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Evaluating and Optimizing Acoustical Reverberation Time and Material Cost for Classrooms Using Building Information Modeling (BIM) and Generative Design (GD) Tools

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ABSTRACT

Reverberation time (RT) measures how long sound takes to decay in a space, affecting speech intelligibility and sound quality. Calculating RT using Sabine's formula is time-consuming and error-prone due to manual extraction of room volume and material surface areas. Balancing RT and cost further complicates material selection. This paper automates RT calculation and optimization using Building Information Modeling (BIM) and generative design (GD). Sound absorption coefficients are input into a BIM model's material properties, and visual programming (VP) extracts room geometries, materials, and absorption coefficients to compute RT and material costs. A multi-objective optimization algorithm in Autodesk GD identifies the best material and room height combination for cost-effective RT. A classroom case study validates the method. This approach enables fast RT calculation and helps designers select cost-efficient materials with optimal RT, aiding acoustic analysis in concert halls, auditoriums, and classrooms while supporting targeted acoustic design.

Keywords: reverberation time, building information modeling, BIM, visual programming, generative design

INTRODUCTION

Acoustics is crucial in architecture and building design, directly affecting sound quality and speech intelligibility. A key parameter in room design is reverberation time (RT) (Galbrun & Kitapci, 2014; Minelli et al., 2022; Nik-Bakht et al., 2021; Puglisi et al., 2021; Pääkkönen et al., 2015; Ratnam et al., 2003). RT measures how long sound takes to decay in a space, influencing speech intelligibility and overall quality (American National Standards Institute, 2010). The standard RT measurement, RT60, denotes the time for sound to decay by 60 dB. Traditionally, RT is estimated using the Sabine formula (refer to Eq. (1)), requiring manual extraction of room volume and surface areas of materials (Aguilar et al., 2022; Nik-Bakht et al., 2021). This process is time-consuming and error-prone. Designers must balance RT with material costs, particularly for acoustic treatments, to optimize classroom acoustics. Achieving this balance is challenging. Recent studies (Gholami & Jalilisadrabad, 2023; Leetongin et al., 2022; Sofian et al., 2020) emphasize material properties' role in environmental and building performance, highlighting the need for integrated approaches in material selection and optimization.

To address RT calculation challenges and enable multi-objective optimization, this paper presents a novel approach combining Building Information Modeling (BIM), Visual Programming (VP), and Generative Design (GD). BIM facilitates creating and managing digital representations of a building’s physical and functional aspects. Integrating BIM with VP and GD enables automated RT calculation and optimization, eliminating manual parameter extraction and supporting informed decision-making. This integrated approach streamlines RT evaluation and enhances acoustic performance in room design.

This research aims to optimize classroom acoustics while minimizing material costs through a multi-objective optimization framework, systematically balancing these competing goals. The method employs a genetic multi-objective optimization algorithm, specifically the Non-dominated Sorting Genetic Algorithm II (NSGA-II) by Deb et al. (2002), widely used in architectural and design optimization (Seghier et al., 2022b). These algorithms are often integrated into generative design (GD) software like Autodesk GD (Autodesk, 2020). Using NSGA-II enhances the approach, enabling optimal trade-offs between RT performance and material costs for acoustic treatments, leading to efficient room designs.

The proposed method begins by integrating sound absorption coefficients of classroom finish materials into a BIM model. Using a VP-based algorithm, the system extracts room geometries, materials, and absorption coefficients to compute RT and material costs. These values serve as objectives for a multi-objective optimization algorithm in Autodesk GD, allowing designers to explore design options and determine the best material and room height combination to achieve target RT values while considering cost constraints.

To validate the proposed method, a case study was conducted using a classroom as an example. The study demonstrated the system's ability to optimize room design by identifying the best material and room height combination, balancing RT values, material costs, and ceiling height. This validation highlights the method's practical applicability and benefits in real-world scenarios.

This research develops an automated method and prototype system that transforms RT calculations and room design optimization in the early design stages. By integrating BIM, VP, and GD, designers gain a fast, precise tool for acoustic analysis, enhancing speech intelligibility and sound quality. The method overcomes manual RT calculation challenges, systematically optimizing room parameters while balancing RT values, material costs, and aesthetics. A multi-objective optimization algorithm provides valuable insights for decision-making. This research advances architectural acoustics by streamlining RT calculations, improving design efficiency, and enabling cost-effective, high-performance indoor spaces.

The paper is structured as follows: the next section presents a comprehensive literature review, followed by a detailed explanation of the proposed method. Then, the prototype system's development and implementation are discussed. The case study section illustrates the method's application and validation. Next, findings, limitations, and future improvements are examined. Finally, the conclusion summarizes key contributions and insights.

LITERATURE REVIEW

Overview of the RT

In recent decades, architects have recognized the importance of acoustics in architectural design, especially in educational buildings (Spence, 2020). Acoustic quality significantly influences teaching and learning. Studies show that reading skills are highly affected by chronic noise in schools (Dohmen et al., 2023; Maxwell & Evans, 2000). Additionally, McKellin et al. (2011) found that noise and reverberation negatively impact student interactions and collaborative learning.

