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Study On the Application Of BIM To Enhance Existing Reverberation Time Estimation Techniques By Including Effect Of Furniture

ENGR 6991: Project and Report III

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1. Abstract

A comprehensive BIM platform which is capable of not just storing information of the building elements but doing all the necessary physical analysis is a must for today's construction projects. It can resolve many problems at the very beginning of the design phase and currently many energy-related tools are available which can improve integrated design approach.

But there is no integrated acoustical analysis tool or external program with acceptable interoperability within the BIM platforms; specifically, the most used one, Autodesk Revit. This research investigates the possibility of developing a BIM-based calculation method for the estimation of acoustical properties of buildings with acceptable accuracy and details.

Such tool can help designers, architects and engineers at the early phases of the design process to make strategic decisions on the shapes and finishes of interior spaces. This can hugely improve the integrated design approach and skip future problems.

To reach this, firstly the basics of estimating acoustical properties of interior spaces and also available tools will get investigated. By selecting the measures, calculation method and computer programming tool, an algorithm is designed and coded to extract data from BIM models and analyze them. It will get tested on many case studies and the results get verified with other existing methods to make sure the code is working properly. Finally, the acoustical properties of an educational building will get studied and analyzed by means of the designed program in different scenarios.

2. Problem Statement

BIM is basically a platform of storing and exchanging all the connected information about buildings in a dynamic fashion that can help to modify and to update them accordingly. It can be defined as a database of all project stakeholders sharing their skills in to reach a comprehensive solution, but it sometimes mistakenly referred to as software.

BIM provides the right tools for performance analysis in the design phases and is helping to improve the building's design to be not just about aesthetic and engineering qualities, but sustainability qualities as well. Although many energy-related analysis (typically energy consumption and daylighting) methods are integrated into BIM platforms there is a lack of an inclusive tool to perform an acoustical analysis in these platforms.

The acoustical analysis is important because in many cases the consequences of the wrong materials and finishes chosen for the building cannot be easily solved during the lifetime of the building. Although it is not affecting the construction cost and lifetime energy usage of the building as much as other factors like solar radiation, it is more practical to do the acoustical analysis at early design phases and select proper finishes for indoor spaces.

The interoperability of the programs designed for acoustical analysis with Autodesk Revit is not satisfying and the currently developed add-ons are not comprehensive. Also, the results from available programs are not showing the effect of non-architectural elements such as furniture.

3. Goals

With the relatively new trend of integrated design approach in the construction industry which brings the idea of gathering all the stakeholders of the project on the same table at the early stages of design process, having such integrated tool for acoustical analysis can help making strategic decision and facilitate decision making on building properties such as finishes.

Based on the above-mentioned problem and limitations, this paper's goal is to investigate the potential solution to include acoustical analysis in the Revit environment.

The final output is desired to be able to investigate any given 3D model within Revit and provide an accurate estimation of the acoustical properties considering different finishes for architectural elements, doors, windows (or curtain walls) and furniture. The method needs to be dynamic to let the users investigate results by updating the model.

4. Methodology

To reach the goals of this study, a scientific yet easy to use tool is to be developed to provide the ability of estimating the acoustical performance of indoor spaces and provide dynamic feedback.

The focus is on minimizing acoustic-specific data entry to the models so that the architects or engineers can easily get the results of acoustical performance of the spaces. The methodology to find the solution is designed in 4 major steps as follows:

- **Literature review:**
    - Acoustics
        - Major factors in the acoustical analysis
        - Calculation techniques
        - Results' reliability and applicability of available methods
        - Method selection
        - Calculation of acoustical properties of non-architectural elements
    - Computer programs for acoustical analysis
        - Available tools, interoperability and limitations
        - Available coding platforms and method selection
- **Solution Development:**
    - Data extraction from models built in the BIM environment
    - Analysis and calculations on the extracted data
    - Enhancements and modifications
    - Results validation
- **Case Study**
    - Applying developed solution
    - Debugging and fine tuning
    - Identifying limitations and potential future improvements
    - Final results validation
- **Conclusion**

5. Literature Review

5.1. Acoustics

5.1.1. Intro on Acoustical Analysis Factors

Although there are several factors to analyze the acoustical properties of a room, Reverberation time (RT_{60}) is the most common one and in many cases is the basis for the calculation of other factors. Also, it is mostly used in the standards to prescribe the acoustic quality of a room.

Some important acoustical analysis parameters are listed below:

- Reverberation Time (RT_{60}): time required for 60 dB reduction in sound.
- Early Decay Time (EDT): time required for 10 dB reduction in sound after the initial 10dB reduction.
- Speech Transmission Index (STI): the quality of speech transmission in the 0-1 range.
- Clarity (C_50, C_{80}): a measure of how clear a sound is in a room in dB unit.
- Sound Strength (G): level of sound in dB (Hansen, 2017)

In the article "Investigation Studies on the Application of Reverberation Time" (Olechowska & Nowoświat, 2016) The authors present the research studies done on reverberation time in respect to theoretical foundation and applicability potentials.

Over the past decades, a considerable number of scientists tried to find the most precise method to analyze the acoustical properties of buildings. They tried many measures such as RT_{60}, Speech intelligibility, sound clarity, articulation and etc. Many of these models are based on Sabine's statistical method of calculating RT_{60}. (Olechowska & Nowoświat, 2016)

The results of many studies confirm that the intelligibility of speech in a room is highly dependent on reverberation time. (Plomb et al., 1980, Houthast, Stteneken, 1984; 1985; Pzimek Ruthkowski, 1985, Galbrun and Kitapci, 2014, cited in (Olechowska & Nowoświat, 2016)). Also, it is mentioned that speech transmission index (STI) is examined to be highly dependent on the reverberation time and signal-noise ratio.

Numerous research studies show the importance in the application of reverberation time in the acoustical analysis which enables users to quickly estimate various factors describing room acoustics. A method for the estimation of sound clarity and center time by just using reverberation time is designed and, in another approach, a reliable link between sound strength and reverberation time is introduced. (Lam, 1999; Artez and Orlowski, 2009 cited in (Olechowska & Nowoświat, 2016)).

In another research and by using statistical analysis a fast estimation method for STI (speech transmission index) is introduced by applying reverberation time. Also, in another effort Lam (1999) presented formulas for estimation of acoustic parameters based on the reverberation time:

$$Clarity:\ C_{80} = 10\log\left(e^{\frac{1.1}{T_{60}}} - 1\right); \qquad Centre\ Time:\ T_c = \frac{T_{60}}{13.8}$$

Nowadays, reverberation time is one of the major factors taken into consideration while designing spaces like lecture rooms, concert halls and auditoriums. To sum up, based on the reviewed literature and available inputs, reverberation time (RT_{60}) is selected as the main factor to investigate acoustical properties of spaces in this report.

5.1.2. Calculation techniques of Reverberation Time

5.1.2.1. Sabine's Formula (1920):

Sabine developed his method based on the statistical theory of sound field in 1920. He assumed that the density of sound energy is equal at any location of the interior space and the probability of incidence was constant in all directions for sound waves. He found out that the decay process of sound energy after the sound source is cut, has an exponential nature and is depending on the speed of sound, surface properties and room volume. He called this RT_{60} which is the time needed for given sound energy to decay its first 60 dB (Olechowska & Nowoświat, 2016).

The main Sabine formula for RT_{60} and a simplified version by assuming a constant number for sound speed is as follows.

$$RT_{60} = \frac{24\,(\ln 10)\,.V}{C_{20\,S_a}} = T_{SAB=}\ \frac{0.161.V}{S\ \overline{\propto}_{SAB}}\ or\ \frac{0.161.V}{\sum_{i=1}^{n} \propto_i S_i}$$

Where: $\overline{\propto}_{SAB} = \frac{1}{S}\sum_{i=1}^{n} \propto_i S_i$ (Nowoświat & Olechowska, 2016)

V: Volume of the room

$\propto_i$: Absorption coefficient of the interior finishes, $\overline{\propto}_{SAB}$: Average absorption coefficient

S_i: Area of each surface inside the room

S: Total interior surface area of the room

C_{20}: Speed of sound which assumed to be 343 m/s at room temperature

This method has limited applicability because it was derived from limited observations and is typically accurate in large diffuse fields with uniform absorption distributions (Brown, 2015).

While this formula has its own limitations, it is very easy to use while noteworthy which makes it a basis for several equations free from the limitations of its own. However, the accuracy of the results of the initial method and the transformations are yet to be discussed. Based on Sabine's formula, many empirical methods and equation have been published for rectangular rooms. These include methods from (Eyring, 1930; Millington and Setter, 1932-1933; Fitzroy, 1959; Pujolle, 1975; Hirata, 1979; Neubauer, Kostek, 2001; Arau-Pichades, 2005; Kuttruff, 2009)

5.1.2.2. Eyring Formula (1930):

Eyring claims that Sabine's formula is not working properly when the room is furnished with highly absorbent surfaces (Passero & Zannin, 2010). He introduced a method by using a logarithmic dependence for $\overline{\propto}_{SAB}$. This modification makes the original formula valid for coefficients larger than 0.2 but limits its applicability for when coefficients are larger than one and lower than 0.2. As an explanation, it has to be mentioned that although 1 is assumed to be the limit for absorption coefficient and means no sound will reflect from a surface with this specification (like an open window) but Sabine calculated several numbers of more than 1 for some finishes based on his experiments. Therefore, the Eyring formula with modification to add air isolation (Knudsen, 1929) is known as below:

$$T_{EYR=} \frac{0.161.V}{S\ \bar{\propto}_{EYR} + 4mV}\ ;\ where\ \ \bar{\propto}_{EYR} = -\ln\left(1 - \bar{\propto}_{SAB}\right)$$

5.1.2.3. Millington and Sette Formula (1932, 1933)

This formula is different in the way it determines average sound absorption coefficient. Unlike Sabine's formula where $\bar{\propto}_{SAB}$ is calculated by arithmetic mean, in this method, $\bar{\propto}_{MIL}$is calculated as the geometric mean. (Nowoświat & Olechowska, 2016) This equation, like the Sabine's formula cannot be used in completely absorbent rooms because of the indeterminacy in the denominator. (Olechowska & Nowoświat, 2016)

$$T_{MIL=} \frac{0.161.V}{S\ \bar{\propto}_{MIL}}\ ;\ where\ \ \bar{\propto}_{MIL} = -\frac{1}{S}\sum_{i=1}^{n} S_i \ln\left(1 - \bar{\propto}_i\right)$$

5.1.2.4. Fitzroy Formula (1959)

This formula takes into account the uneven distribution of absorbent surfaces in the room which in some cases leads to different results compared to previously explained formulas. It is based on extensive tests in a large number of rooms where absorbent material distribution is uneven. (Kang & Neubauer, 2001)

$$T_{FIT} = \left(\frac{S_x}{S}\right).T_x + \left(\frac{S_y}{S}\right).T_y + \left(\frac{S_z}{S}\right).T_z$$

Where:

$$T_x = \frac{0.161.V}{S\ \bar{\propto}_{FIT,x}},\quad T_y = \frac{0.161.V}{S\ \bar{\propto}_{FIT,y}},\quad T_z = \frac{0.161.V}{S\ \bar{\propto}_{FIT,z}}$$

$$\bar{\propto}_{FIT,x} = -\ln(1 - \bar{\propto}_x),\ \ \bar{\propto}_{FIT,y} = -\ln\left(1 - \bar{\propto}_y\right),\ \ \bar{\propto}_{FIT,z} = -\ln(1 - \bar{\propto}_z)$$

S_x, S_y, S_z are surface areas of opposite pairs of walls and $\bar{\propto}_x, \bar{\propto}_y, \bar{\propto}_z$ are corresponding average reverberation sound absorption coefficients of those surfaces.

5.1.2.5. Kuttruff Formula (1973)

By using statistical method and by utilizing Monte Carlo simulation he calculated mean free path (γ^2) as a variation of probability. By this, He introduced three changes to the Eyring equation which were considering the shame of the room and also distribution of absorbing material as well as a correction in the way average sound absorption coefficient is calculated. The formula he proposed is as follows. (Olechowska & Nowoświat, 2016)

$$T_{KUT=} \frac{0.161.V}{S\ \bar{\propto}_{KUT}}\ ;\ \ \bar{\propto}_{KUT} = -\ln\left(1 - \bar{\propto}_{SAB}\right)\left(1 + \frac{\gamma^2}{2}\ln(1 - \bar{\propto}_{SAB})\right)\ ;\ \ \gamma^2{:}\,Mean\ Free\ Path$$

Table 1: Some Monte-Carlo results of the mean free path for rectangular rooms with diffusely reflecting walls (Kuttruff, 2009)

Relative room dimensions (ratio)	$\boldsymbol{\gamma^2}$	**Relative room dimensions (ratio)**	$\boldsymbol{\gamma^2}$
1:1:1	0.342	**1:2:5**	0.403
1:1:2	0.356	**1:2:10**	0.465
1:1:5	0.412	**1:5:5**	0.464
1:1:10	0.415	**1:5:10**	0.510
1:2:2	0.363	**1:10:10**	0.613

5.1.2.6. Pujolle Formula (1975)

This method, like Kuttruff method, uses the mean free path l_m to estimate the value for reverberation time. (Nowoświat & Olechowska, 2016) The method proposed to calculate mean free path is an empirical approach.

$$T_{PUJ} = \frac{0.04.\, l_m}{\overline{\alpha}_{EYR}} \;\; ; \;\; Where\colon l_m = \frac{1}{6}\left(\sqrt{L^2 + w^2} + \sqrt{L^2 + h^2} + \sqrt{h^2 + w^2}\right)$$

L, h and w are the length, height and width of the room

5.1.2.7. Neubauer, Kostek Formula (2001)

It is a modification of the Fitzroy's equation by utilizing Kuttruff's correction element but in two divided parts for floor/ceiling and walls.

$$T_{NEU} = \frac{0.45V}{S^2}\left(\frac{lw}{\overline{\alpha}_{CF}} + \frac{h\,(l+w)}{\overline{\alpha}_{WW}}\right)$$

$$\overline{\alpha}_{CF} = -\ln(1-\overline{\alpha}_{SAB}) + \frac{\rho CF(\rho CF - \bar{\rho})S_{CF}^2}{(\bar{\rho}S)^2} \;, \overline{\alpha}_{WW} = -\ln(1-\overline{\alpha}_{SAB}) + \frac{\rho WW(\rho WW - \bar{\rho})S_{WW}^2}{(\bar{\rho}S)^2}$$

Where l, w, h are length, width and height of the room

$\overline{\alpha}_{CF}, \overline{\alpha}_{WW}$ is average absorption coefficient of the ceiling/floor and walls respectively

$\rho = 1- \alpha$ is the reflection coefficient

S_{CF} & S_{WW} are the surface of are ceiling/floor and walls respectively

5.1.2.8. Arau-Puchades Formula (2005)

This method uses a geometric weighted average of three reverberation times in three different directions (x, y, z) and assumes that decay of reverberation time is of hyperbolic nature. Same as Fitzroy method, the absorption coefficients are average of every two opposite surfaces. (Nowoświat & Olechowska, 2016)

$$T_{ARAU} = \left[\frac{0.161.\, V}{S\;\; \overline{\alpha}_{ARAU,x}}\right]^{\frac{S_x}{S}} \cdot \left[\frac{0.161.\, V}{S\;\; \overline{\alpha}_{ARAU,y}}\right]^{\frac{S_y}{S}} \cdot \left[\frac{0.161.\, V}{S\;\; \overline{\alpha}_{FIT,z}}\right]^{\frac{S_z}{S}}$$

$$\overline{\alpha}_{ARAU,x} = -\ln(1-\overline{\alpha}_x)\,,\;\; \overline{\alpha}_{ARAU,y} = -\ln\left(1-\overline{\alpha}_y\right),\;\; \overline{\alpha}_{ARAU,z} = -\ln(1-\overline{\alpha}_z)$$

5.1.2.9. Standard PNEN 12354-6 method (2005)

This method is depending on the room volume and total equivalent sound-absorbing interior surfaces and objects. The limitations are the room shape which must be regularly shaped and also a small number of objects. (Nowoświat & Olechowska, 2016)

$$T = \frac{55.3\,V\,(1-\psi)}{C_0\,.A} \quad ; \quad A = \sum_{i=1}^{n} \propto_{s,i} S_i + \sum_{j=1}^{o} A_{ob,j} + \sum_{k=1}^{p} \propto_{s,k} k + A_{ir}$$

Where n, i and p are number of surfaces, objects and system objects respectively.

