental building standards set their requirements in two ways: Rate of emission of TVOC from materials and TVOC concentrations in the air. BREEAM and LEED have requirements for the rate of emissions from the materials used whereas WELL and FiSIAQ have requirements for the TVOC concentrations in the air controlled by on-site measurements. LEED set requirements for concentration of individual VOCs, and they require that the TVOC concentration is reported, but they do not present a threshold for TVOC. The use of R-number or HI can resolve this issue since the individual VOCs contribution to the R-number or HI is determined by the concentration and the threshold for that compound. Four environmental labelling schemes for material emission were researched where The Nordic Swan Ecolabel standard presents the strictest threshold for TVOC emission at 50 $\mu\text{g}/\text{m}^2\text{h}$.
3. How are materials tested for TVOC, and is this documentation available?
 - Chamber testing according to EN 16516 built on the chamber testing in ISO 16000-9 was the method that was the most used method since most of the certification schemes refer to that method. By requiring use of low emitting materials and documentation on emission levels, environmental building standards and labelling schemes forces an incentive for the manufacturers to present this type of testing data. This also provides available data that is necessary to perform calculation for both emission levels and concentrations.
4. How can the TVOC concentration be calculated?
 - A dynamic equation for calculation TVOC concentration was developed inspired by reviewed studies in Section 4.2. This equation was Equation (4-4) and was further simplified with assumptions and made up the static Equation (4-7) that was used in the developed add-in. The equation for concentration consists in short of an emission rate, ventilation rate and air volume. The dynamic attribute of the equation is determined whether the emission rate or ventilation rate is for static or dynamic conditions.
5. How can the calculation be implemented in a BIM-oriented program?
 - An add-in for Autodesk Revit was developed in C# in the Revit API environment. The add-in gives the user a way to assign information of the emissions to a surface together with a ventilation rate for a room, which is further used in a TVOC calculation. This has shown to be a simple and quick way to perform a static calculation of TVOC.

7.2 Suggested further work

7.2.1 Further studies

- The use of R-rate instead of TVOC as a measuring parameter could be a better measurement for health effects. This should be investigated further.
- Acclimatization and a person's ability to sense concentration of high levels of TVOC must be investigated further as the smell of TVOC can be quite distinct when entering a room, but after a couple of seconds or minutes, the person has acclimatized and might no longer smell the TVOC.
- The data for emissions from glue around windows are from testing where glue is directly exposed to air, but this might not be the case for all windows. This requires further research.
- LOI in BIM describes the information content in the BIM model such as properties of and object, type of material, color, etc. [69]. As the use of BIM increases, LOI also increases in presence and relevancy. This will lead to more information in the model on e.g. material data and emission which in turn will make calculation of emissions a more feasible operation. The use degree of LOI in BIM is something that should be assessed further.
- The study by Yang et. al [62] developed a MATLAB model for calculation of multiple types of air contaminants with the use of a small database for materials and their emissions. They also considered air flow from one room to another. This would also be a relevant approach for further development.
- The study by Liang et. al [70] developed a tool for IAQ that considers airflow, emission with diffusion and ventilation with contaminated air. The study does not explain in which environment the tool was developed, but they introduce a complex mathematical model that uses multiple factors to determine the concentration of pollution. This model would be something to implement in a tool in a BIM-environment.
- The study performed by Yan et. al [71] uses the state-space method for determining the emissions. It states to be of a higher precision than the analytical method. Further research into the use of a state-space method in a BIM-environment would be of interest.
- In year 2000 Guo [72] presented a study that developed a simulation tool, IAQX, that can simulate IAQ. The tool consists of five packages that presents their own model and calculation [17]. This tool does not qualify as a BIM-tool, but it could be merged with a BIM-model and implemented inside a BIM-environment with its capabilities.
- Further develop and validate the calculation methodology towards on-site measurements of TVOC in buildings.

7.2.2 Further development of the add-in

The add-in is custom made for the Revit model that was used in the case study and should be tested on another model since Revit uses different templates in combination with different default units for measurements and values. This might uncover flaws in the code that would not else be discovered. In addition to this, there are several tasks that are suitable for further development of the add-in:

- Give the user the option to select the ventilation rate by themselves.
- Edit the material database from Revit by adding elements and descriptions.
- Give walls colors depending on the chosen material for the wall.
- Assess the flow of air from one room to another as this will affect the TVOC concentration of the receiving room.
- Give the user opportunity to choose which materials should be default together with the other default values.
- Export the results from all calculations in a .txt or .csv file.
- Create an equation with calculation of TVOCs with overflow from one room to another.
- Create compatibility with the use of walls and spaces from linked files.
- Further verification of the add-in and testing towards the needs of the end-user.
 - A call was made out towards architects for testing of the working method for calculation, but it did not result in a success.