The link between prolonged RT and high ambient noise levels has led to the recognition that some effects previously attributed to noise may result from excessive reverberation (Klatte et al., 2010). Thus, the chronic impact of extended RT on children's learning and well-being at school can be traced to both noise and reverberation. Minelli et al. (2022) found that students perform better with lower RT and noise levels, along with higher signal-to-noise ratios (SNR) and speech transmission index (STI).

Scholars have studied various measures to assess classroom acoustics, including RT, speech clarity, background noise, and the speech transmission index (Dongre et al., 2017). Among these, RT is a critical criterion, influenced more by design aspects like room volume and sound absorption than by the positions of the sound source or recipient. As a result, international building standards, such as the American National Standards Institute (ANSI) and the International Organization for Standardization (ISO), and green building systems such as Leadership in Energy and Environmental Design (LEED) now consider RT a key acoustic parameter for designing learning spaces, alongside visual and thermal factors.

RT is a crucial acoustical metric, widely used in building design, particularly in spaces like classrooms and auditoriums. According to the ANSI (American National Standards Institute, 2010), RT is the time for sound to decay by 60 decibels (dB) after the sound source stops. Building codes specify RT for spaces with critical acoustics, such as classrooms. However, the architect must determine the optimal RT based on the room's purpose (International Standard International Standard, 2003). RT, or RT60, is typically measured in seconds (s) and calculated using Sabine's equation (Eq. (1)), the fundamental formula.

$$\mathrm{RT60} = \frac{0.16\mathrm{V}}{\mathrm{S}*\alpha} \qquad (1)$$

where: V = the volume of the space,

S = the surface area of the materials, and

α = the sound absorption coefficient of the material.

RT calculations, based on Sabine's equation, are typically conducted for unoccupied spaces, establishing a conservative baseline by not accounting for sound absorption from human presence. Additionally, the formula overlooks air absorption, which is significant in large spaces like auditoriums.

Research on acoustic performance in learning spaces has explored how room design parameters, such as RT, background noise reduction, and speech intelligibility, affect acoustics. For example, Dongre et al. (2017) conducted a study in nine Indian classrooms, finding RT values above acoustical standards, prompting the need for acoustic treatments. Similarly, Puglisi et al. (2021) found that increasing RT worsened speech intelligibility in primary school classrooms with complex acoustics.

In-situ measurements of RT have been used in research. Kendrick et al. (2012) performed such measurements and applied the maximum likelihood estimation (MLE) algorithm to develop a model for estimating RT in occupied classrooms and hospitals. Chen and Ou (2021) explored how classroom RT and traffic noise level (TNL) impact English listening comprehension among Chinese university students. The results suggested a TNL limit of 40 dB(A), with subjective assessments proving more relevant than objective ones in these scenarios.

The literature shows that acoustical performance studies mostly use experimental and in-situ measurements to explore the effects of various factors on classroom acoustics. However, a recent trend focuses on evaluating and optimizing the acoustic environment using information technologies like BIM and computer simulation. Studies like Panraluk and Sreshthaputra (2020) have used simulation tools to optimize environmental conditions, highlighting the potential of computational methods to improve occupant comfort and energy efficiency in building design.

Acoustic Simulation Tools

Various acoustic simulation tools are available for evaluating sound performance in architectural environments. A recent study by Tabatabaei Manesh et al. (2024) compares several widely used tools, such as ODEON, EASE, Pachyderm, INSUL, CATT-Acoustic, DIRAC, Troldtekt, JOCAVI, DAMPA, and EXNO. Popular commercial room acoustic simulation software includes ODEON and CATT-Acoustics.

ODEON is a high-accuracy tool for indoor acoustics, noise control, sound transmission, and sound propagation, featuring a material library and 3D modeling. EASE, also highly accurate, supports indoor acoustics with a material library and 3D modeling but does not handle noise control or sound propagation. Pachyderm, a free Grasshopper plug-in, offers medium-accuracy indoor acoustics simulation with no material library. INSUL specializes in indoor acoustics and sound transmission with high accuracy but lacks support for sound propagation. CATT-Acoustic focuses on indoor acoustics and noise control, offering a material library but no 3D modeling, with moderate accuracy and high calculation times. DIRAC is for indoor acoustics and sound system optimization, offering a material library and high accuracy but lacking sound propagation and transmission support. Troldtekt, JOCAVI, and DAMPA are simpler tools for quick assessments, focusing on indoor acoustics and noise control, with low accuracy and no 3D modeling or material library. EXNO focuses on sound transmission and includes a material library and 3D modeling but lacks indoor acoustics and sound propagation support. It is free, with moderate calculation times and limited scope.

Building Information Modeling (BIM)

The architecture, engineering, construction, and operation (AECO) industry has seen a significant rise in adopting information technologies in recent decades. BIM has emerged as an integrated methodology, utilizing intelligent systems and data-rich models throughout the building life cycle (Malleson et al., 2013). BIM authoring tools like Revit enable the creation of digital models, storing both geometric and non-geometric data in a centralized database. This feature allows users to make better-informed decisions throughout the project's lifecycle by leveraging the data within the BIM model.