C_0 is the speed of sound; ψ is the fraction of objects defining the volume of the objects in the room.

5.1.3. Results Reliability and Applicability

So, to choose the method for the purpose of this study, the results of them should be compared. Table 2 is a comparison of the main characteristics of available methods. To compare the results, a sample room with dimensions of 5m x 10m x 5m is considered. The absorption coefficients for facing walls are assumed to be 0.2 and 0.1 and for floor and ceiling is assumed to be 0.4.

The results show that the highest value is for Arau-Puchades method showing 1.24 [s] while the lowest is Millington's at 0.55 [s]. The significant deviation in the results shows that further investigations should be performed to find the most reliable.

Table 2: Comparison of key characteristics of different methods to estimate Reverberation Time and the results for a given sample

	Acoustic Material Distribution	Effect of the shape of the room	$\overline{\propto}_{average}$***	Reverberation time ***	Mean Free Path
Sabine	Even*	No	$\overline{\propto}_{SAB}= 0.24$	0.67 [s]	
Eyring	Even*	No	$\overline{\propto}_{EYR}= 0.27$	0.59 [s]	
Millington & Sette	Even*	No	$\overline{\propto}_{MIL}=0.29$	**0.55 [s]**	
Fitzroy	Un-Even**	Yes	$\overline{\propto}_{x}= 0.5$, $\overline{\propto}_{y}= 0.1$ $\overline{\propto}_{x}= 0.22$	0.91 [s]	
Pujolle	Even*	Yes	$\overline{\propto}_{EYR}= 0.27$	0.72 [s]	4.90
Arau-Puchades (2005)	Un-Even**	Yes	$\overline{\propto}_{x}= 0.5$, $\overline{\propto}_{y}= 0.1$ $\overline{\propto}_{x}= 0.22$	**1.24 [s]**	
Neubauer, Kostek	Un-Even**	Yes	$\overline{\propto}_{CF}= 0.24$ $\overline{\propto}_{WW}= 0.33$	0.78 [s]	
Kuttruff (	Even*	Yes	$\overline{\propto}_{KUT}= 0.27$	0.60 [s]	0.356
Standard PNEN	Even* (+ objects)	No	$\overline{\propto}_{SAB}= 0.24$	0.67 [s]	

** Means that two facing architectural elements have the same absorption; ** Three axes for the propagation of sound is taken into consideration; *** Calculated based on the assumed model explained in the report.*

In another effort to compare the results from available methods, researchers modelled a room of floor area 2.5 x 5.0 m and 2.5m in height. Two Variants was then assumed, one an empty room built from OSB and the second variant with absorbing panels located on the walls as shown in the Figure 1. (Nowoświat & Olechowska, 2016)

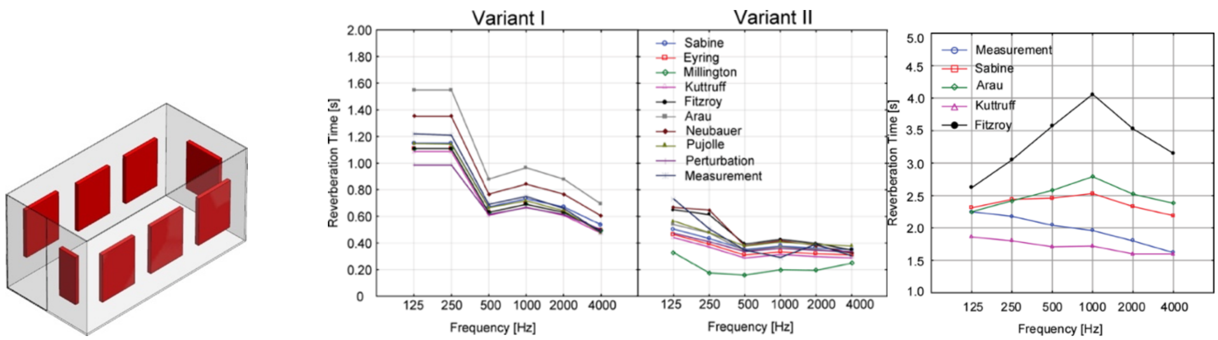
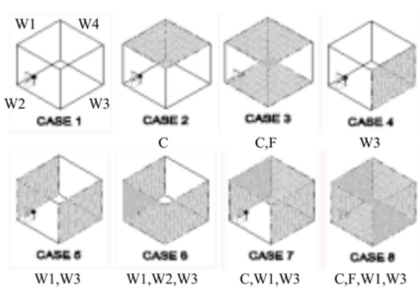


Figure 1: left: sound absorbing the material in the model room
Middle: Comparison of the results (Nowoświat & Olechowska, 2016)
Right : Grosser Musikvereinsaal Hall RT_{60} results comparison (McMinn, 1996)

Also, In a different work, (McMinn, 1996 cited in (Nowoświat & Olechowska, 2016)) presented the results from different methods and compared them with real measurements shown in the Figure 1. The comparison of the results derived from empirical methods to measurements show that the accuracy of the results varies in different frequencies.

Another research by Kang & Neubauer (2001) compares the results of numerous empirical and computer simulation methods for two rooms with 8 different absorption distribution scenarios. Room I is 10m x 10m x 8m high while room II is 10m x 10m x 3m. Figure 2 Shows the 8 different scenarios for absorption distribution.



Configuration	1	2	3	4	5	6	7	8
Sabine	4.53	1.27	0.71	0.48	0.87	0.61	0.57	0.43
Eyring	4.43	1.14	0.59	0.34	0.74	0.48	0.43	0.29
Millington-Sette	4.43	0.69	0.38	0.24	0.46	0.32	0.30	0.22
Fitzroy	5.10	3.26	3.15	2.11	3.67	2.20	1.83	0.33
Arau	4.86	1.93	1.29	0.58	1.68	0.81	0.67	0.30
Fitzroy-Kuttruff	4.43	0.93	0.58	0.34	0.63	0.41	0.36	0.27
prEN 12354	5.26	2.32	1.94	0.59	1.90	0.80	0.73	0.52
CM*,S1,T15	4.43	1.66	1.37	1.70	1.43	0.77	0.76	0.73
CM,S1,T30	4.43	1.80	1.57	1.81	1.62	1.07	1.13	0.96
CM,S2,T15	4.42	1.67	1.42	1.63	1.39	0.73	0.76	0.74
CM,S2,T30	4.42	1.80	1.63	1.70	1.53	0.99	1.00	1.01
RM^,S1,EDT	3.80	0.95	0.57	1.21	0.70	0.46	0.42	0.28
RM,S1,RT30	3.89	0.91	0.56	1.20	0.69	0.46	0.42	0.32
RM,S2,EDT	3.80	0.85	0.55	1.22	0.67	0.44	0.38	0.27
RM,S2,RT30	3.89	0.82	0.57	1.24	0.69	0.46	0.42	0.32
Tohyama	2.98	1.32	0.80	0.36	0.80	0.55	0.55	0.39

* CM: CATT-Acoustic program
^ RM, radiosity model

Configuration	1	2	3	4	5	6	7	8
Sabine	2.85	0.53	0.29	0.45	0.78	0.57	0.35	0.23
Eyring	2.78	0.45	0.20	0.37	0.70	0.49	0.27	0.14
Millington-Sette	2.85	0.28	0.15	0.23	0.44	0.30	0.18	0.11
Fitzroy	3.05	1.29	1.18	1.96	2.52	1.99	0.76	0.16
Arau	2.96	0.66	0.34	0.81	1.55	0.99	0.35	0.14
Fitzroy-Kuttruff	2.85	0.35	0.20	0.37	0.62	0.43	0.21	0.13
prEN 12354	3.59	1.63	1.35	0.54	1.26	0.71	0.46	0.34
CM,S1,T15	2.93	1.19	1.13	1.21	1.01	0.50	0.64	0.59
CM,S1,T30	2.95	1.38	1.52	1.29	1.19	0.53	1.05	0.65
CM,S2,T15	2.94	1.37	1.10	1.23	1.00	0.50	0.67	0.62
CM,S2,T30	2.95	1.61	1.55	1.30	1.17	0.52	1.11	1.08
RM,S1,EDT	1.68	0.31	0.19	0.95	0.53	0.38	0.18	0.12
RM,S1,RT3	1.72	0.35	0.25	1.01	0.59	0.43	0.25	0.24
Tohyama	4.43	0.44	0.11				0.50	0.14

Figure 2: Left: Absorption distributions in model rooms. Grey areas represent absorption coefficient of 0.8 while white areas are representing walls with 0.05 absorption coefficient.
Right: Calculation results for room I and room II (Right) (Kang & Neubauer, 2001)

The results are mean values for frequencies of 500 and 1000 Hz and CATT-Acoustic row represents the results from the ray-tracing simulation program used in the report. As authors mention, the results for bare room case show acceptably similar values using theoretical methods compared to computer simulation but concerning the results for unevenly distributed cases, Eyring formula is providing reasonably accurate results. (Kang & Neubauer, 2001)

In another research, a lecture room was modelled and the results for RT_{60} was calculated by means of both empirical methods and computer simulation methods. Results indicate that the difference is other than varying based on calculation methods, it is dependent on different frequencies as well as room characteristics. (Passero & Zannin, 2010)

Usually, when a new method is published, the author is comparing the results with the most common reverberation estimation methods which are Sabine, Eyring, Millington and Fitzroy. The comparison is both head-to-head between the methods and also between methods and computer simulations. (Nowoświat & Olechowska, 2016) The results vary hugely, and each method is improving the accuracy of results in a given model while still have limitations.

Reviewing the results comparison -between empirical methods and computer simulation or measurements- from different published articles on this subject, one point seems to be clear. Although there are several advantages and limitations for all the available methods, they all provide estimates at different accuracy levels depending on the space specifications and frequencies under investigation. None of these methods are providing accurate results (compared to actual measurement) for all kinds of spaces and the results need to be verified.

5.1.4. Method selection

The difference in results and conclusions for the reviewed spaces confirms that none of the available theoretical methods are generically accurate enough compared to real measurements. Many researchers are still trying to find a comprehensive method for estimation of reverberation time. In some cases, the simple Sabine and Eyring formulas are providing close results to more complicated methods and even actual measurements.

On the other hand, absorption coefficients of some non-architectural elements are more than 1 which makes Sabine's formula applicable to these cases where others cannot tolerate such circumstances.

Interestingly, research shows that the Sabine and Eyring formulas are providing reasonable results among many analytical expressions while computer simulations are not giving better results. (Bistafa and Bradley, 2000 cited in (Beranek, 2006))

To sum up, the literature on this subject confirms that researchers are still not satisfied with existing formulas and many are still trying to develop a comprehensive method. Sabine's formula is not a shortcoming compared to other developed methods and in many cases, the results are accurate enough in reference to measurements.

For the purpose of this study which is enabling BIM platform with acoustical analysis and considering the available input data in early design stages, Sabine's formula which is the most widely used formula in the industry is selected for the estimation of reverberation time.

5.1.5. Non-Architectural elements (Furniture) and Calculation methods

The important effect of non-architectural elements on the reverberation time is studied in many published articles. In an article, researchers claim that in concert halls, the volume of the hall is directly proportional to the audience absorption coefficient. Approximately 10% bigger room volumes are needed when heavily upholstered chairs are selected. (Beranek, 2006)

In an article by Wojnowska & Smardzewski (2016), they investigated the importance of office furniture on the reverberation time considering furniture with perforated HDF or laminated particleboards. Results of their study in Table 3 confirms the important effect of furniture on RT_{60}.

Table 3: Collation of mean values of reverberation time for different furniture constructions (Wojnowska & Smardzewski, 2016)

Frequency [Hz]		125	250	500	1000	2000	4000
		Reverberation time [s]					
	empty room	3,78	5,98	4,50	4,43	3,43	2,05
laminated particleboard	closed construction	3,22	4,35	3,55	2,99	2,32	1,60
	mixed construction	2,91	3,58	3,04	2,49	2,00	1,44
	open construction	2,63	3,05	2,66	2,13	1,78	1,33
perforated HDF	closed construction	3,47	3,37	2,17	1,78	1,45	1,02
	mixed construction	3,13	2,69	1,96	1,61	1,33	0,99
	open construction	2,56	2,19	1,75	1,53	1,34	0,97

The studies on the subject of reverberation time, seating area and audience is helpful to identify the various techniques in estimating the effect of non-architectural elements. These elements can be acoustical suspended ceilings, furniture, audience and even the orchestra.

In the same article by Beraneck (2006), to calculate the effect of audience and seats, the total absorption coefficient of the audience is formulated based on the total absorption coefficient of the room compared to acoustical audience area (area beneath chairs and orchestra). It means that the detailed surface areas of furniture are not taken into consideration and the effect of furniture and audience is estimated by multiplying audience area by proposed absorption coefficient of the audience. Briefly, it is related to the area audience sits and not the number of seats or people.

Currently, there are two major ways the absorption coefficients are published in the industry which are "Per Person" and "Per Unit Area" (Beraneck ,2006). It has to be mentioned that despite my best effort to find reliable sources on comprehensive standards for absorption coefficients, no sources were found to be showing all kinds of non-architectural elements (like desks or book-cases) on a per-person or per-unit-area basis. Table 4 shows sample data from one of the reliable references for the seating and audience absorption coefficients published by Vorländer at 2008 in the appendix of his book.