8 References

- [1] N. E. Klepeis *et al.*, 'The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants', *J. Expo. Sci. Environ. Epidemiol.*, vol. 11, no. 3, pp. 231–252, Jul. 2001, doi: 10.1038/sj.jea.7500165.
- [2] 'Air pollution data portal'. <https://www.who.int/data/gho/data/themes/air-pollution> (accessed Apr. 01, 2023).
- [3] O. US EPA, 'What are volatile organic compounds (VOCs)?', Feb. 19, 2019. <https://www.epa.gov/indoor-air-quality-iaq/what-are-volatile-organic-compounds-vocs> (accessed Mar. 31, 2023).
- [4] O. US EPA, 'Volatile Organic Compounds' Impact on Indoor Air Quality', Aug. 18, 2014. <https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality> (accessed May 13, 2023).
- [5] WELL, 'WELL Standard', *WELL Standard*. <https://v2.wellcertified.com/en/wellv2/air/feature/1> (accessed Mar. 19, 2023).
- [6] U.S. Green Building Council, 'LEED v4.1 BUILDING DESIGN AND CONSTRUCTION', Jan. 2019.
- [7] Grønn Byggallianse, 'BREEAM-NOR-v6.0_ENG New Construction', 2022.
- [8] Y.-W. Lim, 'Building Information Modeling for Indoor Environmental Performance Analysis', *Am. J. Environ. Sci.*, vol. 11, no. 2, pp. 55–61, Feb. 2015, doi: 10.3844/ajessp.2015.55.61.
- [9] M. S. Altaf, Z. Hashisho, and M. Al-Hussein, 'A method for integrating occupational indoor air quality with building information modeling for scheduling construction activities', *Can. J. Civ. Eng.*, vol. 41, no. 3, pp. 245–251, Mar. 2014, doi: 10.1139/cjce-2013-0230.
- [10] M. S. Altaf, 'Integrating occupational indoor air quality with building information modeling (BIM)', *ERA*, Fall 2011. <https://era.library.ualberta.ca/items/40c1ee7a-91ff-4fe3-86e3-e1ae7becffe4> (accessed Apr. 11, 2023).
- [11] A. D'Amico, G. Bergonzoni, A. Pini, and E. Currà, 'BIM for Healthy Buildings: An Integrated Approach of Architectural Design based on IAQ Prediction', *Sustainability*, vol. 12, no. 24, p. 10417, Dec. 2020, doi: 10.3390/su122410417.
- [12] 'Revit Software | Get Prices & Buy Official Revit 2023'. <https://www.autodesk.com/archive-glfy24/revit/overview1> (accessed May 05, 2023).
- [13] 'Construction Solutions :: Vicosoft - Virtual Construction | 4D and 5D BIM Modeling'. <https://www.synergy-software.com/industry-verticals-construction-vicosoft.htm> (accessed May 05, 2023).
- [14] A. D'Amico, A. Pini, S. Zazzini, D. D'Alessandro, G. Leuzzi, and E. Currà, 'Modelling VOC Emissions from Building Materials for Healthy Building Design', *Sustainability*, vol. 13, p. 184, Jan. 2021, doi: 10.3390/su13010184.
- [15] 'CONTAM', *NIST*, Mar. 2012, Accessed: May 05, 2023. [Online]. Available: <https://www.nist.gov/services-resources/software/contam>
- [16] P. H. Kirkegaard (ed.) and A. Kamari (ed.), 'Building Information Modeling (BIM) for Indoor Environmental Performance Analysis', *Tech. Rep. Civ. Archit. Eng.*, vol. 4, no. 3, Art. no. 3, Apr. 2017, Accessed: May 05, 2023. [Online]. Available: <https://tidsskrift.dk/cae/article/view/26257>
- [17] O. US EPA, 'Simulation Tool Kit for Indoor Air Quality and Inhalation Exposure (IAQX)', Sep. 23, 2014. <https://www.epa.gov/air-research/simulation-tool-kit-indoor-air-quality-and-inhalation-exposure-iaqx> (accessed Apr. 15, 2023).
- [18] Y. Xu and Y. Zhang, 'An improved mass transfer based model for analyzing VOC emissions from building materials', *Atmos. Environ.*, vol. 37, no. 18, pp. 2497–2505, Jun. 2003, doi: 10.1016/S1352-2310(03)00160-2.
- [19] Jianyin Xiong, Yinping Zhang, and Shaodan Huang, 'Characterisation of VOC and Formaldehyde Emission from Building Materials in a Static Environmental Chamber: Model Development and Application', *Indoor Built Environ.*, vol. 20, no. 2, pp. 217–225, Apr. 2011, doi: 10.1177/1420326X103874801.
- [20] X. Wang, Y. Zhang, and R. Zhao, 'Study on characteristics of double surface VOC emissions from dry flat-plate building materials', *Chin. Sci. Bull.*, vol. 51, no. 18, pp. 2287–2293, Sep. 2006, doi: 10.1007/s11434-006-2110-4.