BIM has gained recognition for enhancing building performance analysis workflows and outcomes (Azhar & Brown, 2009; Seghier et al., 2022a; Seghier et al., 2022b). Building performance can be measured quantitatively, such as energy efficiency, ventilation, or lighting. However, BIM's application in acoustical analysis has developed more slowly compared to other performance criteria like energy or daylight. Nik-Bakht et al. (2021) noted that BIM-based acoustical simulations have mainly been used to evaluate noise from mechanical systems in buildings.

Recent advancements have integrated BIM platforms with various tools, enabling increased automation in data extraction and design optimization (Seghier et al., 2022b). For instance, Autodesk Revit can integrate with VP tools like Dynamo and Grasshopper, allowing researchers and developers to create customized scripts that expand BIM tools' capabilities in acoustical analysis and related research.

Visual Programming (VP)

The current integration of technologies within the BIM environment includes VPL, ML-based optimization algorithms, and GD approaches. VPL provides architects and engineers with a user-friendly scripting environment for developing algorithms integrated into BIM platforms. These algorithms automate processes, conduct performance analyses, and manage BIM data (Kensek, 2015). By incorporating VPL, BIM tools' capabilities are expanded, enabling custom scripts for data extraction, task automation, and integration with external databases and optimization algorithms (Lim et al., 2019; Seghier et al., 2020). VPL offers greater flexibility for performance analysis compared to commercial software, as users can interact directly with the API of the BIM software and control all data within the BIM model. While VP has been used for performance studies, its application in acoustic performance remains limited.

VP tools like Dynamo and Grasshopper allow users to integrate optimization algorithms into design workflows, solving optimization problems related to building performance. These algorithms can also be employed in GD platforms such as Autodesk GD, which provides a user-friendly environment for multi-objective optimization studies (Leitão et al., 2012). Autodesk GD uses the NSGA-II algorithm for multi-objective optimization and solution searches. NSGA-II applies non-dominated sorting and crowding distance to identify the optimal solution (Deb et al., 2002). Non-dominated sorting ranks each solution based on dominance, with the highest rank indicating a solution that dominates others. Crowding distance ensures diversity by prioritizing solutions with greater spatial separation (Jeong et al., 2019; Nasruddin et al., 2019; Vachhani et al., 2015). This approach improves computational efficiency and avoids user-defined parameters. Crowding distance is calculated by measuring the distance between neighboring solutions within a predefined boundary, with a smaller distance indicating a better, more crowded solution.

Existing Research

The advancement of acoustic evaluation in classroom design relies on emerging technologies in the AECO industry, such as BIM. Researchers have worked on methods leveraging BIM to enhance RT evaluation. For example, Nik-Bakht et al. (2021) developed a BIM-based tool for accurate RT calculations. Sušnik et al. (2021) created a Dynamo script for RT evaluation in classrooms. Russo and Ruggiero (2019) and Eldakdoky (2017) conducted simulations and experiments to optimize acoustic designs for classrooms and lecture rooms, focusing on RT. However, these methods lack feedback on acoustic properties and simulation results within the BIM model.

Tan et al. (2017) studied integrating BIM for acoustic simulation, focusing on room geometry, speaker locations, and surface finishes, with RT as the dependent variable. They emphasized BIM's accuracy and time-saving benefits. Similarly, Aguilar et al. (2022) developed a BIM-based framework using Dynamo to automate airborne sound insulation estimation during the early design stage, allowing for compliance with acoustic standards. Mastino et al. (2019) proposed a BIM tool for acoustic insulation code-checking based on ISO standards. The tool, a Revit plugin in C#, used data from an IFC file and successfully highlighted the building's acoustic properties throughout the construction phase.

Researchers have also examined data interoperability in acoustic performance analysis. BIM TUDublin et al. (2021) conducted interviews investigating the integration of acoustic simulation within BIM workflows, revealing a disconnection between architectural design and acoustic performance due to data interoperability challenges. Šujanová & Müllner (2018) developed a BIM tool to improve data interoperability for basic acoustic calculations like sound absorption coefficients. In urban-scale acoustical performance, Butorina et al. (2019) proposed using BIM data and SoundPLAN to map noise data onto building and infrastructure projects, demonstrating its potential to aid noise reduction in design.

Current BIM-based methods for improving RT evaluation have two main limitations. First, they focus on automating RT calculations rather than identifying the optimal design solution, lacking automated decision support. Second, these methods often ignore the cost implications of design alternatives. Therefore, integrating multi-objective optimization algorithms to address RT-related optimization problems offers great potential for advancing research in this area.

Research Gap and Proposed Objectives of the Research

Despite various commercial software options like Odeon, EASE, and CATT-Acoustic for evaluating RT, none offer a workflow that optimizes both RT performance and the cost of acoustical treatments during the design stage. Current workflows focus only on RT evaluation, lacking insights into the optimal combination of design parameters for decision-making. This research aims to develop a BIM-based method that identifies the best trade-off between RT performance and material surface finish costs using BIM data, VP, and GD techniques. The following section details each stage of the method's development.

METHODOLOGY

The proposed method automates RT calculation and optimization, considering trade-offs between RT and material costs. It integrates BIM, VP, and optimization techniques to streamline processes, enhance efficiency, and facilitate informed decision-making. The method consists of five main processes, shown in Figure 1.