Table 4: Tables of random-incidence absorption coefficients, α (Vorländer, 2008)

Seating (2 seats per m^2)

Material	Octave band frequency in Hz						
	125	250	500	1k	2k	4k	8k
Wooden chairs without cushion	0.05	0.08	0.10	0.12	0.12	0.12	–
Unoccupied plastic chairs	0.06	0.10	0.10	0.20	0.30	0.20	0.20
Medium upholstered concert chairs, empty	0.49	0.66	0.80	0.88	0.82	0.70	–
Heavily upholstered seats, unoccupied	0.70	0.76	0.81	0.84	0.84	0.81	–
Empty chairs, upholstered with cloth cover	0.44	0.60	0.77	0.89	0.82	0.70	0.70
Empty chairs, upholstered with leather cover	0.40	0.50	0.58	0.61	0.58	0.50	0.50
Unoccupied, moderately upholstered chairs (0.90 m × 0.55 m)	0.44	0.56	0.67	0.74	0.83	0.87	–

Audience (unless not specified explicitly, 2 persons per m^2)

	Octave band frequency in Hz						
	125	250	500	1k	2k	4k	8k
Areas with audience, orchestra or choir including narrow aisles	0.60	0.74	0.88	0.96	0.93	0.85	0.85
Audience on wooden chairs, 1 per m^2	0.16	0.24	0.56	0.69	0.81	0.78	0.78
Audience on wooden chairs, 2 per m^2	0.24	0.40	0.78	0.98	0.96	0.87	0.87
Orchestra with instruments on podium, 1.5 m^2 per person	0.27	0.53	0.67	0.93	0.87	0.80	0.80
Audience area, 0.72 persons / m^2	0.10	0.21	0.41	0.65	0.75	0.71	–
Audience area, 1 person / m^2	0.16	0.29	0.55	0.80	0.92	0.90	–
Audience area, 1.5 persons / m^2	0.22	0.38	0.71	0.95	0.99	0.99	–
Audience area, 2 persons / m^2	0.26	0.46	0.87	0.99	0.99	0.99	–
Audience in moderately upholstered chairs 0,85 m × 0,63 m	0.72	0.82	0.91	0.93	0.94	0.87	–
Audience in moderately upholstered chairs 0,90 m × 0,55 m	0.55	0.86	0.83	0.87	0.90	0.87	–

To select the per-person or per-unit-area approach for the estimations, Beraneck (2006) reviewed available literature which shows that there are recommendations for method selection for concert halls and reverberant chambers. He claims that the results would be identical if the same row-to-row and seat-to-seat spacing was used in the case studies. Also mentioned, it is believed that if seating is highly absorbent, it doesn't matter if the chairs are occupied or not. Beraneck (2006) calculated the absorption coefficient of chairs by means of the method explained before and presented the results in Figure 3. He was looking to find an explanation for the different outcomes. The results confirm that the per-area method to include the effect of furniture provides a wide range of results and it is highly dependent to the concert hall's layout.

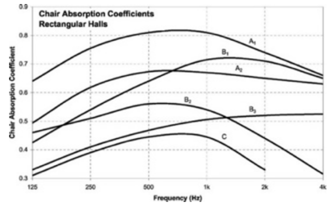


Figure 3: Chair absorption coefficient for rectangular halls using the Sabine equation (A1) Kyoto Hall (2) Amsterdam Hall. (B1) Average of Belin Konzerthaus, Lenox, Seattle, and Lucene Halls. (B2) Boston Hall. (B3) Vienna Hall. (C) Tokyo City Hall (Beranek, 2006)

In 2018, Two researchers investigated the possibility of introducing a standard measure for each piece of non-laminar objects like furniture and lamps to facilitate the acoustical analysis of interior spaces. (Nocke & Oldenburg, 2018) The results show that it is possible to introduce one single absorption coefficient for each furniture, but it requires that manufacturers provide such information based on a solid standardized system which currently does not exist. Also, Nowicka (2005) tried to categorize chairs and provide generic absorption coefficients for them based on ISO354:2003 measurement techniques. The results are a link between object area, object per unit area and absorption coefficient which can be useful for the purpose of this study but it is just for one kind of chair and the author mentions the results need to be verified.

So it looks like the per-unit-area method can be used for the purpose of this study. To investigate this option, I modelled 3 different desks in 3 different sizes (Figure 13-Appendix) and measured detailed surface areas based on the 3D model. The reason for this calculation was to introduce a generic coefficient for each type of furniture which its multiplication by the footprint area of that furniture gives an acceptable estimation of the total absorption independent from surface areas.

*Table 5: Estimated **α**.f Coefficient for 3 modeled furniture in 3 sizes to be multiplied by the footprint and surface coefficient for estimated total absorption (A')*

	500 HZ	**S.f** Footprint (m2)	**S** Total surface Area (m2)	**α** (surface absorption coefficient)	**A** Total Absorption (S x α)	**α'** Absorption per unit area of footprint (A total / Footprint)	**α'.mean**	**(A')** Total Absorption calculated by foorptinr and α' mean (α' mean x Footprint)	Deviation **A** compared to **A'**	**α.f** General Coefficient free from surface type and frequency (α' mean / α)
Single-sided plane	Plane 0-1 (1 sided)	1	1	0.11	**0.11**	0.11	**0.11**	**0.11**	0.00%	**1**
	Plane 0-2 (1 sided)	1.25	1.25	0.11	**0.14**	0.11		**0.1375**	0.00%	
	Plane 0-3 (1 sided)	1.78	1.78	0.11	**0.20**	0.11		**0.20**	0.00%	
Two-Sided plane	Plane 1-1 (2 sided)	1	2	0.11	**0.22**	0.22	**0.22**	**0.22**	0.00%	**2**
	Plane 1-2 (2 sided)	1.25	2.5	0.11	**0.28**	0.22		**0.275**	0.00%	
	Plane 1-3 (2 sided)	1.78	3.56	0.11	**0.39**	0.22		**0.39**	0.00%	
Simple desk	Table 1-1 : PARTICLE BOARD	1	2.28	0.11	**0.25**	0.25	**0.25**	**0.25**	-2.08%	**2.23**
	Table 1-2 : PARTICLE BOARD	1.25	2.79	0.11	**0.31**	0.25		**0.31**	0.02%	
	Table 1-3 : PARTICLE BOARD	1.78	3.89	0.11	**0.43**	0.24		**0.44**	2.15%	
Desk with side planes	Table 2-1 : PARTICLE BOARD	1	4.25	0.11	**0.47**	0.47	**0.44**	**0.44**	-6.41%	**3.98**
	Table 2-2 : PARTICLE BOARD	1.25	5.01	0.11	**0.55**	0.44		**0.55**	-0.76%	
	Table 2-3 : PARTICLE BOARD	1.78	6.54	0.11	**0.72**	0.40		**0.78**	8.25%	
Desk with integrated filing cabinet	Table 3-1 : PARTICLE BOARD	1	5.39	0.11	**0.59**	0.59	**0.55**	**0.55**	-7.47%	**4.99**
	Table 3-2 : PARTICLE BOARD	1.25	6.29	0.11	**0.69**	0.55		**0.69**	-0.89%	
	Table 3-3 : PARTICLE BOARD	1.78	8.08	0.11	**0.89**	0.50		**0.98**	9.86%	

Firstly, for each category (3 desks, 1 single-sided plane and 1 double sided plane) and in 3 different sizes, the Total absorption “A” is calculated. The surfaces are assumed to be made of particle board and for this study, 500 Hz frequency is selected for the calculations.

Then the α’ is calculated by dividing “A” by footprint area. “α’ ” is depending to the size of the furniture so an average value) “α’.mean”) is calculated to make it independent of the furniture size.

Then the new total absorption “A’ ” is calculated by multiplying “α’.mean” by footprint area. Comparing A’ to A shows an maximum deviation of 9.86% for the cases studied.

“α’.mean” can be used to calculate total absorption of each category by just knowing the footprint area but it is dependent to the absorption coefficient of surface finishes “α”.

So to make it generic, “α’.mean/α” which is called “α.f” (total surface area/footprint) can be introduced for each category. By multiplying it by the surface finish “α” and footprint area, the total absorption of each furniture is calculated.

α.f x α x (footprint area) = A_{total}

This method eliminates the need to know the exact surfaces areas of the furniture and could be useful in this report but has many limitations. While the results -shown in Table 5- can be used for estimating total absorption of the examined desks but to introduce reliable results, further investigating on each piece of furniture and in more variety of sizes is required. Although by studying many models, a specific measure can be introduced per square meter of unit area for each specific kind of furniture, the process is not feasible where the possibility of geometry analysis in BIM is existing.

Given all these, the possibility of estimating the effect of furniture by modelling them into the BIM platform and calculating their acoustical properties based on the actual surface areas and corresponding absorption coefficient of each surface can be a potential solution which will be studied in this research through the code development process.

5.2. Computer Tools for Acoustical Analysis

5.2.1. Available tools, interoperability and limitations

Before Autodesk stopped supporting Ecotect, it had the ability to calculate Reverberation time, sound decay time and animation of sound ray tracings in a space. But currently just some energy analysis parts of Ecotect are integrated into Revit and acoustical analysis is yet to be added while there is no information if Autodesk is planning to do so. On the other hand, the existing external platforms which are capable of sharing files with Revit have its own limitations like low level of interoperability or broken BIM link. Figure 4 shows a graphical presentation of the links between Revit and the available programs. Software like COMSOL does the acoustical analysis, but these tools are not integrated into Autodesk Revit and also the interoperability between these platforms are not great. That is the main reason this research is trying to propose a practical method to help designers at early stages to analyze and predict the acoustical performance of indoor spaces. It also can be used to take essential measures to improve the acoustical properties of a space in the preliminary design phases.

There are many simulation tools available, but the problem is linking data between these tools and BIM platform which is Autodesk Revit in this report. Normally, geometrical data can be linked between these platforms but the level of detail that can be translated without flaws fluctuates depending on the programs.

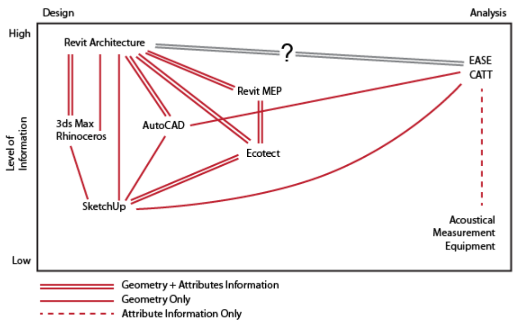


Figure 4: Interoperability of Design Tools and Acoustical Analysis Tools. Interoperability can be categorized according to the level of information while transmitting models between different design and analytical tools. (Kim, Coffeen, & Sanguinetti, 2013)

CATT and Pachyderm are two of the software usable for acoustical analysis but miss the BIM link. Other software like Odeon, CATT, EASE, Ramsete, SoundPlan, VNoise and STEAM 3D are capable of performing acoustical analysis and it is possible to import 3D models from other software, but the problem is that other data like material, finishes and non-architectural elements cannot be imported and the link between models are broken. This means that the essential goal of BIM is neglected. Table 6 shows the comparison of different available computer tools for acoustics analysis in respect to the interoperability between them, input and output data, pros and cons. The results confirm that the most widely used BIM software which is Autodesk Revit does not work with other available BIM-based acoustic analysis software (Christensen, 2017). This shows the essential need to develop a tool for such analysis in the Revit environment.

Table 2 Investigation of relevant software in accordance to acoustic comfort and IAQ simulations.

Software	***Inter operability***	***Simulations tools***		***Input***	***Output***	***Pros***	***Cons***
		Acoustic	***IAQ***				
IES	-Autodesk, REVIT -gbXML	-	- (Apache Loads)	-3D model (ModelIT) -Weather -Solar shading -Construction and materials -Thermal templates -HVAC systems	-Sizing ventilation systems based on IAQ requirements -Heating/Cooling loads	Broad variety of outputs	Not able to do a separate IAQ simulation.
Rhino ceros	-Graphisoft -(REVIT)	- Pachyderm -Bizz	-	-Geometrical model -Materials	-Reverberation Time -Early Decay Time -Center Time -Clarity -Definition -Strength/Loudness	Many parameters can be simulated	Output in file format, no visualization of results
iDbuild	-	-	- iDbuild	-Number of people -Activity level -Clothing level	-Indoor Air Quality Class	Quick simulations	Only rectangular rooms with windows on one wall.
IAQX	-	-	-IAQX	-Number and volume of air zones -Number of Sink Materials -Sources, including source model, (e.g. source area, initial emission factor, decay constant)	-VOC	Quick calculations	No interoperability to 3D models
TUCT™ v2	-	-CATT-Acoustic™ v9.1	-	-Geometrical model -Absorption coefficients	-Reverberation Time -Early Decay Time -Center Time -Clarity -Definition -Strength/Loudness Etc.	2D representation of output.	Only geometrical information

Table 6: Investigation of relevant software in accordance with acoustic comfort and IAQ simulations. (Christensen, 2017)

The tool EASE can be used for acoustical analysis with the ability to import and export all kinds of data (geometry, acoustic information and finishes via CAD files) (Hansen, 2017). However, it is a useful feature of this program, but it still needs analysis of data outside of Revit platform and it is not possible to interoperate between EASE and Revit because of its primitive design modelling methods which forces the engineers rebuild the model. (Kim, Coffeen, & Sanguinetti, 2013)

In a different tactic , a Dynamo tool named Acustamo (Vannini, 2015) is developed for acoustical analysis in Revit, but it does not satisfy the acoustical analysis requirement for a designed building. Reviewing Acustamo reveals that it is a ray-tracing add-on which cannot be useful at early design phases of the project and for multiple rooms. It has to be attached to different surfaces of rooms via Dynamo interface. The inputs include surfaces, sound source, the first direction of rays and maximum bounce numbers. The output will be poly-curves indicating bounce paths which can be used for acoustical analysis. To be able to use this extension, the user needs to have comprehensive knowledge of Dynamo and programming, thus it is not a convenient tool for most users.

In the article "Acoustic Comfort and Indoor Air Quality (IAQ)" by Christensen (2017), the writer mentions that although acoustic simulation tools are not integrated into Revit, the possibility of extracting data from the model and adding absorbance coefficients to the material library can help to estimate acoustical properties such as Reverberation Time (RT_{60}). Although the idea of populating the model with such properties would be helpful for customizing the analysis, using a generic external database with all the needed properties would be more intuitive in the early design phases.

In the article "BIM-based acoustic simulation framework" (Wu & Clayton, 2013), an acoustical analysis tool based on Revit API is developed. The program is very useful to analyze the acoustical performance of a single modelled room. The interesting part of this program is that it records any custom sound and simulates the sound in the modelled room to give designer, architect or engineer the feel of how exactly it sounds in that specific room. It also is able to calculate the most important -dominant- frequencies of the given sound for acoustical analysis purposes.

In another effort, researchers from Concordia University (Erfani, Mahabadipour, Nik-Bakht, & Lee, 2018) developed a method for Autodesk Revit by using Dynamo algorithms. The proposed method calculates the RT_{60} of any room in a model using Sabine's formula. This Dynamo tool is capable of calculating and colour coding all the rooms in a given model. Although the code is relatively easy to use, it has limitations. A major issue is that because the program is assuming same material for floors and ceilings and also furniture effect is not included, the researchers had to manipulate the absorption coefficients to include the effect of furniture in the final results.

To sum up, there are a couple of tools capable of simulating acoustical analysis of indoor spaces, but a wide variety of challenges makes them less useful compared to integrated methods of energy analysis in Revit or external programs. Thus, the stakeholders prefer to remodel the design in alternative platforms and break the BIM link which affects future modifications. On the other hand, the available tools are not designed to include the effect of non-architectural elements in a room such as suspended ceilings, columns, furniture, doors and windows. Non-architectural elements beside acoustic surfaces are playing a huge role in reducing RT_{60} and not including it in the calculations, make the results less reliable.

5.2.2. Coding Platforms review and selection

There are two main platforms suitable for the purpose of this research, Dynamo and Revit API. Dynamo is an open-source visual programming platform which is developed for Autodesk Revit and consists of an integrated library an extensive library of user-developed nodes. Basically, in Dynamo the programs are assembled by means of "Nodes" and "Links" between these nodes. Dynamo works alongside Revit but is dependent from Revit itself.

On the other hand, Revit API is a coding platform integrated into Revit and mostly used to write Macros for different automation tasks. Despite Microsoft Office, Adobe Photoshop or any other computer program that supports macros, Revit API does not include action recording capability and the macros have to be written from scratch and need coding knowledge. Macros are fast and can be used as add-ons in the Revit environment. (Kilkelly, 2016)

Table 7: Comparison of Dynamo and Revit API (Kilkelly, 2016)

	Fast to Create	Runs Fast	Ease of Use	Easy to Modify	Few Users	Lots of Users
Dynamo	Excellent	Fair	Good	Excellent	Excellent	Fair
Revit API	Fair	Excellent	Excellent	air	Very Good	Excellent

The Dynamo platform is easier to create and easier to modify for relatively simple programs. Also, it is suitable when the users are a small group and support for the program is easily accessible. Typically, understanding a Dynamo code is way easier for future development and modifications.