- [21] K. Qian, Y. Zhang, J. C. Little, and X. Wang, 'Dimensionless correlations to predict VOC emissions from dry building materials', *Atmos. Environ.*, vol. 41, no. 2, pp. 352–359, Jan. 2007, doi: 10.1016/j.atmosenv.2006.07.042.
- [22] Z. Liu, A. Nicolai, M. Abadie, M. Qin, J. Grunewald, and J. Zhang, 'Development of a procedure for estimating the parameters of mechanistic VOC emission source models from chamber testing data', *Build. Simul.*, vol. 14, no. 2, pp. 269–282, Apr. 2021, doi: 10.1007/s12273-020-0616-3.
- [23] B. Deng and C. N. Kim, 'An analytical model for VOCs emission from dry building materials', *Atmos. Environ.*, vol. 38, no. 8, pp. 1173–1180, Mar. 2004, doi: 10.1016/j.atmosenv.2003.11.009.
- [24] B. Deng, S. Tang, J. T. Kim, and C. N. Kim, 'Numerical modeling of volatile organic compound emissions from multi-layer dry building materials', *Korean J. Chem. Eng.*, vol. 27, no. 4, pp. 1049–1055, Jul. 2010, doi: 10.1007/s11814-010-0208-5.
- [25] Z. Guo, 'Review of indoor emission source models. Part 1. Overview', *Environ. Pollut.*, vol. 120, no. 3, pp. 533–549, Dec. 2002, doi: 10.1016/S0269-7491(02)00187-2.
- [26] T. Salthammer, 'TVOC - Revisited', *Environ. Int.*, vol. 167, p. 107440, Sep. 2022, doi: 10.1016/j.envint.2022.107440.
- [27] 'About BIM', *The BIM Center*. <https://www.thebimcenter.com/p/d.html> (accessed May 17, 2023).
- [28] 'BIM Benefits | Why Use BIM? | Autodesk'. <https://www.autodesk.com/industry/aec/bim/benefits-of-bim> (accessed May 11, 2023).
- [29] 'BIM Levels', *Catenda*. <https://catenda.com/glossary/bim-levels/> (accessed May 11, 2023).
- [30] 'What is BIM (Building Information Modeling)', Apr. 06, 2022. <https://constructible.trimble.com/construction-industry/what-is-bim-building-information-modeling> (accessed May 11, 2023).
- [31] S. Abelmann, 'German Committee on Indoor Air Guide Values', *Umweltbundesamt*, Nov. 27, 2013. <https://www.umweltbundesamt.de/en/topics/health/commissions-working-groups/german-committee-on-indoor-air-guide-values> (accessed Apr. 23, 2023).
- [32] European Commission. Directorate General for Health and Consumers., 'Agreed EU-LCI values (December 2021)'. Mar. 16, 2022. [Online]. Available: <https://ec.europa.eu/docsroom/documents/49239>
- [33] 'Guidelines for Ventilation Requirements in Buildings'.
- [34] R. Jäckh *et al.*, *Harmonisation framework for health based evaluation of indoor emissions from construction products in the European Union using the EU-LCI concept*. LU: Publications Office of the European Union, 2013. Accessed: May 17, 2023. [Online]. Available: <https://data.europa.eu/doi/10.2788/26234>
- [35] 'Permissible Exposure Limits – OSHA Annotated Table Z-1 | Occupational Safety and Health Administration'. <https://www.osha.gov/annotated-pels/table-z-1> (accessed May 19, 2023).
- [36] ongreening, 'BREEAM Rating System | 5-minute guide', *Ongreening - Green Building made easier and more accessible to all.*, Nov. 19, 2020. <https://ongreening.com/breem-rating-system-5-minute-guide/> (accessed Apr. 10, 2023).
- [37] International WELL Building Institute, 'WELL Performance Rating Q1 2022 PERFORMANCE VERIFICATION GUIDEBOOK'. Jan. 01, 2022. Accessed: Apr. 10, 2023. [Online]. Available: https://a.storyblok.com/f/52232/x/429c2c0e9c/well-performance-verification-guidebook_q1-2022_final.pdf
- [38] 'What is LEED certification?', *U.S. Green Building Council*, Apr. 07, 2022. <https://support.usgbc.org/hc/en-us/articles/4404406912403-What-is-LEED-certification-> (accessed Apr. 10, 2023).
- [39] 'LEED rating system | U.S. Green Building Council'. <https://www.usgbc.org/leed> (accessed Apr. 10, 2023).
- [40] J. Säteri, 'Finnish classification of indoor climate 2000: revised target values', *Indoor Air*, 2002.
- [41] M. Ahola, J. Säteri, and L. Sariola, 'Revised Finnish classification of indoor climate 2018', *E3S Web Conf.*, vol. 111, p. 02017, 2019, doi: 10.1051/e3sconf/201911102017.
- [42] C.-A. Roulet and F. Foradini, 'NATIONAL REPORT OF SWITZERLAND'.
- [43] C. Jia and X. Fu, 'Diffusive Uptake Rates of Volatile Organic Compounds on Standard ATD Tubes for Environmental and Workplace Applications', *Environments*, vol. 4, no. 4, p. 87, Dec. 2017, doi: 10.3390/environments4040087.
- [44] R. Oppl, 'New European VOC emissions testing method CEN/TS 16516 and CE marking of construction products', 2014.