The first process involves creating a BIM model with components for walls, floors, ceilings, doors, and windows. The room element and name are defined, and furniture components are added to the model.

In the second process, the BIM model is prepared for RT evaluation by creating sound absorption coefficient parameters in the material properties. The coefficients and cost values are input from the database into the BIM model. These materials are then assigned to the layers of walls, floors, and ceilings, with sound absorption coefficients also specified for doors and windows.

The third process involves evaluating the RT. The surfaces of walls, floors, ceilings, doors, windows, and furniture are extracted, and their sound absorption coefficients are obtained. The net room volume is calculated by subtracting the furniture volume from the room's total. RT is then computed using Sabine's formula, with results visualized based on normalized sound absorption coefficients (0 to 1). The color scheme is red for 0, green for 0.5, and blue for 1.

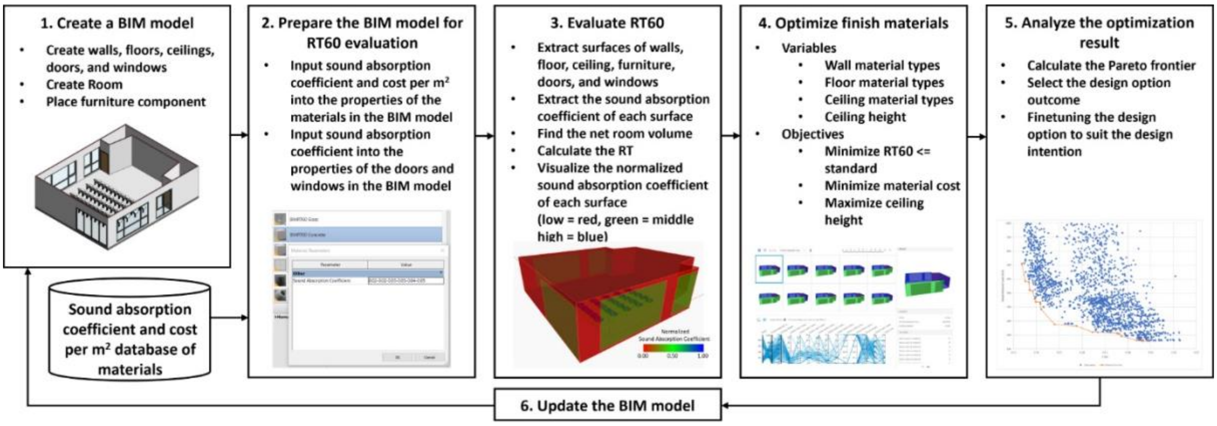
In the fourth process, finishing materials are optimized using the NSGA-II algorithm in Autodesk GD. Variables such as wall, floor, and ceiling material types, along with ceiling height, are considered. The objectives are to minimize RT to meet standards, minimize material cost, and maximize ceiling height.

The fifth process analyzes the optimization results by calculating the Pareto frontier to identify optimal design options. This frontier shows solutions where improvements in one objective require sacrifices in another. Designers select and refine the chosen option to align with design intentions.

Finally, the BIM model is updated to incorporate all modifications and optimizations based on the chosen design option.

Figure 1

Overview of the Proposed Method



RESULTS

Development of a Prototype System

The prototype system was developed using Autodesk Revit 2021.1.3 and Dynamo 2.6.1.8850. Dynamo, an open-source VP extension for Revit, allows users without programming experience to create algorithms and visualize outcomes (Autodesk, 2019). Autodesk Revit 2021 also includes a GD tool that utilizes the NSGA-II algorithm for optimization (Autodesk, 2021b). By combining Dynamo with this GD tool, a multi-objective optimization system is created.

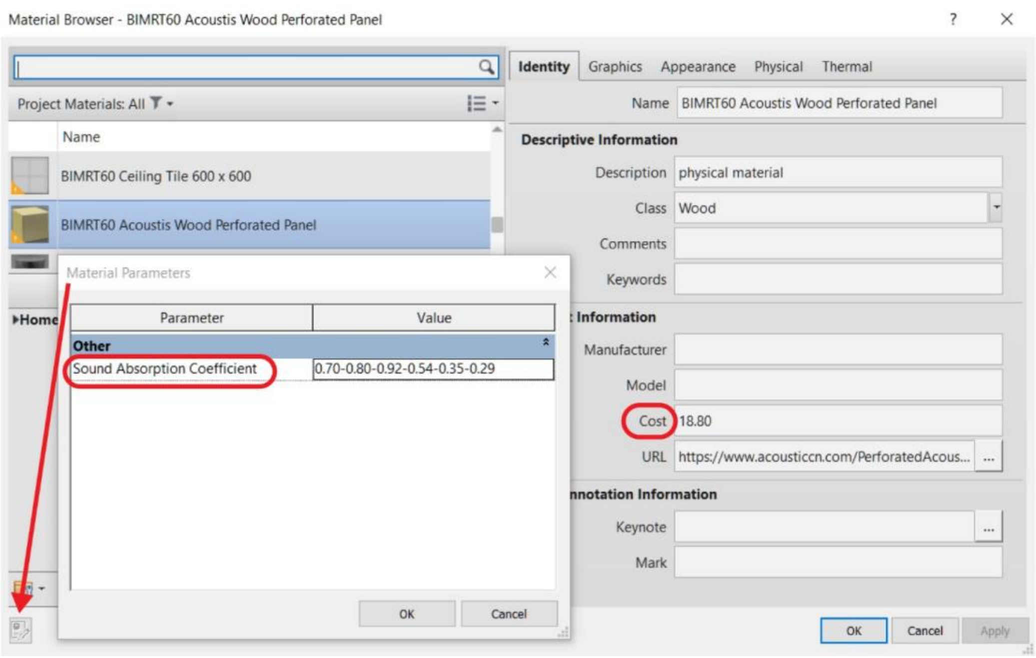
The description of the prototype system's development is organized into six main processes. Processes 1, 2, and 6 are carried out within Autodesk Revit, while processes 3 and 4 use Dynamo and the GD tool. Process 5 occurs in Excel.