On the other hand, Revit API is faster -specially for complicated models- and easier to use for the end-user. Besides, it is suitable when there are more users and less support is provided by the developer.

Bearing in mind all these and considering the importance of ease of modification on the outcome of this research, Dynamo platform is selected for the solution development.

6. Solution Development

Thankfully, The research team Erfani, Mahabadipour, Nik-Bakht & Lee (2018) who developed a Dynamo code for estimation of reverberation time on a case study (Concordia university's John Molson building) provided the code and the case study model which made it possible to review their approach to the problem. The reviews of their approach was very informative but also revealed that some of the limitations the provided Dynamo code has derives from the method of data extracting from the Revit model.

To solve this, the Dynamo code was written from scratch and based on finding and indexing all possible elements inside the rooms of the model.

The elements of each room including architectural and non-architectural are extracted and categorized in Dynamo dictionaries (instead of lists) which makes it possible to minimize errors working with data structures and numerical indexes. Various initial analysis sessions on the extracted data from different small case studies revealed error points which were solved by enhancing data extraction techniques.

The developed code translates the raw information from the model (Gross areas of walls, ceilings, floors, windows, doors, curtain walls and furniture) and geometries (single geometries and intersections of geometries) to processed newly defined values such as "Exposed Areas" and "Net Areas". These new values are then used for the calculation of total absorption area in each room.

The circular loop of coding, testing, re-coding and debugging was done several times and the output is a comprehensive Dynamo code which provides outputs with a reasonable level of accuracy. The algorithm (without cross-references and checkpoints) consists of the major steps described below.

1. Extracting architectural elements properties of rooms
    a. Gross Areas of surfaces (Wall, Floor, Ceiling, Curtain Wall)
    b. Finishes
    c. Geometry and Volume
2. Extracting doors and windows properties
    a. Location
    b. Area
3. Extracting each furniture properties
    a. Gross Area(s)
    b. Finish(es)
    c. Geometry(ies)
4. Calculating NET Areas
    a. Architectural elements and furniture
5. Geometry analysis
    a. Inner Intersection of geometries
    b. Geometries intersection with other elements
6. Calculating NET, EXPOSED and EFFECTIVE properties
    a. NET and EXPOSED furniture area
    b. NET and EXPOSED architectural elements area
    c. EFFECTIVE volume of rooms
7. Reading absorption coefficients from an external database
8. RT_{60} Calculations

Figure 14 (Appendix) is a simplified algorithm using Dynamo nodes showing the major elements of the Dynamo code and their corresponding inputs and outputs. The cross-references are vaguely shown in this algorithm and the full description of the code follows.

The algorithm shown in the Figure 5 is the overview of the major steps and checkpoints in the developed code. As shown, there are various points of geometry analysis to address the intersecting surfaces of furniture and architectural elements and also the inner surfaces of the furniture. These intersections are used to calculate "Net" and "Exposed" areas useful for the final calculations.

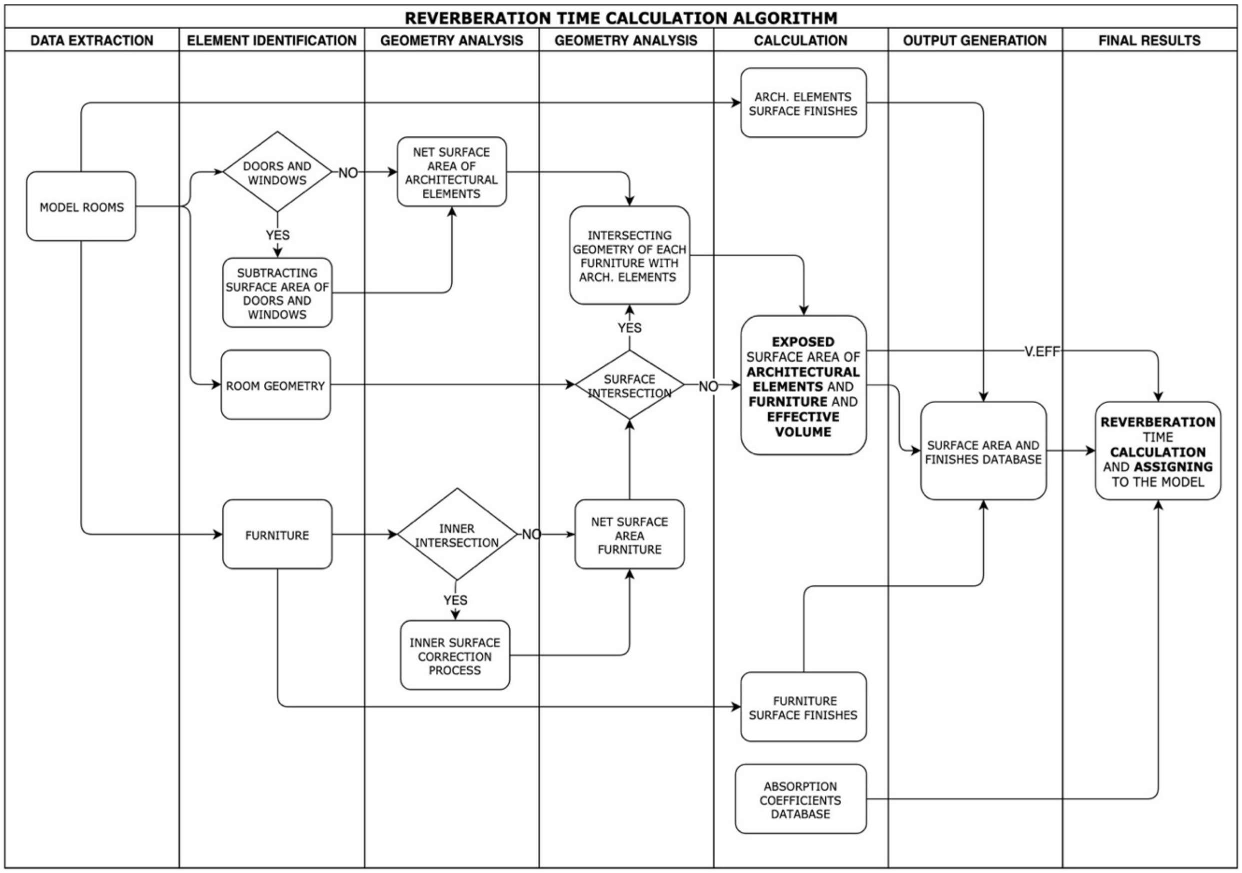


Figure 5: Simplified algorithm showing methodology of the written code

An overview of the final code is shown in the Figure 6 to demonstrate the cross-references between major algorithm sets. Major elements are further explained in detail. The custom Dynamo extension that are used include archilab, Bakery, ClockWork, Python, Rhythm and Springs.

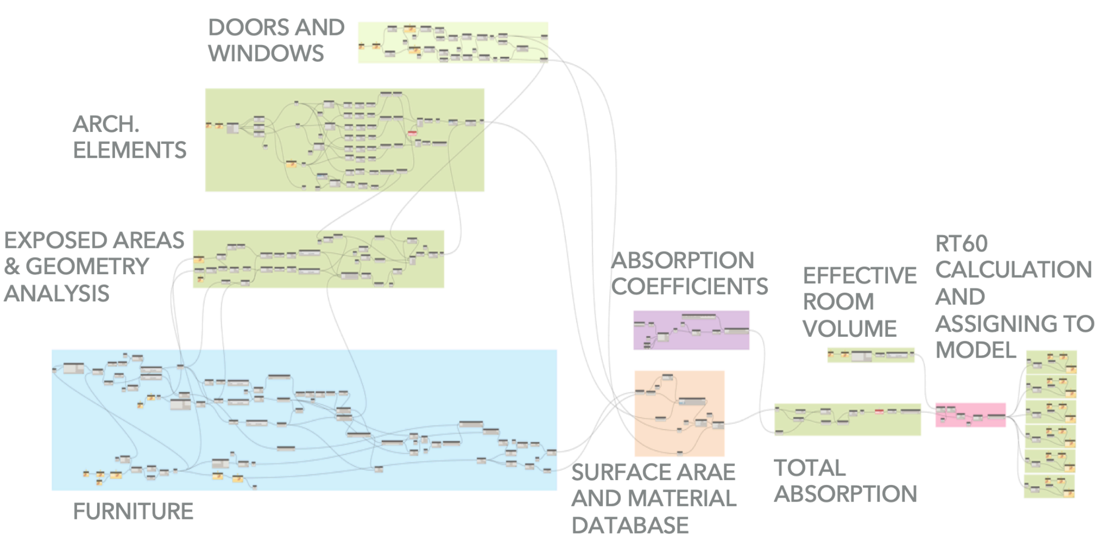


Figure 6: Final Dynamo Code Overview, different sections and their function

6.1. Data Extraction

One of the challenges in working with different properties of various elements from a Revit model is to maintain the data structures and links between them in a fashion that can be referenced to without error. Such structure should not be prone to error when data sorting or elements sorting change. Many error checking and debuggings are needed to be executed for this purpose. That being said, the data extracted from elements categorized based on location (rooms) are:

- Architectural elements: Area, finishes, geometry of rooms
- Non-architectural elements: Area, finishes, geometry of elements

To start programming, after investigating different capabilities of Dynamo for the intended analysis, the initial algorithm (graph) was designed and was tested on different small models including one room, two rooms, rooms with furniture, rooms with doors and windows, non-rectangular rooms and combination of these cases. The goal was to reduce the errors that might happen when the case study is offering something new.

For example, while the code was working perfectly for a case with 3 rooms which had doors and windows, not having furniture in one of the rooms was resulting in wrong answers. Many other cases were tested to make sure the designed algorithm is not prone to errors in various situations.

6.1.1. Architectural Elements Block (Gross Numbers)

In this block, by identifying placed rooms in the Revit model, all architectural elements and their corresponding surface area and finish material are extracted. This enables the code to consider different material for walls, ceiling and floor for each room in a model and store them in a proper structure categorized by room, surface type (side, bottom, top) for future analysis on the data.

One of the modifications that made this part of the code complicated was to add the ability to identify curtain walls from simple walls and windows.

This section provides these outputs:

- Gross wall area and finishes in each room
- Gross ceiling area and finishes in each room
- Gross floor area and finishes in each room
- Gross curtain wall area and finishes in each room

6.1.2. Non-Architectural Elements

6.1.2.1. Furniture (Gross and Net areas)

By identifying all the furniture existing in the model and their location (rooms), the needed information including surface areas and corresponding materials were extracted for each element.

The main issue was that some furniture elements (Revit families) were built with different geometries that might have internal surfaces. These internal surfaces are mistakenly included in the overall surface area of the furniture in RT_{60} calculations. On the other hand, these separate geometries of a single model might have different materials with different absorption coefficients.

In the next step, each element got translated into Dynamo geometries ($SF.I_i$, $SF.I_j$, ….. $SF.I_z$). Unionizing these geometries ($S.U_1$) gives proper total surface areas but not the portion of the areas corresponding to each finish of the object.

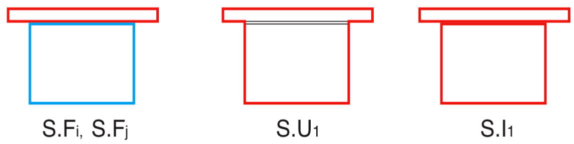


Figure 7: section of furniture models and the defined variables for furniture surfaces

To solve this, the comparison between unified geometry surface area ($S.U_1$) to the summation of individual geometry surfaces ($S.I_1$) area (shown in Figure 7) provides a specific coefficient for each object that can be multiplied by individual surfaces areas of each material ($SF.I_i$, $SF.I_j$, ….. $SF.I_z$). The results are specific net surface area for each material used in the element.

$$\frac{S.U_1}{S.I_1} = \propto_1 \quad ; \quad \left(SF_i + \ SF_j + \cdots + \ SF_z\right) = \ S.I_1 \ ;$$

$$\propto_1 \times SF_{i,i,\ldots,z} : Finish\ of\ the\ surface\ i, j, \ldots, z\ for\ furniture\ \#1$$

This section provides these outputs:

- Furniture geometries (exploded and unified)
- Furniture Net areas and finishes in each room

6.1.2.2. Doors and Windows

In this section of the code, the area of the doors and windows located in each room is extracted. The assumption made here is that the frame and panel are of the same material for each door or window. This assumption is made because differentiating frames from panels makes the Dynamo code complicated and slow while the effect of them on the final RT_{60} estimation is negligible.

These elements are stored separately and will be called as “Doors” and “Windows” instead of their materials. This method is selected because in the reviewed sources, typically the absorption coefficients are provided by the type and manufacturer of these elements and not by the finish material.

This section provides 3 outputs:

- Doors area and finishes in each room
- Windows area and finishes in each room
- Total fenestration area in each room

6.2. Geometry Analysis: Net and Exposed Surface Areas

Firstly, the Net area of the walls was calculated by subtracting doors and windows surface areas in each room from masonry walls (Curtain walls are separated in this calculations).

Secondly, a major enhancement to the calculations is to determine the “Exposed” surface area of architectural and non-architectural elements. “Exposed” areas mean the surface area of any element inside the room which is exposed to the sound field.

While for each category of architectural elements, exposed area can be the summation of all of the same elements in that room (all walls); for the furniture, exposed surface areas are unique for each furniture and has to be calculated independently.

To do so, rooms and furniture are simulated and converted into Dynamo geometries (solids) and the intersections of these solids provides the needed information. The surfaces areas are defined as S_1, S_2, … S_8 (Figure 8). S_1 and S_2 are extracted directly from the model while S3 is calculated by subtracting solid geometry of all elements inside the room from the room solid geometry and calculating the surface area of the resulting solid.

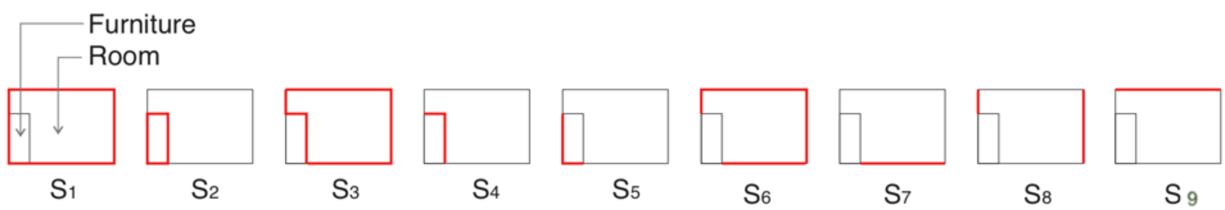


Figure 8: Sections of a sample furniture in a room, geometries and intersecting cases and variables. S1 and S2 are extracted from the model. S3, S7, S9 are calculated by geometry intersection. S4, S5, S6 and S8 are calculated mathematically.

For the furniture, each piece of furniture is converted into a solid. Then based on the formula below the "Exposed Surface Area" (S_4) of the furniture is calculated. This process takes a lot of processing in Dynamo and is time-consuming specially when model consists of several elements.

$$S_4 = S_2 - S_5 \; ; \quad where: S_5 = (S_1 + S_2 - S_3)/2$$

Where:

- S_1: Total Room boundary areas
- S_2: Total Net Furniture Areas
- S_3: Total surface area of subtracting furniture geometry from Room geometry
- S_4: Exposed Surface Area of each furniture
- S_5: Intersection surface area

Then again like the method used to calculate Net areas of the furniture, a dedicated coefficient for each furniture is calculated. The coefficient is the ratio of S_4 to $S.U_1$ and get multiplied by each surface (different finishes) of the furniture elements to make sure exposed surfaces are determined.