- [45] M. Marć, 'Problems and challenges associated with estimating the emissions of organic compounds from indoor materials', *TrAC Trends Anal. Chem.*, vol. 97, pp. 297–308, Dec. 2017, doi: 10.1016/j.trac.2017.09.022.
- [46] 'About us', *Rakennustietosäätiö*. <https://cer.rts.fi/en/about-us/> (accessed Apr. 10, 2023).
- [47] K. Saarela, 'Classification of Building Materials 2000'.
- [48] 'M1 Criteria', *Rakennustietosäätiö*. <https://cer.rts.fi/en/m1-emission-class-for-building-material/m1-criteria-2/> (accessed Apr. 10, 2023).
- [49] 'NS-EN 15251:2007'.
<https://www.standard.no/no/nettbutikk/produktkatalogen/Produktpresentasjon/?ProductID=277326> (accessed Mar. 25, 2022).
- [50] EMICODE, 'GEV Testing Method'. Sep. 20, 2022.
- [51] EMICODE, 'Emission classes', *EMICODE*. <https://www.emicode.com/en/emission-classes/> (accessed Apr. 09, 2023).
- [52] 'The Nordic Swan Ecolabel', *Svanemerket*. <https://svanemerket.no/en/the-nordic-swan-ecolabel/> (accessed Apr. 28, 2023).
- [53] 'Global Ecolabelling Network', *Global Ecolabelling Network*. <https://globalecolabelling.net/> (accessed Apr. 28, 2023).
- [54] Nordic Ecolabelling, 'Nordic Ecolabelling for new buildings'. Feb. 15, 2023.
- [55] Nordic Ecolabelling, 'Nordic Ecolabelling for Construction and facade panels, and mouldings'. Feb. 25, 2015.
- [56] Nordic Ecolabelling, 'Nordic Ecolabelling for Indoor paints and vanishes'. Nov. 05, 2015.
- [57] 'Logo og retningslinjer', *Svanemerket*. <https://svanemerket.no/markedsforing-og-kommunikasjon/logo-og-retningslinjer-2/> (accessed May 12, 2023).
- [58] J. C. Little, A. T. Hodgson, and A. J. Gadgil, 'Modeling emissions of volatile organic compounds from new carpets', *Atmos. Environ.*, vol. 28, no. 2, pp. 227–234, Jan. 1994, doi: 10.1016/1352-2310(94)90097-3.
- [59] H. P. Hu, Y. P. Zhang, X. K. Wang, and J. C. Little, 'An analytical mass transfer model for predicting VOC emissions from multi-layered building materials with convective surfaces on both sides', *Int. J. Heat Mass Transf.*, vol. 50, no. 11–12, pp. 2069–2077, Jun. 2007, doi: 10.1016/j.ijheatmasstransfer.2006.11.024.
- [60] F. Haghghat and H. Huang, 'Integrated IAQ model for prediction of VOC emissions from building material', *Build. Environ.*, vol. 38, no. 8, pp. 1007–1017, Aug. 2003, doi: 10.1016/S0360-1323(03)00064-7.
- [61] F. H. E, 'COMIS - an international multizone air-flow and contaminant transport model.', Jan. 1999, Accessed: May 12, 2023. [Online]. Available: <https://www.aivc.org/resource/comis-international-multizone-air-flow-and-contaminant-transport-model>
- [62] S. Yang, S. Duque Mahecha, S. Aguacil Moreno, and D. Licina, 'Integration of Indoor Air Quality Prediction into Healthy Building Design', *Sustainability*, vol. 14, p. 7890, Jun. 2022, doi: 10.3390/su14137890.
- [63] N. Liu, X. Zhang, L. Wang, K. Liang, Y. Zhang, and J. Cao, 'Early-Stage Emissions of Formaldehyde and Volatile Organic Compounds from Building Materials: Model Development, Evaluation, and Applications', *Environ. Sci. Technol.*, vol. 56, no. 20, pp. 14680–14689, Oct. 2022, doi: 10.1021/acs.est.2c04572.
- [64] S. B. Holøs, A. Yang, M. Lind, K. Thunshelle, P. Schild, and M. Mysen, 'VOC emission rates in newly built and renovated buildings, and the influence of ventilation – a review and meta-analysis', *Int. J. Vent.*, vol. 18, no. 3, pp. 153–166, Jul. 2019, doi: 10.1080/14733315.2018.1435026.
- [65] J. Zhang and C. Shaw, 'Modelling of Volatile Organic Compound (VOC) Emissions from Building Materials/Furnishings--A Literature Review', Jan. 1997, doi: 10.4224/20331444.
- [66] European Commission. Directorate General for Health and Consumers., *Toxicity and assessment of chemical mixtures*. LU: Publications Office, 2012. Accessed: May 19, 2023. [Online]. Available: <https://data.europa.eu/doi/10.2772/21444>
- [67] A. D'Amico, A. Pini, S. Zazzini, D. D'Alessandro, G. Leuzzi, and E. Currà, 'Modelling VOC Emissions from Building Materials for Healthy Building Design', *Sustainability*, vol. 13, no. 1, p. 184, Dec. 2020, doi: 10.3390/su13010184.
- [68] S. Brown, F. Boulaire, S. Tucker, and S. Egan, *Estimating indoor air quality using integrated 3D CAD building models*. 2008.