In Process 1, a BIM model is created in Autodesk Revit, where users can model a single room or an entire building. For a room, the room element is used and named to help calculate the materials within it. The room's height offset should match the ceiling height. Wall, floor, and ceiling elements are assigned finish material layers, and components like doors, windows, and furniture are added. The properties of these materials and components are configured in Process 2.

In Process 2, the BIM model is prepared for RT evaluation. First, the sound absorption coefficient and cost per square meter of each material are compiled in an Excel spreadsheet and input into the BIM model's material properties. While cost data can be added directly to the cost parameter, Autodesk Revit lacks a predefined parameter for the sound absorption coefficient. To resolve this, a custom parameter is created via project parameters, making the coefficient available in the properties of doors, windows, and materials. A material library is then established by inputting the sound absorption coefficients and costs into their respective parameters (Figure 2). For doors and windows, the coefficients are entered through the instant properties, as shown in Figure 3. For furniture, sound absorption coefficients are assigned in Dynamo by separating the components and assigning the coefficients to each part.

Figure 2

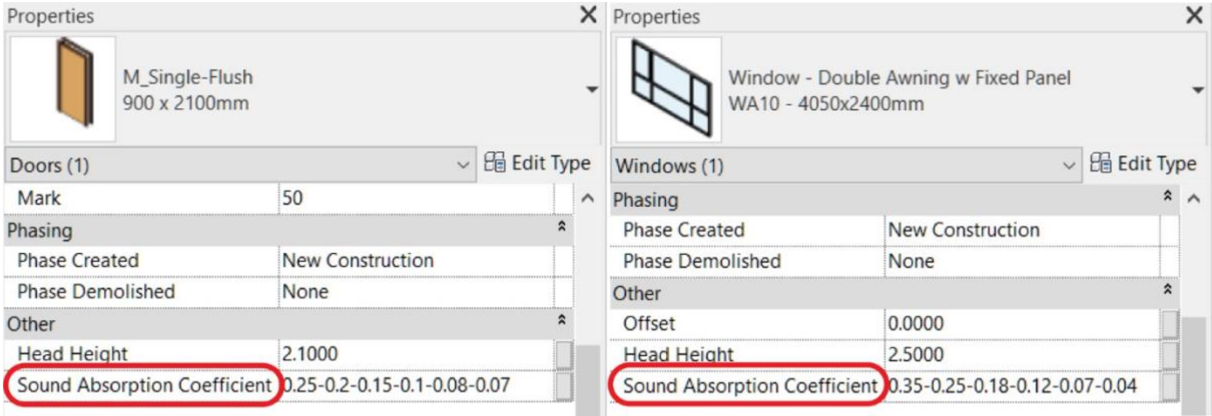
The Sound Absorption Coefficient Parameter and the Cost Parameter in the Material Library



Note. From *The Sound Absorption Coefficient Parameter and the Cost Parameter in the Material Library in Autodesk Revit 2021.1.3,* by Autodesk Inc., 2025.

Figure 3

The Sound Absorption Coefficient Parameter in the Instant Properties of the Doors and Windows



Note. From *The Sound Absorption Coefficient Parameter in the Instant Properties of the Doors and Windows in Autodesk Revit 2021.1.3,* by Autodesk Inc., 2025.