Now that we have the intersected surface areas of furniture and architectural elements, we can calculate the "Exposed Area of Architectural Elements" (S_6). But to identify the position of the hidden surfaces behind the furniture, a new geometrical analysis is needed.

In this step, the subtraction of geometries of all furniture from the room is intersected with two planes at floor and ceiling height and by knowing S_5 (intersection surfaces), the exposed surface area of every architectural element is calculated independently (S_7, S_8 and S_9)

This section provides 3 outputs:

- The exposed surface area of every furniture in rooms (separately)
- The exposed surface area of walls
- The exposed surface area of floors
- The exposed surface area of ceilings

6.3. Calculations on the Extracted Information, Data Assigning and Presentation

6.3.1. Absorption Coefficients Database

Previously in the research completed by Erfani, Mahabadipour, Nik-Bakht, & Lee, (2018) an external database (OpenMAT) was used to store and parse the data from. Although for this research I have tried to use the same method, but because of the limitations which will follow, an excel database was chosen.

Firstly, the OpenMAT database is not accessible online and the Dynamo code need to refer to an offline file on the computer which does not make much difference compared to an Excel file.

Secondly, all my efforts (using different XML editors) to edit the existing database to add more materials to it failed and I decided to use an Excel database instead. This file is currently stored offline on the computer but an opportunity for future development is to make its shared link available online for everybody and the Dynamo reads from the shared file through Google API.

On the other hand, Excel data structure is chosen because it is much easier for users to manipulate the data and modify it for the custom coefficients or adding new material properties based on the model specifications. Table 8 shows the absorption coefficient used throughout this study.

Table 8: Absorption Coefficients used in the project extracted from (Wojnowska & Smardzewski, 2016), (Vorländer, 2008) and Troldtekt online acoustic calculator (for acoustic ceiling tile)

Finish	125 HZ	250 HZ	500 HZ	1000 HZ	2000 HZ	4000 HZ
Plastic (MDF)	0.08	0.11	0.11	0.194	0.24	0.24
Gypsum Wall Board	0.15	0.1	0.06	0.04	0.04	0.04
Ceiling Tile 600 x 600	0.45	0.8	0.85	0.85	0.95	0.95
Metal	0.02	0.02	0.03	0.05	0.05	0.05
Doors	0.25	0.2	0.15	0.1	0.08	0.07
Windows	0.35	0.25	0.18	0.12	0.07	0.04
Ceramic Tile	0.01	0.01	0.02	0.02	0.02	0.03
Wood (HPL)	0.04	0.22	0.42	0.58	0.62	0.92
Concrete	0.02	0.02	0.03	0.03	0.04	0.05
Glass	0.1	0.05	0.04	0.03	0.03	0.03
Plaster	0.01	0.01	0.02	0.02	0.05	0.05

6.3.2. RT_{60} Calculation

At this point, all the needed information is gathered, indexed and categorized in structured databases (Dynamo dictionaries) to be used for acoustical analysis. Compiling all the data, the database is finalized with corresponding material areas and coefficients in each room and it no longer refers to elements such as walls or furniture. Finally, the coefficients are linked to the surfaces and total absorption for each room is calculated

Although it seems like all the information needed for the Sabine equation is provided, one of the last steps is to calculate "Effective Room Volume" (V_{EFF}) by subtracting furniture geometry volume from the room volume.

6.3.3. Assigning Data to the Model

The final step is to calculate RT60 in 6 main frequencies and assigning the calculations to the Revit model. Although in some sources 7 frequencies were used for RT_{60}, because in some sources the coefficients in the 8k frequency are not provided, this frequency is excluded from the results. The results are assigned to the project parameters that are defined in the Revit model at the final step. The parameters area names “Reverberation Time 1 ~ 6” and the assigning method is the same as the work by Erfani, Mahabadipour, Nik-Bakht & Lee (2018).

6.4. Visualization

At the final phase, the same method that was proposed by Erfani, Mahabadipour, Nik-Bakht, & Lee (2018) to colour-code the floor plans for a better visual presentation of the results is used. Figure 17 and Figure 18 (Appendix) are showing the colour-coded plans for two selected frequencies of 125 of 500 Hz using the same method mentioned above.

6.5. Verification of the Results

To ensure that the method is working properly, and results are reliable, the outcomes need to be compared with other methods. Field measurements are the best way to verify the results because it can be directly modelled in Revit to compare the results but measuring techniques need specific equipment and are out of the scope of this project. So, the results are compared with other available simulating tools.

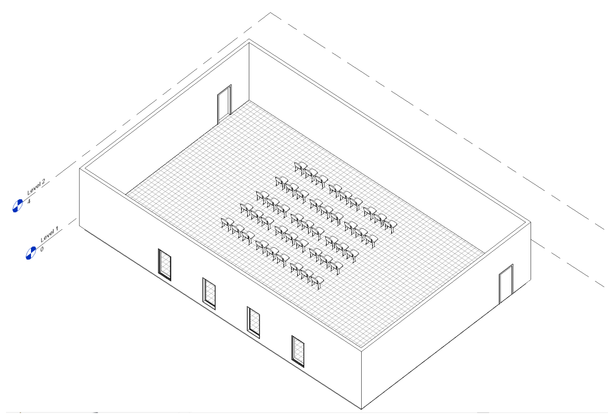


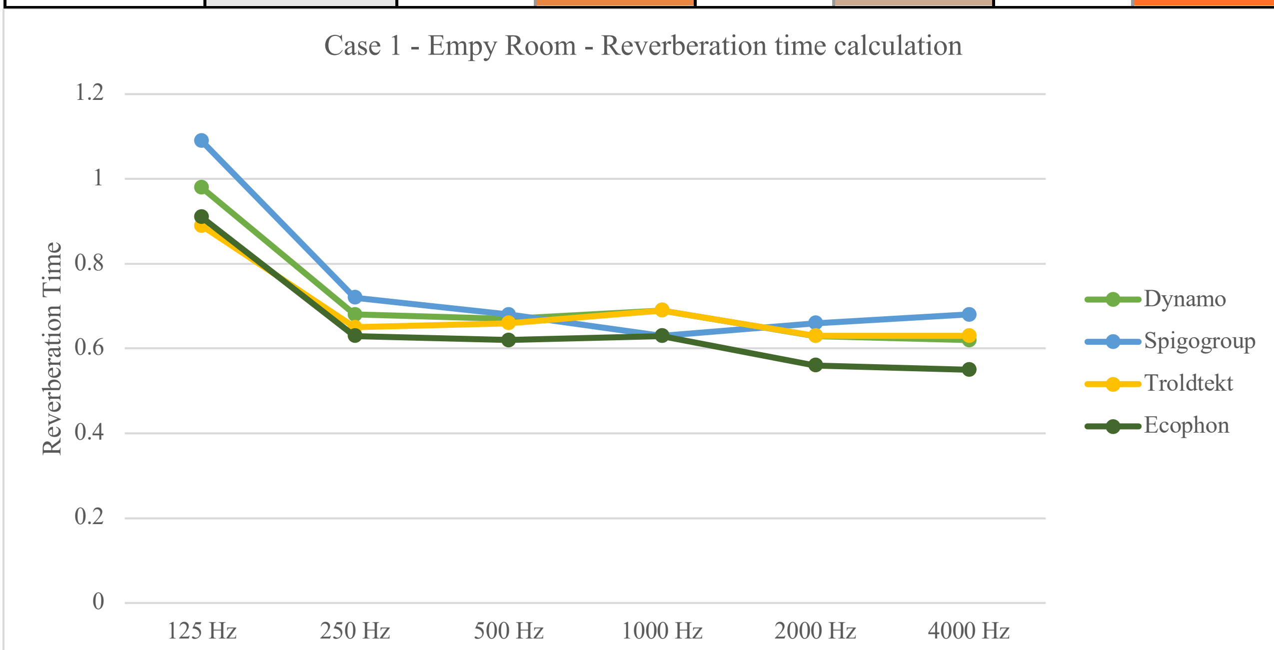
Figure 9: Case study modeled in Revit for the results verification of the Dynamo code

The model used is a simple room with dimensions of 10m x 10m x 4m. The first scenario is an empty room and scenario 2 is the room with 40 wooden upholstered chairs as shown in the Figure 9. The room is assumed to have 4 windows having overall 12.8 m^2 area and two doors corresponding to 6.4 m^2 of wall area. The floor is ceramic tiles and the ceiling is acoustical ceiling tiles. The selected materials for walls, floors and ceilings in different calculators are the same to have a consistent basis for the comparison. The absorption coefficients of the suspended ceiling for Troldtekt (troldtekt calculator, n.d.), Ecophon and the Dynamo code are the same and based on Ecophon Access™ C 20mm specifications. For the Spigogroup calculator, Spigoacustic 28-16-16 is selected which has almost the same absorption coefficient distribution in different frequencies. The estimation technique used in Spigogroup and Ecophon is Sabine’s equation while for troldtekt it is not stated.

It is mentionable that there is no standard procedure for including the effect of furniture in simulating tools so that might cause some inconsistency between the BIM-based estimation of this research with other tools we are comparing results with. But to minimize this, almost identical furniture types will be used for both approaches.

Table 9: Results comparison for reverberation times for sample room without furniture

	Dynamo Code (Reference)	**Spigogroup Calculator**		**Troldtekt Calculator**		**Ecophon Calculator**	
	RT60 [s]	RT60 [s]	Deviation	RT60 [s]	Deviation	RT60 [s]	Deviation
125 Hz	**0.98**	1.09	11.22%	0.89	-9.18%	0.91	-7.14%
250 Hz	**0.68**	0.72	5.88%	0.65	-4.41%	0.63	-7.35%
500 Hz	**0.67**	0.68	1.49%	0.66	-1.49%	0.62	-7.46%
1000 Hz	**0.69**	0.63	-8.70%	0.69	0.00%	0.63	-8.70%
2000 Hz	**0.63**	0.66	4.76%	0.63	0.00%	0.56	-11.11%
4000 Hz	**0.62**	0.68	9.68%	0.63	1.61%	0.55	-11.29%



The results comparison for case 1 show that the deviation is between +11% to -11%. The results deviation is in an acceptable range, but the effects of this difference need to be investigated.

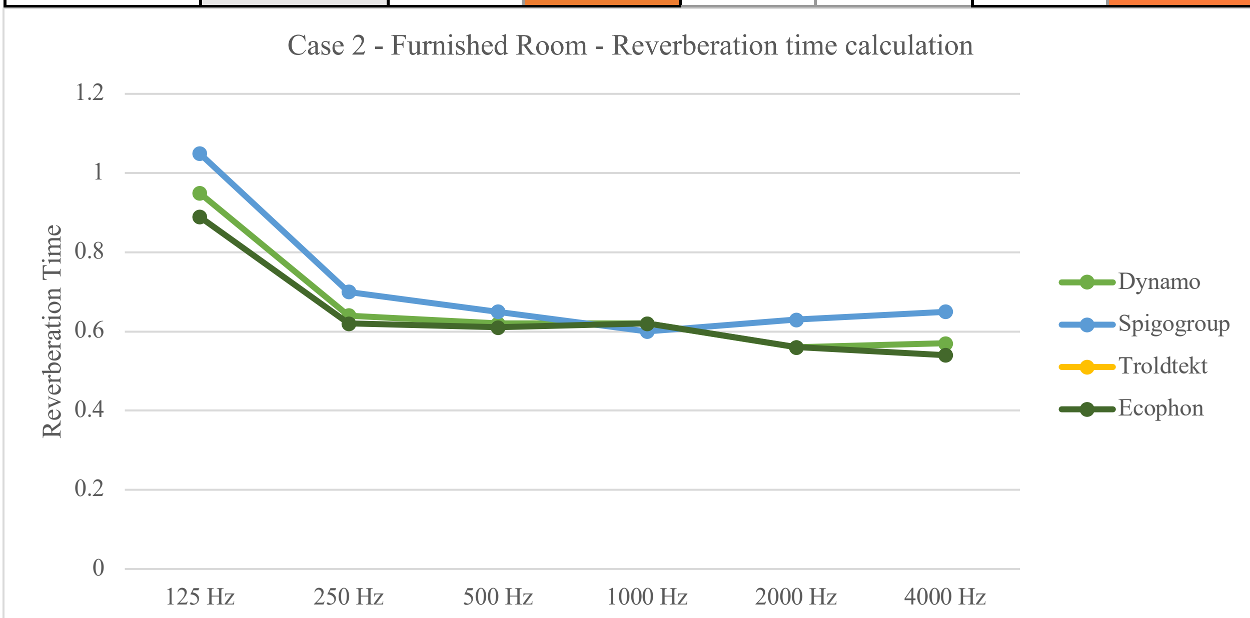
One of the main reasons are the difference in the calculator approaches. Troldtekt has the option to modify the absorption coefficients and provide them as well while the two others do not provide the numbers and the user can just select the type of finishes.

Also, doors and windows are not included in Troldtekt and Spigogroup calculators which might affect the results as well.

So, by considering the possible minor differences in the absorption coefficients of the materials, the results show that the method is reliable for calculating rooms' RT_{60}.

Table 10: Results comparison for reverberation times for sample room including furniture

	Dynamo Code (Reference)	**Spigogroup Calculator**		**Troldtekt Calculator**		**Ecophon Calculator**	
	RT60 [s]	RT60 [s]	Deviation	RT60 [s]	Deviation	RT60 [s]	Deviation
125 Hz	**0.95**	1.05	10.53%	-	-	0.89	-6.32%
250 Hz	**0.64**	0.7	9.37%	-	-	0.62	-3.13%
500 Hz	**0.62**	0.65	4.84%	-	-	0.61	-1.61%
1000 Hz	**0.62**	0.6	-3.23%	-	-	0.62	0.00%
2000 Hz	**0.56**	0.63	12.50%	-	-	0.56	0.00%
4000 Hz	**0.57**	0.65	14.04%	-	-	0.54	-5.26%



In the results for case 2, Troldtekt calculator is not included because it does not offer inclusion of furniture in the estimations. Comparing the results shows that the maximum deviation increases to around 14% for Spigogroup while for the Ecophone calculator, the results are almost the same (6.3% deviation) compared to the proposed BIM-based method. This comparison confirms that the proposed model-based estimation technique for including the effect of furniture instead of per-area or per-unit models used in other calculations is reliable and can be used in bigger case studies. However, to validate the results further, a comparison with real measurements is necessary.

7. Standards

There is no specific part in the codes or bylaws indicating the acceptable acoustical behavior (including reverberation time) for different spaces. The National Building Code is focusing on sound transmission between spaces and not acoustical properties of spaces. But from various academical and industry-standard sources some ranges can be extracted. Table 11 is showing results derived from articles by Warnock (2001), Bradley (2002) and Spigogroup simulator (Spigogroup Simulator TRO, n.d.) The results for the same categories are in the same range and the difference is in the categorization of the spaces.