- [69] M. Baldwin, 'BIM concepts in 2 minutes', *Bimconnect*, Dec. 21, 2017. <https://bimconnect.org/en/wiki/five-concepts-in-90-seconds/> (accessed May 13, 2023).
- [70] W. Liang, X. Yang, F. Chen, M. Lv, and S. Yang, 'A Pre-assessment and Control Tool for Indoor Air Quality (PACT-IAQ) Simulation in Actual Buildings', *Procedia Eng.*, vol. 205, pp. 219–225, Jan. 2017, doi: 10.1016/j.proeng.2017.09.956.
- [71] W. Yan, Y. Zhang, and X. Wang, 'Simulation of VOC emissions from building materials by using the state-space method', *Build. Environ.*, vol. 44, no. 3, pp. 471–478, Mar. 2009, doi: 10.1016/j.buildenv.2008.04.011.
- [72] Z. Guo, 'Development of a Windows-based indoor air quality simulation software package', *Environ. Model. Softw.*, vol. 15, no. 4, pp. 403–410, Jun. 2000, doi: 10.1016/S1364-8152(00)00020-7.

9 APPENDICES

Appendix A - Further details about the add-in

Appendix B - The reviewed studies with their calculation methods

9.1 Appendix A – Further details about the add-in

Basic knowledge about Revit API is recommended for further reading this appendix.

9.1.1 Using spaces for calculation

The use of spaces in the Revit model was the main way to collect information from the model. Using spaces, information about all its parameters and its boundary elements can be retrieved from the model as visualized in Figure 35.

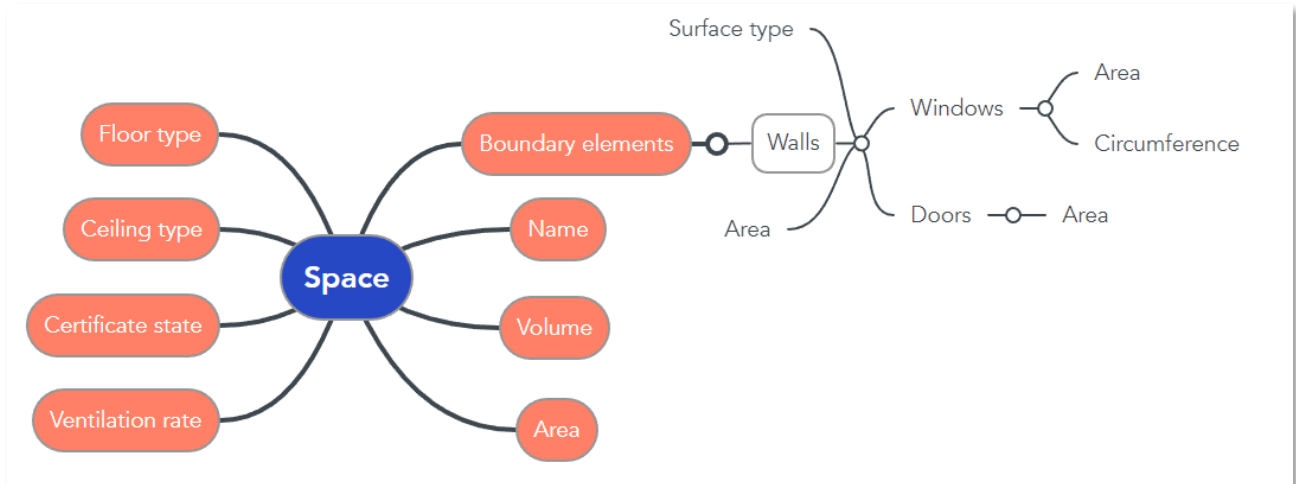


Figure 35 - Data collection from space

By selecting a space, the elements creating the space will be retrieved from the model along with the boundary lines. This data is merged to get the total length and area of each wall in the room.

9.1.2 Area of a wall

When selecting a wall, the whole wall will be selected regardless if it goes over multiple floors or across the whole building. To get the correct area of the wall that is in a space, the curve line in a boundary segment creating the space is used to get the correct length of the wall. This length is multiplied by the height of the space.