Figure 4

Flowchart for Process 3 and Process 4

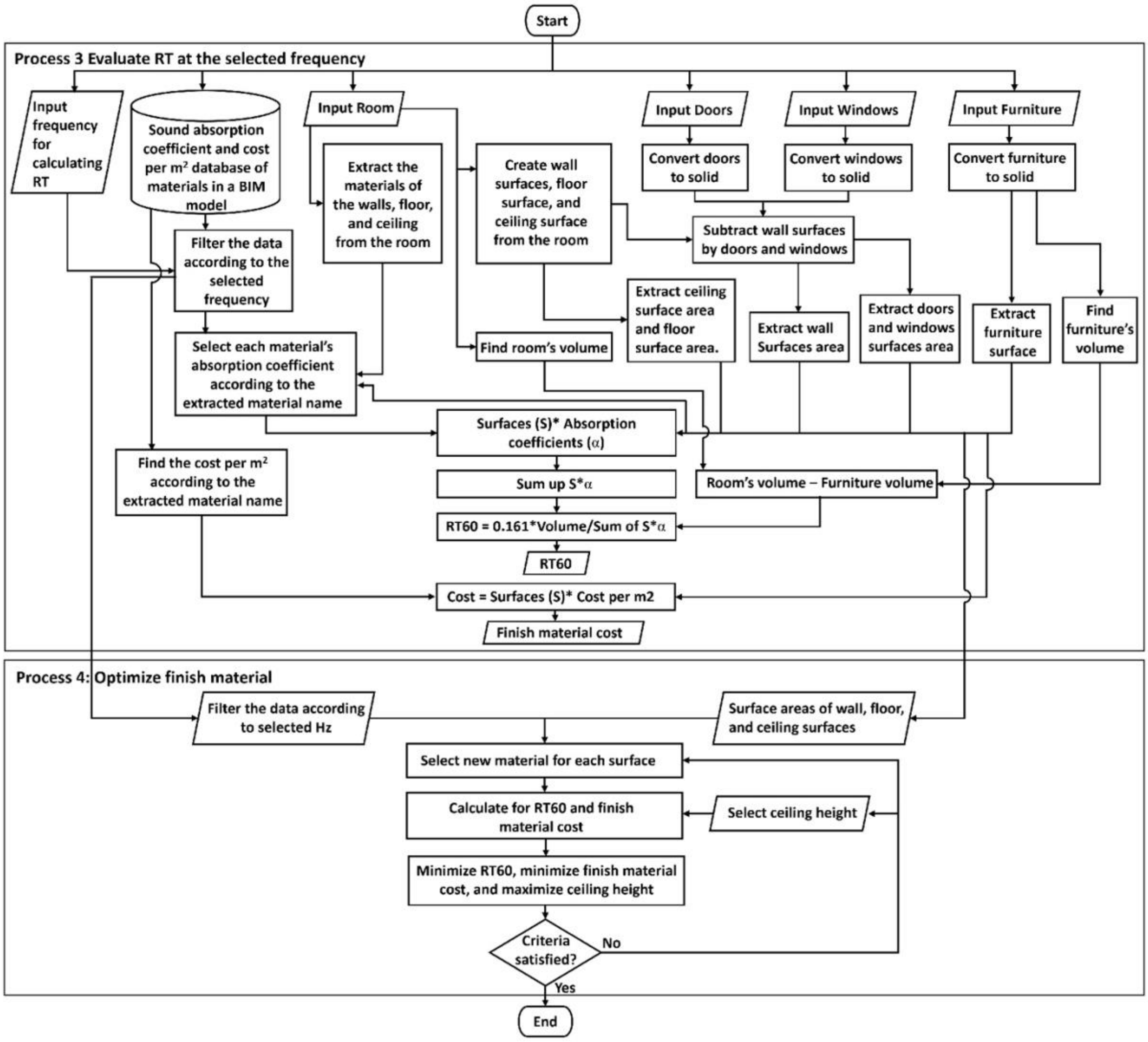


Figure 4 shows a flowchart for Process 3 and Process 4. In Process 3, the RT is evaluated at the selected frequency. To calculate the RT using Sabine's formula, three variables are needed: volume (V), surface area (S), and sound absorption coefficient (α), as shown in Eq. (1).

First, the sound absorption coefficients are extracted from the walls, floors, and ceiling. Building model elements, such as doors, windows, rooms, and furniture, are imported from the BIM model. Material data is loaded into the system using input material names from Autodesk Revit. The room for RT calculation is selected by its name. Python scripts extract materials for the walls, floor, and ceiling from the selected room. The sound absorption coefficients and cost parameters are obtained from the materials. The coefficients for doors and windows are extracted from their respective parameters. For furniture, elements are loaded, converted into solids, and grouped by material. The coefficient of each material is manually inputted. The selected frequency determines the corresponding sound absorption coefficient from the material parameters.

Second, the surface area of each material is extracted. Wall, floor, and ceiling surfaces are created based on room geometry. The wall surfaces are adjusted by subtracting the areas occupied by doors and windows to get the net wall surfaces. The surfaces of doors and windows are obtained by intersecting their solids with the wall surfaces. For furniture, solid objects are exploded into individual surfaces, which are then joined to form polysurfaces. If a furniture item consists of multiple materials, separate polysurfaces are created for each.

Third, the room volume is extracted from the room element, and the volume of each furniture item is determined based on its solid representation. The net room volume is then calculated by subtracting the furniture volume from the room's total volume.

At this stage, all variables are ready for RT calculation. The surface area of each material is multiplied by its sound absorption coefficient, and the results are summed. The net room volume is multiplied by 0.161, and this value is divided by the sum of the surface area multiplied by the sound absorption coefficient. The finish material cost is calculated by multiplying the surface areas by their cost per square meter, and the results are totaled.

Finally, the sound absorption coefficient of each model element is visualized using a color gradient. The coefficients are normalized by remapping the values to a range from 0 to 1. The value 0 is represented by red, 1 by blue, and 0.5 by green. The range between 0 and 1 transitions from blue to green to red. An example of this visualization in Dynamo is shown in Figure 5.

Figure 5

Visualization of the Sound Absorption Coefficient in Dynamo

Note. From *Visualization of the Sound Absorption Coefficient in Dynamo 2.6.1.8850,* by Autodesk Inc., 2025.