Table 11: Reverberation Time standard ranges for different spaces

Space	**SpigoGroup Simulator**	**NRC Construction Technology update No.50**	**NRC Construction Technology update No.51**
Classrooms	0.5 ~ 0.8	0.6 (up to 300 m^3) 0.7 (over 300 m^3)	0.5 (Primary school) 0.7 (High school)
Meeting room	-	0.5	0.7
Conference rooms	0.7 ~ 1.0		
Auditorium	0.7 ~ 1.0		0.7
Library	-	0.7	
Offices	0.7 ~ 1.0		
Cinema	0.8 ~ 1.2		
Multi-Purpose	1.2 ~ 1.5		
Concert Halls (various purposes)	1.3 ~ 2.1		
Sport Center	1.0 ~ 3.0	1.0	
Studio	0.2 ~ 0.4		
Theater (<500 occupant)	1.0 ~ 1.2		
Theater (>500 occupant)	1.2 ~ 1.4		
Bar, restaurant and cafeteria	0.5 ~ 0.9	0.8	

8. Case Study, Results and Comparison

The case study is the same educational building model, which is investigated in the research by Erfani, Mahabadipour, Nik-Bakht, & Lee (2018) with some modification made on it. The model is showing LOD3 of detail level including architectural elements finishes. Figure 15 and Figure 16 (Appendix) show the floor plan of the level 6 with and without furniture which later will be subject to reverberation time estimation by means of the Dynamo algorithm developed. Because all the calculations are based on the "Rooms" of the Revit model and their boundaries, the constraints of the upper and lower limit have to exactly define floor and ceiling levels.

In the provided model, the exterior glass surfaces are assumed to be "Walls" but with glass finish which is limiting the work so they are all updated to "Curtain walls" and have a dedicated calculation algorithm in the developed Dynamo program.

To investigate the effect of furniture on the reverberation time, 3 scenarios are considered.

1. Same finish materials as the previous research but with standard coefficients
2. Adding furniture to scenario 1
3. Adding suspended ceiling and double gypsum-boards walls to scenario 2
4. Excluding furniture from Scenario 3

The results of these three scenarios will be compared to understand the effect of furniture and other absorbant surfaces. finally a comparison of the final results will be carried on with results from the previous research on the same case study.

The surfaces finishes are: Plaster or gypsum wallboard, tiles on concrete, plaster or 600x600 ceiling tiles, metal, textile and MDF. The corresponding coefficients are shown in the Table 8.

8.1. Scenario 1 and 2 Comparison: Effect of Furniture on the Reverberation Time

RT_{60} estimation results for scenario 1 and 2 are shown in the Table 12 and Table 13 for level 6 of the case study. First set of results are for the model without any furniture and the next one is a furnished version of the model.

Table 12: Scenario 1 results: Reverberation Time estimation results for floor level 6 of the case study assuming all room are empty

Scenario 1: No furniture or suspended ceiling, Plaster walls							
Frequency (Hz)	125	250	500	1000	2000	4000	average
Room 1	4.63	6.83	5.79	6.47	3.95	3.73	5.23
Room 2	3.07	4.48	4.62	5.66	4.3	4.1	4.37
Room 3	3.07	4.48	4.62	5.66	4.3	4.1	4.37
Room 4	3.07	4.48	4.62	5.66	4.3	4.1	4.37
Room 5	3.07	4.48	4.62	5.66	4.3	4.1	4.37
Room 6	3.07	4.48	4.62	5.66	4.3	4.1	4.37
Room 7	3.52	5.27	5.23	6.25	4.56	4.3	4.86
Room 8	5.9	6.88	6.49	7.7	5.39	5.07	6.24
Room 9	11.55	12.65	9.59	10.34	6.28	5.75	9.36
Room 10	16.08	16.79	11.16	11.5	6.61	5.98	11.35
Room 11	11.28	12.39	9.48	10.25	6.26	5.73	9.23
Room 12	7.72	10.68	8.56	9.32	5.83	5.34	7.91
Room 13	6.67	9.09	7.75	8.66	5.62	5.18	7.16
Room 14	8.46	9.59	8.12	9.14	5.91	5.47	7.78
Room 15	2.85	4.35	4.5	5.49	4.18	3.97	4.22

Table 13: Scenario 2 results: Reverberation Time estimation for floor level 6 of the case study assuming room are furnished

Scenario 2: Furniture added to scenario 1							
frequency	125	250	500	1000	2000	4000	average
Room 1	4.29	5.35	4.24	4.19	2.99	2.9	3.99
Room 2	2.91	3.79	3.57	3.83	3.18	3.12	3.40
Room 3	2.91	3.79	3.57	3.83	3.18	3.12	3.40
Room 4	2.91	3.79	3.57	3.83	3.18	3.12	3.40
Room 5	2.91	3.79	3.57	3.83	3.18	3.12	3.40
Room 6	2.91	3.79	3.57	3.83	3.18	3.12	3.40
Room 7	3.39	4.62	4.3	4.65	3.67	3.54	4.03
Room 8	5.61	6.03	5.37	5.79	4.4	4.24	5.24
Room 9	8.46	6.49	4.51	3.96	3.22	3.17	4.97
Room 10	11.85	8.92	5.81	5.1	3.88	3.76	6.55
Room 11	9.01	7.49	5.31	4.82	3.75	3.65	5.67
Room 12	6.48	6.57	4.79	4.37	3.45	3.36	4.84
Room 13	5.69	5.84	4.44	4.13	3.32	3.25	4.45
Room 14	7.81	7.82	6.24	6.32	4.61	4.4	6.20
Room 15	2.74	3.78	3.62	3.94	3.24	3.16	3.41

Results in Table 12 (non-furnished scenario) shows very large numbers in some cases for the reverberation time. The maximum is 16.79 [s] for the room number 10 at 250 Hz frequency. This is because the room is in this case basically a reverberant chamber without any absorbing surfaces in it. As can be seen clearly in the results for the next scenario in the Table 13 the numbers are hugely reduced and the maximum is at 11.85 [s] for the same room but at 125 Hz. It confirms that the effect of furniture is huge on the reverberation time.

Table 14: Difference of the results from scenario 1 and 2 in second, percentage, mean and SD of the difference

	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz				
	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Mean [s] difference	Mean [%] difference	SD [s] of difference
Room 1	0.34	7.34%	1.48	21.67%	1.55	26.77%	2.28	35.24%	0.96	24.30%	0.83	22.25%	1.24	22.93%	0.68
Room 2	0.16	5.21%	0.69	15.40%	1.05	22.73%	1.83	32.33%	1.12	26.05%	0.98	23.90%	0.97	20.94%	0.55
Room 3	0.16	5.21%	0.69	15.40%	1.05	22.73%	1.83	32.33%	1.12	26.05%	0.98	23.90%	0.97	20.94%	0.55
Room 4	0.16	5.21%	0.69	15.40%	1.05	22.73%	1.83	32.33%	1.12	26.05%	0.98	23.90%	0.97	20.94%	0.55
Room 5	0.16	5.21%	0.69	15.40%	1.05	22.73%	1.83	32.33%	1.12	26.05%	0.98	23.90%	0.97	20.94%	0.55
Room 6	0.16	5.21%	0.69	15.40%	1.05	22.73%	1.83	32.33%	1.12	26.05%	0.98	23.90%	0.97	20.94%	0.55
Room 7	0.13	3.69%	0.65	12.33%	0.93	17.78%	1.60	25.60%	0.89	19.52%	0.76	17.67%	0.83	16.10%	0.48
Room 8	0.29	4.92%	0.85	12.35%	1.12	17.26%	1.91	24.81%	0.99	18.37%	0.83	16.37%	1.00	15.68%	0.53
Room 9	3.09	26.75%	6.16	48.70%	5.08	52.97%	6.38	61.70%	3.06	48.73%	2.58	44.87%	4.39	47.29%	1.69
Room 10	4.23	26.31%	7.87	46.87%	5.35	47.94%	6.40	55.65%	2.73	41.30%	2.22	37.12%	4.80	42.53%	2.17
Room 11	2.27	20.12%	4.90	39.55%	4.17	43.99%	5.43	52.98%	2.51	40.10%	2.08	36.30%	3.56	38.84%	1.46
Room 12	1.24	16.06%	4.11	38.48%	3.77	44.04%	4.95	53.11%	2.38	40.82%	1.98	37.08%	3.07	38.27%	1.42
Room 13	0.98	14.69%	3.25	35.75%	3.31	42.71%	4.53	52.31%	2.30	40.93%	1.93	37.26%	2.72	37.27%	1.24
Room 14	0.65	7.68%	1.77	18.46%	1.88	23.15%	2.82	30.85%	1.30	22.00%	1.07	19.56%	1.58	20.28%	0.76
Room 15	0.11	3.86%	0.57	13.10%	0.88	19.56%	1.55	28.23%	0.94	22.49%	0.81	20.40%	0.81	17.94%	0.47

Table 14 is the difference of the results of scenario 1 and 2 in seconds, percentage, mean and standard deviation of the difference. As indicated, the highest improvement in the reverberation time is happening at room 10 with the amount of 7.87 [s] and the lowest is at small rooms of 1 to 8 and also 15 with results varying from 0.11 to 0.34 [s]. Also, the average of difference for room 10 is 4.80 [s] while for the same room, standard deviation is 2.17 which shows the intense fluctuation of results for this specific room. Also Figure 10 shows how the reverberation time is affected by adding furniture to the rooms. The effect is mostly on the larger rooms with up to 7.87 second of improvement in the reverberation time. So, furniture alone is not enough to make the room in the standard range of reverberation time for classrooms (0.5~0.8).

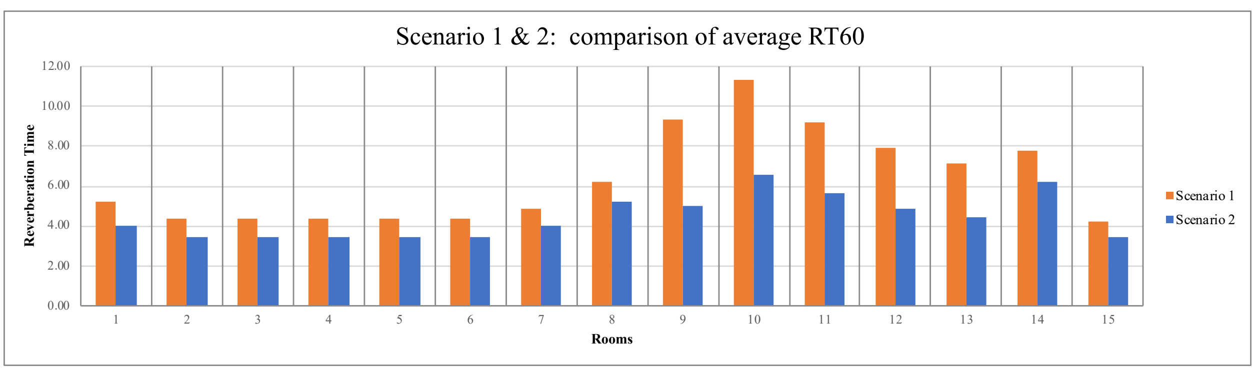


Figure 10: Comparison of the average RT60 results for scenario 1 and 2

8.2. Scenario 2 & 3 Comparison: Effect of Acoustical Ceiling on RT_{60}

Scenario 3 is designed to include the effect of other absorbant surfaces like acoustical ceiling and gypsum wall boards. So in the scenario 3, the plaster ceiling and walls are replaced with acoustical ceiling and double gypsum-board walls respectively. The results are shown in the Table 15.

Table 15: Scenario 3 results: Reverberation Time estimation results for floor level 6 of the case study with acoustical ceiling and double gypsum board walls replacing plaster ceiling and walls

Scenario 3: Suspended Ceiling and Double Gypsum-board walls added to scenario 2							
frequency	125	250	500	1000	2000	4000	average
Room 1	0.9	0.63	0.61	0.62	0.56	0.55	0.65
Room 2	0.94	0.64	0.61	0.62	0.56	0.56	0.66
Room 3	0.94	0.64	0.61	0.62	0.56	0.56	0.66
Room 4	0.94	0.64	0.61	0.62	0.56	0.56	0.66
Room 5	0.94	0.64	0.61	0.62	0.56	0.56	0.66
Room 6	0.94	0.64	0.61	0.62	0.56	0.56	0.66
Room 7	0.99	0.66	0.63	0.64	0.57	0.57	0.68
Room 8	1.11	0.69	0.65	0.65	0.59	0.59	0.71
Room 9	1.19	0.69	0.63	0.62	0.56	0.56	0.71
Room 10	1.24	0.71	0.65	0.64	0.58	0.58	0.73
Room 11	1.2	0.7	0.65	0.64	0.58	0.57	0.72
Room 12	1.14	0.69	0.64	0.63	0.57	0.57	0.71
Room 13	1.12	0.68	0.63	0.63	0.56	0.56	0.70
Room 14	1.18	0.7	0.66	0.66	0.59	0.59	0.73
Room 15	0.92	0.64	0.61	0.62	0.56	0.56	0.65

The effect of acoustical ceiling is more significant than furniture as shown in the Table 16. It reduces the reverberation time by 80% to 92% in bigger rooms and between 65 to 88% in smaller rooms. The classrooms almost meet the standards at all frequencies except 125 Hz and with considering another type of acoustical ceiling, they will meet the requirements (RT_{60}<0.8).

Table 16: Difference of the results from scenario 2 and 3 in second, percentage, mean and SD of the difference

	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz				
	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Mean [s] difference	Mean [%] difference	SD [s] of difference
Room 1	3.39	79.02%	4.72	88.22%	3.63	85.61%	3.57	85.20%	2.43	81.27%	2.35	81.03%	3.35	83.39%	0.88
Room 2	1.97	67.70%	3.15	83.11%	2.96	82.91%	3.21	83.81%	2.62	82.39%	2.56	82.05%	2.75	80.33%	0.46
Room 3	1.97	67.70%	3.15	83.11%	2.96	82.91%	3.21	83.81%	2.62	82.39%	2.56	82.05%	2.75	80.33%	0.46
Room 4	1.97	67.70%	3.15	83.11%	2.96	82.91%	3.21	83.81%	2.62	82.39%	2.56	82.05%	2.75	80.33%	0.46
Room 5	1.97	67.70%	3.15	83.11%	2.96	82.91%	3.21	83.81%	2.62	82.39%	2.56	82.05%	2.75	80.33%	0.46
Room 6	1.97	67.70%	3.15	83.11%	2.96	82.91%	3.21	83.81%	2.62	82.39%	2.56	82.05%	2.75	80.33%	0.46
Room 7	2.40	70.80%	3.96	85.71%	3.67	85.35%	4.01	86.24%	3.10	84.47%	2.97	83.90%	3.35	82.74%	0.64
Room 8	4.50	80.21%	5.34	88.56%	4.72	87.90%	5.14	88.77%	3.81	86.59%	3.65	86.08%	4.53	86.35%	0.69
Room 9	7.27	85.93%	5.80	89.37%	3.88	86.03%	3.34	84.34%	2.66	82.61%	2.61	82.33%	4.26	85.10%	1.88
Room 10	10.61	89.54%	8.21	92.04%	5.16	88.81%	4.46	87.45%	3.30	85.05%	3.18	84.57%	5.82	87.91%	2.98
Room 11	7.81	86.68%	6.79	90.65%	4.66	87.76%	4.18	86.72%	3.17	84.53%	3.08	84.38%	4.95	86.79%	1.94
Room 12	5.34	82.41%	5.88	89.50%	4.15	86.64%	3.74	85.58%	2.88	83.48%	2.79	83.04%	4.13	85.11%	1.27
Room 13	4.57	80.32%	5.16	88.36%	3.81	85.81%	3.50	84.75%	2.76	83.13%	2.69	82.77%	3.75	84.19%	0.98
Room 14	6.63	84.89%	7.12	91.05%	5.58	89.42%	5.66	89.56%	4.02	87.20%	3.81	86.59%	5.47	88.12%	1.34
Room 15	1.82	66.42%	3.14	83.07%	3.01	83.15%	3.32	84.26%	2.68	82.72%	2.60	82.28%	2.76	80.32%	0.54

As shown in the Figure 8, the huge effect of suspended ceiling is significant. It reduces the average reverberation time to under 1 second for all the rooms no matter the size. As previously discussed, the effect of acoustical ceiling is huge and referring to Table 16, the maximum difference is

10.61[s] while the minimum is at 1.97 [s]. Overall, it enhances the reverberation time between 80% to 88%.