9.1.3 Getting the elements in the room

A space (marked in green in Figure 36) is made up of boundary segments (red) created by walls, ceiling and floors. These elements can be retrieved from the information about the space. Ceilings and floor were not used in this study, only walls (blue). By retrieving the walls, it was possible to get the elements (orange) hosted by the walls. Not all these elements are a part of the space as seen in the figure. To only get the elements in the space, the XYZ-coordination of the elements were retrieved and compared to the curve lines created by the boundary segments.

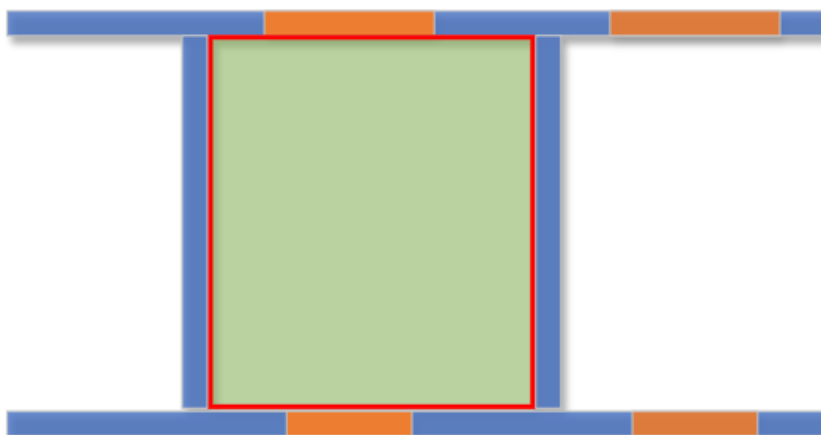


Figure 36 - Getting elements from a space

9.1.4 Area and circumference of doors and windows

It was no simple way to get the dimensions of a wall hosted element like windows and doors. To get this information, a bounding box was used. The bounding box is a cube around the element. The upper and lower most point is available and can be retrieved from the box. This data can be used to calculate the height and the diagonal of the box which roughly corresponds to the dimensions of the windows and doors. For the doors, a measuring error will occur since the modelled door is in an open state which impacts the diagonal of the bounding box. This is illustrated in Figure 37. The orientation of the bounding box is unknown.

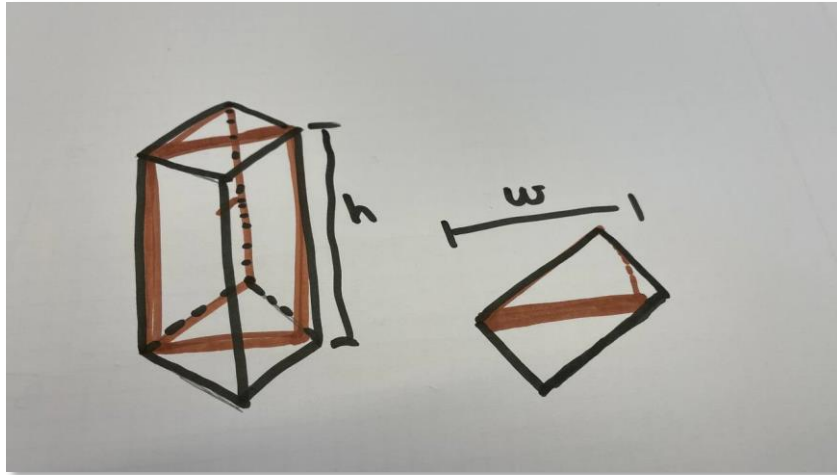


Figure 37 - Bounding box around a door

9.1.5 Methods created in the add-in

The methods created in the add-in are presented in Table 20. The classes used as button actions are shown in Table 21.