Process 4 optimizes the finished materials using the GD tool in Dynamo. A Dynamo script is prepared for this purpose. Initially, finish material names are inputted into Dynamo and categorized into three lists: wall, floor, and ceiling materials. These materials are imported from Autodesk Revit into Dynamo based on the input lists.

Eleven integer sliders are created for optimization. One slider adjusts the ceiling height, affecting the room's volume and wall surface area. Eight sliders are created for modifying wall materials, and one each is for the floor and ceiling materials. Each slider selects a new material from the finish material list, updating the sound absorption coefficient and cost values. The RT and material costs are recalculated based on the new selections.

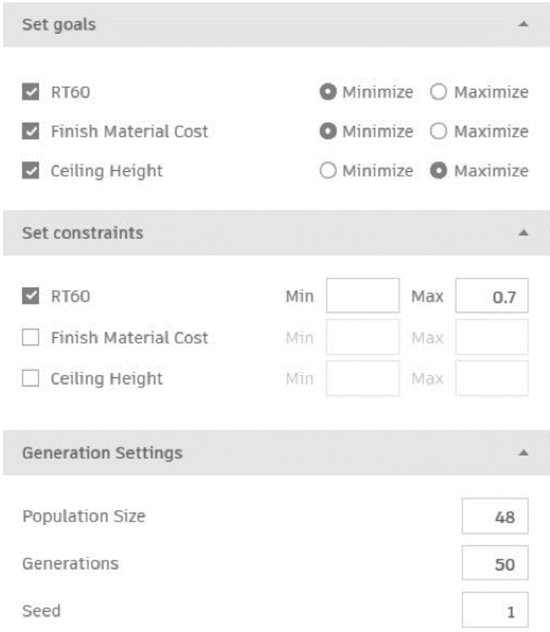
The GD process aims to calculate RT, material cost, and ceiling height. The objectives are to minimize RT, minimize material cost, and maximize ceiling height, with users able to set constraints within desired ranges. For example, users can set a maximum RT based on acoustic standards and limit material costs according to the budget.

The GD tool has three parameters: population size, generations, and seed. Population size controls the number of design solutions per generation, balancing diversity and computational demands. The generations parameter sets the number of iterations, influencing design exploration and solution quality. The seed parameter ensures reproducibility by setting the initial state, which is useful for comparisons and documentation. Figure 6 shows an example of the GD tool settings.

Process 5 analyzes the optimization results from the GD process. The results are exported to Excel for further analysis, with multiple optimization runs combined to explore a broader range of outcomes. A scatter plot is created, with the X-axis representing RT and the Y-axis representing finished material cost. Each point represents a design solution. The Pareto frontier is calculated, representing the set of non-dominated solutions where improving one objective requires sacrificing another, defining the optimal trade-off between RT and material cost.

Figure 6

An Example of the GD Tool Settings



Note. From *An Example of the GD Tool Settings in Dynamo 2.6.1.8850,* by Autodesk Inc., 2025.

To calculate the Pareto frontier, the finished material cost values are sorted in ascending order, and the RT rankings are determined. Design solutions are considered part of the Pareto frontier if their ranking is higher than the previous row's and the highest encountered so far. If not, they are excluded. The Pareto frontier is then visualized using a scatter plot and a straight line, helping designers identify optimal trade-offs between RT and material cost. This enables informed decision-making, guiding designers to select and refine the most suitable options.

Finally, in process 6, after designers select materials based on the Pareto frontier and make adjustments, the final step is to update the BIM model to reflect the chosen design. The selected finished materials are assigned to the walls, floors, and ceilings, ensuring the model accurately represents the design and its acoustic performance for evaluation.

Case Study

A classroom from the Faculty of Architecture, Chulalongkorn University, was used to test the prototype system. The rectangular classroom has slanted front walls and a storage room behind the front (see Figure 7). The floor-to-floor height is 4.1 m, with four windows, three doors, eight wall surfaces, one floor surface, and one ceiling surface. The floor area is 87.51 m^2, and the volume is 332.54 m^3. The BIM model was created in Autodesk Revit 2021.1.3. This classroom was selected for its real-world conditions, and the adaptable BIM model allows for exploring design variations, including adjustable ceiling height, to aid in diverse architectural decisions.

For the initial setup, all wall finishes are plaster, the floor is concrete, and the ceiling is the bottom surface of the floor above, also concrete. The room contains 60 seats made of fabric and metal. The sound absorption coefficient data for these materials, collected from various manufacturers and suppliers in Thailand, is presented in Table 1. In cases of duplicated material names, the authors selected one source for the sound absorption coefficients.