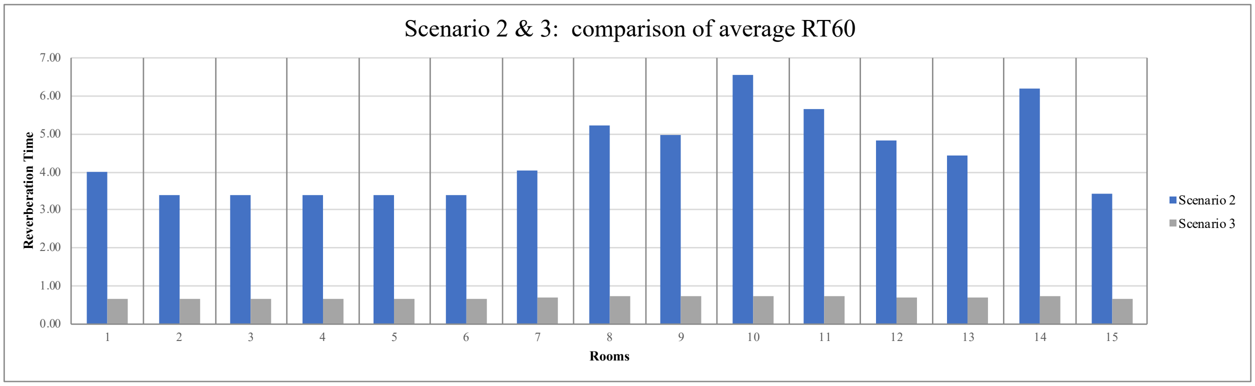


Figure 11: Comparison of scenario 2 and 3 based on average RT60

8.3. Scenario 4 and 3 comparison: Effect of furniture

The final comparison in the results of this study is to investigate the effect of furniture where acoustical ceiling is installed (Table 17). The results comparison of this scenario 4 to the previous case shows that when a hugely absorbent element like acoustical ceiling is installed, the effect of furniture is not that significant. Excluding furniture from the rooms increases the reverberation time in the range of 2% to 13% which corresponds to 0.02 [s] to 0.08 [s] for this case study.

Table 17: Difference between Scenario 4 and 3 to investigate effect of furniture where acoustical ceiling in installed

	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz				
	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Mean [s] difference	Mean [%] difference	SD [s] of difference
Room 1	0.02	2.17%	0.02	3.08%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.04	6.78%	0.03	4.91%	0.01
Room 2	0.03	3.09%	0.03	4.48%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	5.01%	0.01
Room 3	0.03	3.09%	0.03	4.48%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	5.01%	0.01
Room 4	0.03	3.09%	0.03	4.48%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	5.01%	0.01
Room 5	0.03	3.09%	0.03	4.48%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	5.01%	0.01
Room 6	0.03	3.09%	0.03	4.48%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	5.01%	0.01
Room 7	0.02	1.98%	0.02	2.94%	0.02	3.08%	0.03	4.48%	0.03	5.00%	0.03	5.00%	0.03	3.75%	0.01
Room 8	0.04	3.48%	0.01	1.43%	0.02	2.99%	0.03	4.41%	0.03	4.84%	0.02	3.28%	0.03	3.40%	0.01
Room 9	0.08	6.30%	0.05	6.76%	0.06	8.70%	0.08	11.43%	0.07	11.11%	0.06	9.68%	0.07	8.99%	0.01
Room 10	0.07	5.34%	0.04	5.33%	0.05	7.14%	0.06	8.57%	0.05	7.94%	0.04	6.45%	0.05	6.80%	0.01
Room 11	0.06	4.76%	0.04	5.41%	0.04	5.80%	0.06	8.57%	0.05	7.94%	0.05	8.06%	0.05	6.76%	0.01
Room 12	0.06	5.00%	0.04	5.48%	0.05	7.25%	0.06	8.70%	0.05	8.06%	0.05	8.06%	0.05	7.09%	0.01
Room 13	0.05	4.27%	0.04	5.56%	0.05	7.35%	0.06	8.70%	0.06	9.68%	0.05	8.20%	0.05	7.29%	0.01
Room 14	0.04	3.28%	0.03	4.11%	0.02	2.94%	0.03	4.35%	0.03	4.84%	0.03	4.84%	0.03	4.06%	0.01
Room 15	0.03	3.16%	0.02	3.03%	0.03	4.69%	0.04	6.06%	0.04	6.67%	0.03	5.08%	0.03	4.78%	0.01

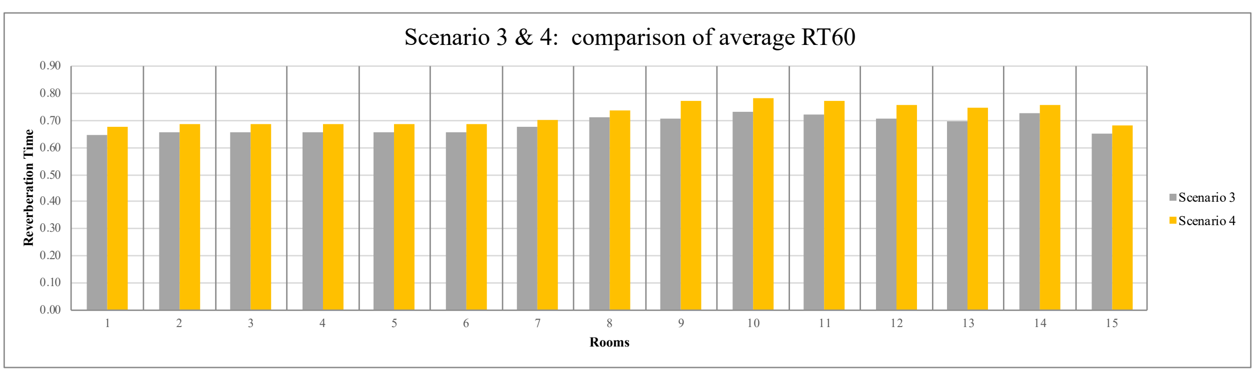


Figure 12 Shows the overall comparison of the 4 main scenarios tested on the case study. Investigating the results from all 4 scenarios shows that the effect of furniture is significant in larger rooms (1, 9, 10, 11, 12 and 13) and specially when no other highly absorbent finishes are inside the room. If highly absorbent finishes like acoustical ceiling are installed, the results are more sensitive to the type of that finish instead of the finishes. The effect of heavily-upholstered furniture instead of the medium-upholstered one in this study can be investigated via same method.

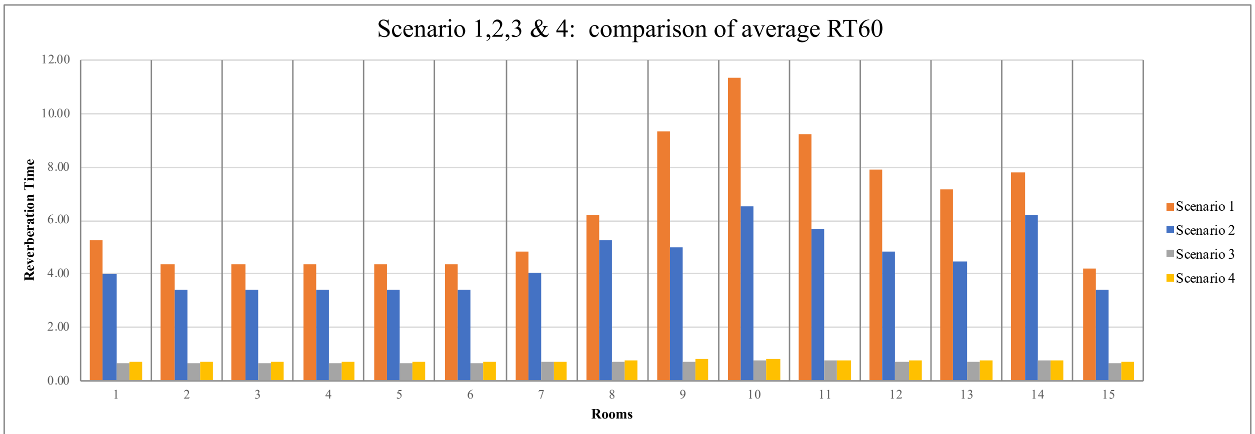


Figure 12: Comparison of the results for all scenarios

8.4. Comparing the results with previous research on the same case study

Previously in the research on the same case study, the absorption coefficients were multiplied by a factor of 7 to include the effect of furniture and other absorbent surfaces. To see if this correcting method is accurate, the results from research done by Erfani, Mahabadipour, Nik-Bakht, & Lee (2018) is compared to the final results of the scenario 3 of this study. The results from that study is shown in the Table 18.

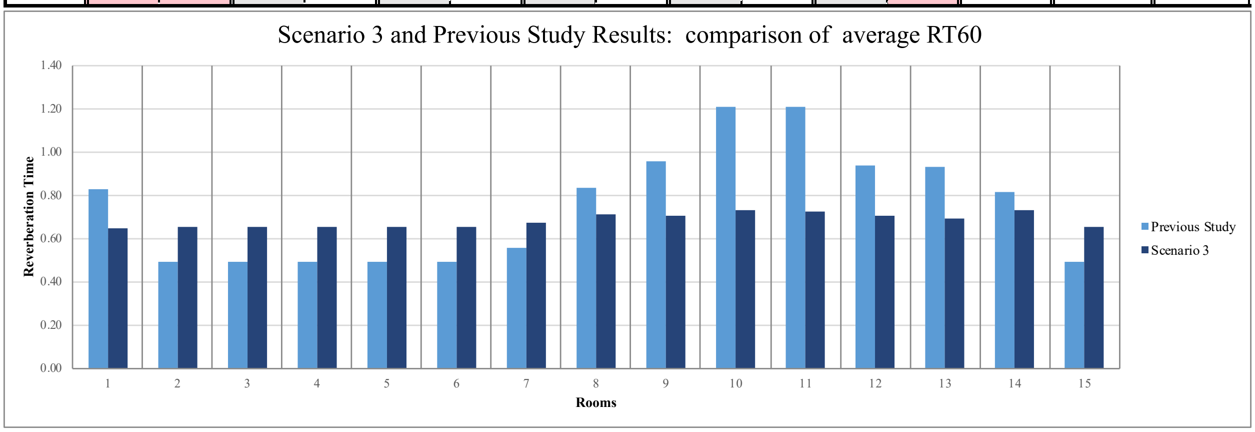
Table 18: Results from previous research on the same case study

Scenario 0: No furniture or suspended ceiling, Plaster walls							
frequency	125	250	500	1000	2000	4000	average
Room 1	0.709	1.08	0.86	0.94	0.85	0.52	0.83
Room 2	0.481	0.69	0.5	0.53	0.5	0.26	0.49
Room 3	0.483	0.69	0.5	0.53	0.5	0.26	0.49
Room 4	0.483	0.69	0.5	0.53	0.5	0.26	0.49
Room 5	0.483	0.69	0.5	0.53	0.5	0.26	0.49
Room 6	0.483	0.69	0.5	0.53	0.5	0.26	0.49
Room 7	0.52	0.76	0.57	0.61	0.57	0.31	0.56
Room 8	1.31	1.31	0.71	0.71	0.65	0.31	0.83
Room 9	1.51	1.51	0.82	0.82	0.75	0.36	0.96
Room 10	1.88	1.88	1.05	1.05	0.94	0.48	1.21
Room 11	1.88	1.88	1.05	1.05	0.94	0.48	1.21
Room 12	1.01	1.35	0.93	0.98	0.88	0.49	0.94
Room 13	1	1.34	0.93	0.97	0.87	0.48	0.93
Room 14	1.28	1.28	0.69	0.69	0.64	0.3	0.81
Room 15	0.43	0.66	0.51	0.55	0.52	0.28	0.49

The outcome shows that for larger rooms the previous research is showing higher RT60 (negative numbers in the Table 19) while for smaller rooms the results are closer. The maximum difference is 115% (0.3 seconds) where new method is showing higher numbers and 62% (1.18 seconds) where the old method is showing higher numbers.

Table 19: Results difference of scenario 3 and the previous research

	125 Hz		250 Hz		500 Hz		1000 Hz		2000 Hz		4000 Hz				
	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Δ [s]	Δ [%]	Mean [s] difference	Mean [%] difference	SD [s] of difference
Room 1	0.19	26.94%	-0.45	-41.67%	-0.25	-29.07%	-0.32	-34.04%	-0.29	-34.12%	0.03	5.77%	-0.18	-17.70%	0.24
Room 2	0.46	95.43%	-0.05	-7.25%	0.11	22.00%	0.09	16.98%	0.06	12.00%	0.30	115.38%	0.16	42.42%	0.18
Room 3	0.46	94.62%	-0.05	-7.25%	0.11	22.00%	0.09	16.98%	0.06	12.00%	0.30	115.38%	0.16	42.29%	0.18
Room 4	0.46	94.62%	-0.05	-7.25%	0.11	22.00%	0.09	16.98%	0.06	12.00%	0.30	115.38%	0.16	42.29%	0.18
Room 5	0.46	94.62%	-0.05	-7.25%	0.11	22.00%	0.09	16.98%	0.06	12.00%	0.30	115.38%	0.16	42.29%	0.18
Room 6	0.46	94.62%	-0.05	-7.25%	0.11	22.00%	0.09	16.98%	0.06	12.00%	0.30	115.38%	0.16	42.29%	0.18
Room 7	0.47	90.38%	-0.10	-13.16%	0.06	10.53%	0.03	4.92%	0.00	0.00%	0.26	83.87%	0.12	29.42%	0.21
Room 8	-0.20	-15.27%	-0.62	-47.33%	-0.06	-8.45%	-0.06	-8.45%	-0.06	-9.23%	0.28	90.32%	-0.12	0.27%	0.29
Room 9	-0.32	-21.19%	-0.82	-54.30%	-0.19	-23.17%	-0.20	-24.39%	-0.19	-25.33%	0.20	55.56%	-0.25	-15.47%	0.33
Room 10	-0.64	-34.04%	-1.17	-62.23%	-0.40	-38.10%	-0.41	-39.05%	-0.36	-38.30%	0.10	20.83%	-0.48	-31.81%	0.42
Room 11	-0.68	-36.17%	-1.18	-62.77%	-0.40	-38.10%	-0.41	-39.05%	-0.36	-38.30%	0.09	18.75%	-0.49	-32.60%	0.42
Room 12	0.13	12.87%	-0.66	-48.89%	-0.29	-31.18%	-0.35	-35.71%	-0.31	-35.23%	0.08	16.33%	-0.23	-20.30%	0.29
Room 13	0.12	12.00%	-0.66	-49.25%	-0.30	-32.26%	-0.34	-35.05%	-0.31	-35.63%	0.08	16.67%	-0.24	-20.59%	0.29
Room 14	-0.10	-7.81%	-0.58	-45.31%	-0.03	-4.35%	-0.03	-4.35%	-0.05	-7.81%	0.29	96.67%	-0.08	4.51%	0.28
Room 15	0.49	113.95%	-0.02	-3.03%	0.10	19.61%	0.07	12.73%	0.04	7.69%	0.28	100.00%	0.16	41.83%	0.19



To sum up, it is mentionable that although the results from the new method and old method are within an acceptable range of RT_{60} estimation, the differences are not negligible and the improved method by doing geometry analysis on the furniture is more accurate compared to the old approach.