Table 20 - Methods developed in the add-in

No	Method name	Return type	Input type 1	Input type 2	Input type 3	Input type 4	Input type 5	Description
1	GetAllSpatialElements	List<SpatialElement>	Document					Gets all spatial elements from the document
2	GetSpatialElements FromSelection	List<SpatialElement>	Document	ICollection<ElementId>				Gets all spatial elements from the selection
3	GetSpatialElementBoundary Elements	List<Element>	SpatialElement	UIApplication				Gets a list of all boundary elements creating a spatial element
4	GetInsertsFromWall	List<Element>	Document	Wall				Gets the components that is hosted by the wall
5	GetWallInsertsFromWallsIn SpatialElement	List<Element>	UIApplication	SpatialElement				Gets the all components that is hosted by wall with a boundary to the spatial element
6	GetWallInsertsInSpatial Element	List<Element>	List<Element>	List<Curve>				Gets the all components that is hosted by a wall and are placed on a boundary line of the spatial element
7	GetWallInserts	List<Element>	UIApplication	BoundarySegment	SpatialElement			Compares the components in the wall with the boundary line of the wall
8	GetSpatialElementBoundary Segments	List<BoundarySegment>	SpatialElement	UIApplication				Gets the boundary segments creating the spatial element
9	GetSpatialBoundary SegmentCurves	List<Curve>	UIApplication	SpatialElement				Gets the lines made by the boundary segments of the spatial element
10	GetWallInsertXYZPosition	XYZ	Element					Gets the position of the component in the wall
11	SingleSpatialElementSelection	SpatialElement	UIApplication					Prompts the user to select a spatial element
12	GetSpatialElementArea	double	SpatialElement					Gets the area of a spatial element (floor/ceiling)
13	GetWallEmissions	double	UIApplication	SpatialElement				Gets all the emissions from wall in a spatial element
14	GetWallFaceArea	double	SpatialElement	BoundarySegment				Gets the area of the part of a wall that makes up the spatial element
15	GetWallEmissionsInfo	string	UIApplication	SpatialElement				Gets the information of the emission data for wall in a spatial element
16	GetCeilingEmissions	double	SpatialElement					Gets the emission from the ceiling in a spatial element
17	GetFloorEmissions	double	SpatialElement					Gets the emission from the floor in a spatial element
18	CalculateGlueEmissions	double	UIApplication	SpatialElement				Calculates the emissions from the glue in a spatial element
19	SumInsertCircumference	double	UIApplication	SpatialElement				Sums up all the circumferences of elements in walls in a spatial element
20	TotalEmissions	double	UIApplication	SpatialElement				Sums up all the emissions for a spatial element
21	GetWallInsertArea	double	UIApplication	BoundarySegment	SpatialElement			Gets the area of a element hosted by a wall

22	GetBoundingBoxCutArea	double	Element					Gets the area of the cross section of a bounding box around the element hosted by a wall
23	GetWallInsertCircumference	double	UIApplication	BoundarySegment	SpatialElement			Gets the circumference of windows hosted by a wall in the spatial element
24	CreateSharedParameter	void	Document	string	BuiltInCategory	ForgeTypeId	BuiltInParameterGroup	Creates a shared parameter
25	CustomSharedParameters	void	UIApplication					Calls the method "CreateSharedParameter" with the data
26	SetVentilationRateByArea	void	SpatialElement	double				Gets the area of a spatial element and sets the ventilation rate
27	VentilationIterateSpatialElementSet	void	Document	List<SpatialElement>	double			Iterates through list of spatial elements and callsthe method "SetVentilationRateByArea"
28	SetVentilationRateOnMultipleSpatialElementSelection	void	UIApplication	double				Prompts the user to select a spatial element that will get a new ventilation rate
29	CalculateHeight	double	SpatialElement					Calculates height of a spatial element
30	CalculateConsentration	double	double	double				Calculates the concentration of TVOC with ventilation rate and emission rate
31	CalculateNettoWallFace	double	double	double				Subtracts the area of inserts in a wall from the area of the wall
32	SetFloorTypeInSpace	void	Document	int	SpatialElement			Sets a number for the floor type in a spatial element
33	SetCeilingTypeInSpace	void	Document	int	SpatialElement			Sets a number for the ceiling type in a spatial element
34	SetFloorAndCeilingInSpace	void	Document	int	int	SpatialElement		Sets the floor and ceiling type in a spatial element
35	SetCeilingAndFloorInSpaceFromList	void	Document	int	int	List<SpatialElement>		Iterates through list of spatial elements and calls the method "SetFloorAndCeilingInSpace"
36	SetSpaceCertificateState	void	Document	SpatialElement	int			Sets the parameter value in a spatial element
37	SetSpaceCertificateFromList	void	Document	List<SpatialElement>	int			Iterates through list of spatial elements and calls the method "SetSpaceCertificateState"
38	SetWallSurfaceType	void	Document	int	Element			Sets wall surface type
39	SetWallSurfaceTypeFromList	void	Document	int	List<Element>			Iterates through list of elements and calls the method "SetWallSurfaceType"
40	SetVentilationDefaultFromList	void	Document	double	List<SpatialElement>			Set default ventilation rate from a list of spatial elements
41	CreateColorScheme	void	UIApplication					Creates a color scheme for coloring the spaces
42	ChangeSpaceCertificateStateBasedOnTest	void	UIApplication	SpatialElement	double			Sets the parameter value based on the results of the certificate test
43	DataBaseReturnWallEmission	double	int					Gets emission value based on surface type

44	DataBaseReturnWallType	string	int					Gets surface name based on surface type
45	DataBaseReturnFloorEmission	double	int					Gets emission value based on floor type
46	DataBaseReturnGlueEmission	double	int					Gets emission value based on glue type
47	DataBaseReturnCeilingEmission	double	int					Gets emission value based on ceiling type
48	DataBaseReturnFloorType	string	int					Gets floor name based on floor type
49	DataBaseReturnCeilingType	string	int					Gets ceiling name based on ceiling type
50	DataBaseReturnGlueType	string	int					Gets glue name based on glue type
51	CalculateSurfaceEmission	double	double	double				Calculates the emission with area and emission rate
52	CertificateDatabase	bool	double	string				Compares the concentration with the threshold for certifications
53	VerifyCertificateConcentrations	string	double					Creates a text summary and calls the method "CertificateDatabase"
54	CreateButton	PushButtonData	string	string	string	string	string	Takes data and creates a pushbutton
55	VOCTextHandler	void	UIApplication	SpatialElement				Takes spatial element, calls methods for calculation, handles text and presents TVOC emissions
56	VerifyCertificateSpace	string	UIApplication	SpatialElement				Certifies single spatial element, calls methods for calculation, handles text and presents TVOC concentration
57	VerifyCertificateSingleSpace	void	UIApplication	SpatialElement				Calls the method "VerifyCertificateSpace"
58	VerifyCertificateMultipleSpaces	void	UIApplication	List<SpatialElement>				Iterates through list of spatial elements and calls the method "VerifyCertificateSpace"
59	VOCTextHandlerFloorCeiling	string	UIApplication	SpatialElement				Gets the data for floor and ceiling and returns it
60	PresentMessage	void	string					Presents a message in a text box

Table 21 - Classes in the add-in for button actions

No	Class name	Function called 1	Function called 2	Description
1	SetVentilationRatesOnSelectedSpace	SetVentilationRateOnMultipleSpatialElementSelection		Sends all selected elements to the method
2	SetVentilationRatesOnAllSpaces	GetAllSpatialElements	VentilationIterateSpatialElementSet	Gets all spatial elements and sends them to get a new ventilation rate
3	SetVentilationRatesOnPreSelected	GetSpatialElementsFromSelection		Gets all selected spatial elements and sends them to get a new ventilation rate
4	CalculateTotalEmission	SingleSpatialElementSelection	VOCTextHandler	Prompts user to select space and performs calculation of emission
5	CertificateSpace	SingleSpatialElementSelection	VerifyCertificateSingleSpace	Prompts user to select space and performs certification
6	CertificateAllSpaces	GetAllSpatialElements	VerifyCertificateMultipleSpaces	Gets all spaces and performs certification
7	SetDefaultValuesOnComponents	CustomSharedParameters GetAllSpatialElements SetCeilingAndFloorInSpaceFromList SetVentilationDefaultFromList SetSpaceCertificateFromList	GetAllWallElements SetWallSurfaceTypeFromList SetVentilationDefaultFromList SetSpaceCertificateFromList	Creates parameters and sets default values on all parameters
8	GetHelp	PresentMessage	CustomSharedParameters	Presents help message and creates parameters
9	CreateColorScheme	CreateColorScheme		Creates color scheme

9.2 Appendix B – The reviewed studies with their calculation methods

Table 22 - Reviewed studies with calculation method

Study	Calculation method	Publish year	Publish country	Short description
BIM for Healthy Buildings: An Integrated Approach of Architectural Design based on IAQ Prediction	Empirical method	2020	Italy	Uses revit to calculate VOC concentration
An improved mass transfer based model for analyzing VOC emissions from building materials	Mass transfer model	2002	China	Mass transfer model. Biot, Fourier, ratio of VOC mass
Characterisation of VOC and formaldehyde emission from building materials in a static environmental chamber: model development and application	Mass transfer model	2010	China	Mass transfer model. Biot, Fourier, ratio of VOC mass
Study on characteristics of double surface VOC emissions from dry flat-plate building materials	Mass transfer model	2006	China	Emission from double layered emissions
A method for integrating occupational indoor air quality with building information modeling for scheduling construction activities	Personal measurement	2014	Canada	Using BIM to predict pollution. Particulate matter
Dimensionless correlations to predict VOC emissions from dry building materials	Mass transfer model	2006	China	Mass transfer model. Biot, Fourier, ratio of VOC mass, air exchange rate, ratio of area to volume
Modelling VOC Emissions from Building Materials for Healthy Building Design	Empirical method	2021	Italy	Using multi zone and box model(with mass balance) to determine VOC
Integrating occupational indoor air quality with building information modeling (BIM)	Personal measurement	2011	Canada	Mass balance model. Determines the amount of emission pr worker in the area. Using BIM with on-site sampling to estimate pollutions during construction activities
Development of a procedure for estimating the parameters of mechanistic VOC emission source models from chamber testing data	Mass transfer model	2021	USA	Developes a way to get mass transfer data from chamber test data
An analytical model for VOCs emission from dry building materials	Mass transfer model	2004	China	Developes analytical model for determinaton of emission from materials. 5 dimensionless number needed to determine characteristics of VOC from the material to the air
BUILDING INFORMATION MODELING (BIM) FOR INDOOR ENVIRONMENTAL PERFORMANCE ANALYSIS	Decay model	2017	Denmark	Uses emission rate, source area, initial emission factor, decay constant, time
Numerical modeling of volatile organic compound emissions from multi-layer dry building materials	Mass transfer model	2010	China	Analytical model tested with experiments
Review of indoor emission source models. Part 1. Overview	Decay model	2002	USA	Describes multiple models for mass transfer through materials and emission to air