9. Conclusion

This study focused on proposing an improved BIM-based method to estimate reverberation time of spaces within the BIM platform. The major achievement was extracting detailed data of all elements in the model. This data includes architectural and non-architectural elements, their type, location, surface area, material and the possible intersection with other elements.

The possibility of updating the model and re-analyzing it with new properties is what makes this code more useful in comparison to other acoustic analysis software outside the Revit environment.

This feature provides the user with the ability to test different situations and can become handy for educational purposes for understanding the acoustical properties and effects of different surfaces.

It is confirmed that a model-based acoustical analysis of interior spaces can be successfully done within the Revit environment using Dynamo nodes and algorithms. The model can be a simple empty room or a room with non-architectural and non-laminar surfaces like furniture.

The proposed method for including the effect of furniture which is based on detailed exposed surface areas of each component in the room and their corresponding finish materials is proven to be working properly. The method takes into account exposed areas which and excludes hidden areas not applicable for the calculation of reverberation time.

The results are within the range of other empirical methods using either per-area or per-unit estimation techniques.

10. Limitations

10.1. Processing Speed

The current code includes heavy data processing that makes it relatively slow for large models with more than 20 rooms and numerous furniture items (especially if furniture is modelled with high level of detail like door handles or casters).

Running the Dynamo code on the case study scenario 3 -including furniture- takes about 3 minutes. The computer used is a 2012 Macbook Retina with 2.6 Ghz intel Core i7 processor and 8 GB of RAM running Windows 10 on Bootcamp. Running the code on models with more rooms and relatively more furniture takes more time with the current system. Using a more up-to-date computer might improve the processing speed.

It is advised to reduce the level of detail of the furniture to increase the speed of the program but finding a way to decrease the number of geometry intersection processes would enhance the overall performance of the code. Also, at least one furniture element should be located in the model prior to calculating the reverberation time.

10.2. Limitations of Sabine's equation for RT_{60}

Currently, the method is based on Sabine's equation and can be easily modified to use Eyring's or another empirical method which assume an even distribution of absorbent surfaces or finishes in the space. It might be a good idea to use a different equation which uses the un-even distribution of absorbent materials (e.g. Fitzroy) or ray-tracing methods and compare the results with the current method.

10.3. Connection to an Online Database

As mentioned, the efforts to make the Dynamo code independent from an offline database was not successful. Currently an Excel file is attached to the code to read the absorption coefficients.

It is possible to make the Excel file available through Google API and Spreadsheets, however it is preferable to use an industry-wide accepted database for future reference.

11. Future Work

11.1. Results verification with field measurements

The results of the RT_{60} estimation on the case study has to verified with the field measurements in future research. This helps check the reliability of the proposed method by an accurate benchmark.

11.2. Comparing results with different calculation methods

As studied in the literature review of this research, there are several methods than can be used to estimate the reverberation time of any given space. Some of them take into account un-even distribution of materials and some include effect of room shape. Developing this Dynamo to calculate RT_{60} based on these methods and comparing the results might help finding the most accurate calculation technique.

11.3. Simulating method for calculation of room acoustics

There are several simulating methods like ray-tracing which can be used to estimate acoustical properties of spaces. Such methods might be able to provide more accurate results.

11.4. Automatic Data Validation with Standards and Codes

The proposed method is not designed to identify the utilization type of the spacs like offices, classrooms or auditorium. On the other hand, this information cannot be easily added to the Revit model at the early stages of the designs where this study is focusing on. Designing a method to include the room functions in Revit and thus the Dynamo code would be genuinely beneficial. The method can help the architects and engineers to check if the designed spaces are as per code and requirements or if they need to modify the finishes of the interior spaces.

11.5. Dynamo algorithm enhancement

The current method does all the needed calculations in a single algorithm. Translating the method into Revit API or separating the major calculation groups and linking them via defined benchmarks might increase the stability of the code even for huge models.

12. Acknowledgement

The author would like to thank Doctor Mazdak Nik-Bakht for his continued supports and advises. Also Kaveh Erfani, Sara Mahabadipour and Doctor Joonhee Lee for making the results and resources of their research available.

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14. Appendix

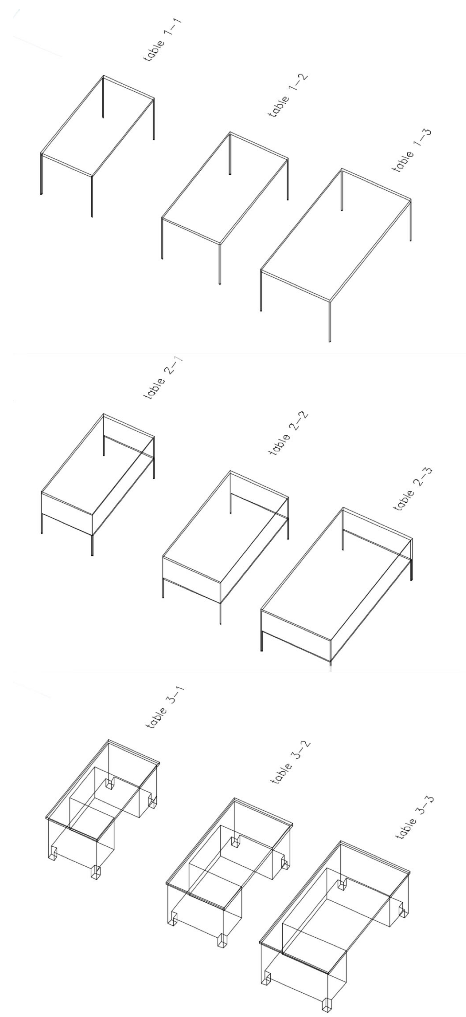

Figure 13: 3 modeled desks in 3 different sizes and design details

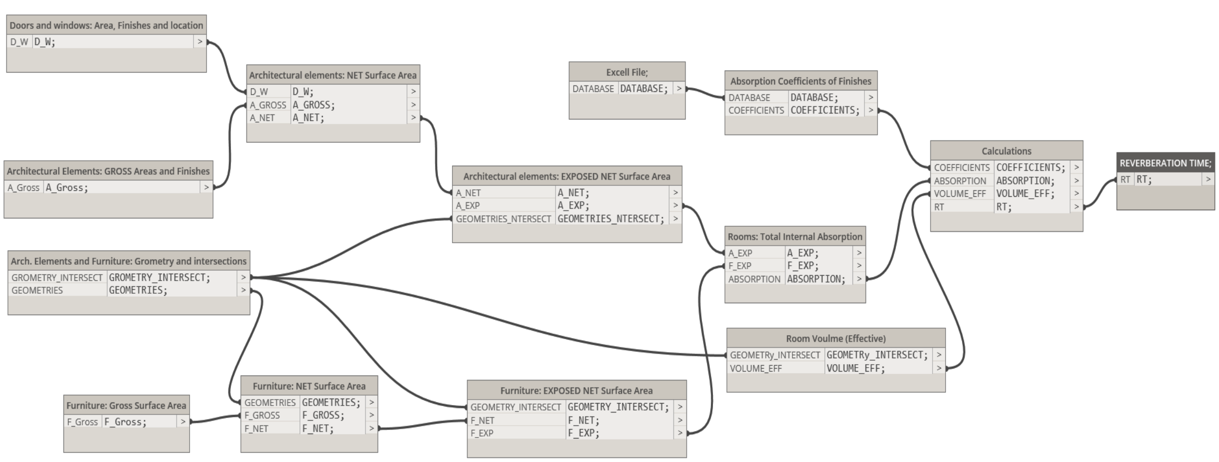

Figure 14: Schematic Diagram of the developed Dynamo Code

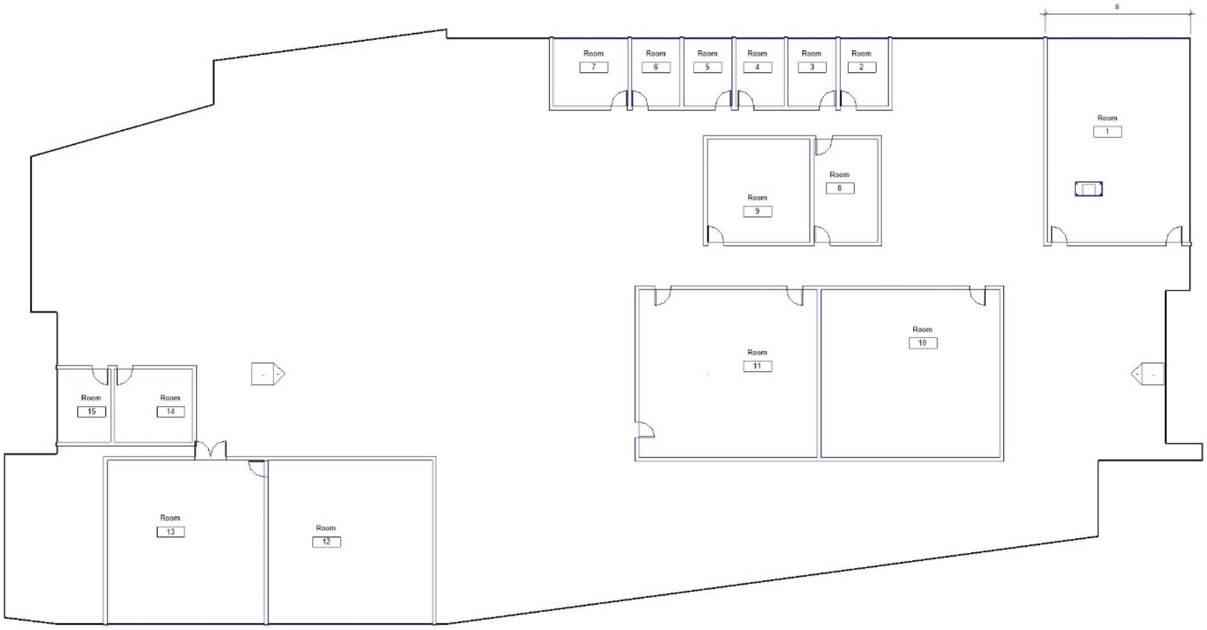

Figure 15: Floor plan, Level 6 of the case study – Not Furnished - Concordia University, John Molson Building

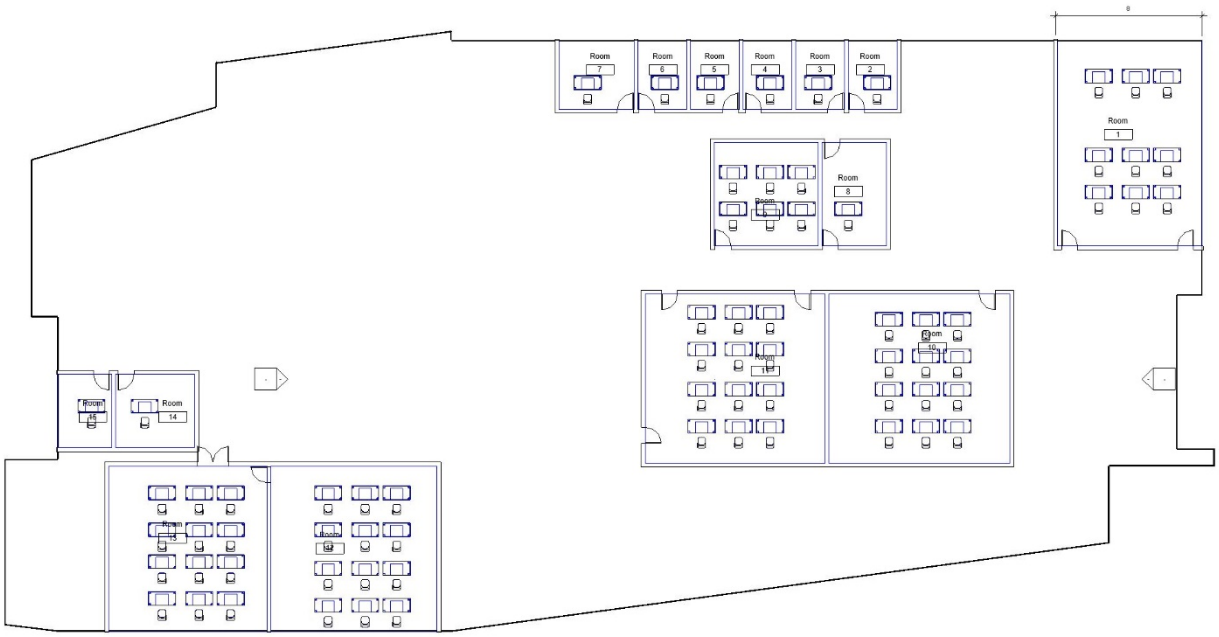

Figure 16: Floor plan, Level 6 of the case study – Furnished - Concordia University, John Molson Building

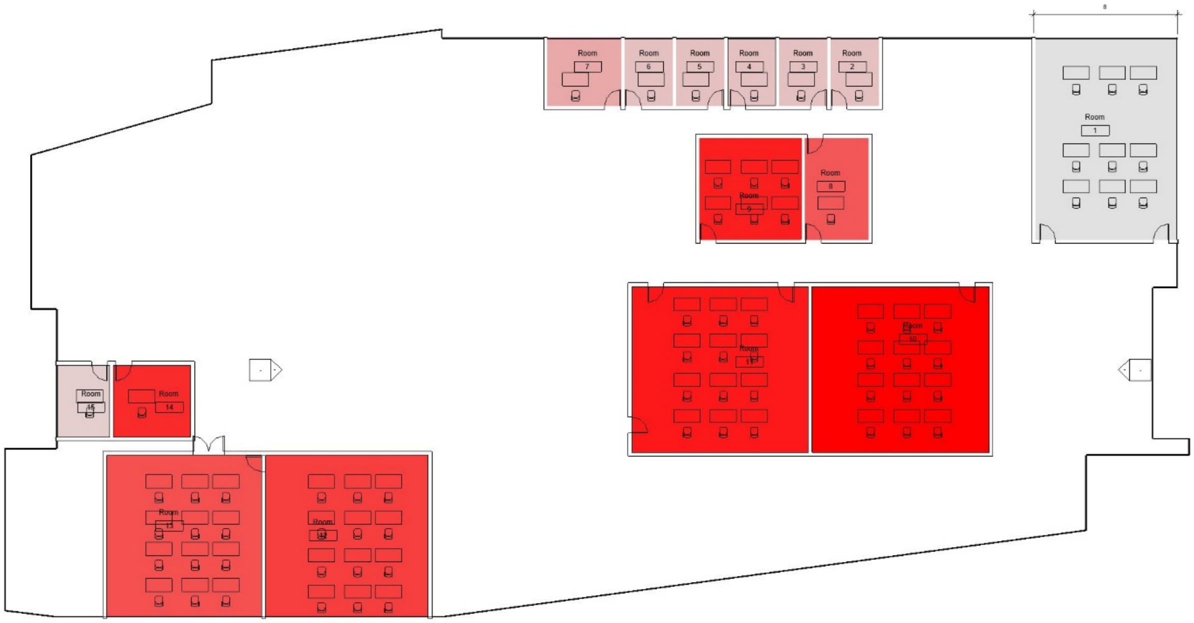

Figure 17: color coded floor plan, level 6, furnished and at 125 Hz frequency

Figure 18: color coded floor plan, level 6, furnished and at 500 Hz frequency