Figure 7

The Case study Classroom

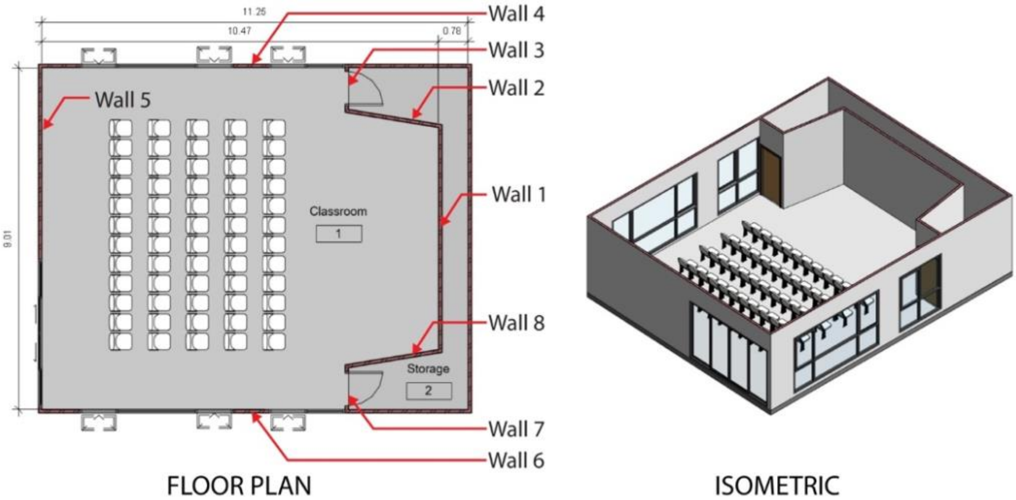


Table 1

The Sound Absorption Coefficients Data Used in the Initial Setup

Material	Sound Absorption Coefficient		
	500Hz	1,000Hz	2,000Hz
Concrete	0.03	0.03	0.04
Plaster	0.02	0.02	0.05
Windows (Glass)	0.18	0.12	0.07
Doors (Glass)	0.18	0.12	0.07
Wood Doors	0.15	0.10	0.08
Fabric well-upholstered seats	0.56	0.67	0.61
Chair, metal or wood seats	0.22	0.39	0.38

The sound absorption coefficients for concrete and plaster are entered into the material parameters in Autodesk Revit. The coefficients for the doors and windows are entered in the instant parameters of the respective elements. For the seats, consisting of fabric and metal, the sound absorption coefficients are inputted as a list in Dynamo.

After executing the Dynamo script to calculate the RT, the results show that the classroom's RT, including the seats, is 1.222 at 500Hz, 1.082 at 1,000Hz, and 1.077 at 2,000Hz. According to the ANSI S12.60-2010 standard (American National Standards Institute, 2010), classrooms with an enclosed volume between 283 m³ and 566 m³ should have an RT of 0.7 or less at these frequencies. Thus, the classroom's RT does not meet the standard and requires improvement.

The classroom improvement objectives are: (1) minimize the RT at 500Hz, 1,000Hz, and 2,000Hz to 0.7 or below by changing the finish materials; (2) minimize the cost of the finish materials; and (3) maximize the ceiling height within a range of 2.60 to 3.80 m. These three objectives create a multi-objective optimization problem. Increasing ceiling height raises the room's volume, which in turn increases the RT, while adding sound-absorbing materials to reduce RT also raises the material cost. The optimal solution that balances all three objectives must be found.

Table 2 presents the sound absorption coefficients and cost per square meter of finished materials used to improve the classroom's RT. The data, sourced from various material suppliers in Thailand, includes cost values for wall plaster and concrete flooring, which are set to zero as they are part of the initial setup. Choosing these materials indicates no changes to these surfaces.

Table 2

Sound Absorption Coefficients Data and Cost per Square Meter of the Finished Materials

Type No.	Material	Sound Absorption Coefficient			Cost per square meter (USD/m²)
		500Hz	1,000Hz	2,000Hz	
	Wall				
0	Plaster (Existing)	0.02	0.02	0.05	0.00
1	Acoustic PET Felt Panel	0.14	0.38	0.70	2.10
2	Polyester Fiber Acoustic Panel	0.84	0.75	0.81	2.26
3	Acoustic Mineral Wool with Cavity Insulation	0.90	0.90	0.90	2.50
4	Acoustic Sound Barrier	0.42	0.50	0.47	3.38
5	Cork Board	0.17	0.52	0.50	3.75
6	Wedged Acoustic Foam Panels	0.79	0.94	1.00	5.00
7	Egg Crate Acoustic Foam Panels	1.32	1.22	1.06	7.50
8	Acoustic Wood Perforated Panel	0.92	0.54	0.35	18.80
9	Fiberglass Acoustic Panel	1.11	1.10	1.13	18.80
10	Fabric Wrapped Acoustic Panel	0.82	0.72	0.69	26.00
11	Slat Wooden Acoustic Panel	0.82	0.82	0.70	32.60
12	Grooved Acoustic Panel	0.91	0.63	0.59	33.90

Table 2 (Continued)

Type No.	Material	Sound Absorption Coefficient			Cost per square meter (USD/m^2)
		500Hz	1,000Hz	2,000Hz	
	Floor				
0	Concrete (Existing)	0.03	0.03	0.04	0.00
1	EVA Foam Mats	0.90	1.25	1.15	1.15
2	Cement Screeding	0.04	0.06	0.08	1.28
3	Rubber Tiles	0.10	0.10	0.05	3.00
4	Ceramic Tiles	0.01	0.01	0.02	3.00
5	Stone Plastic Composite Flooring	0.02	0.01	0.05	4.65
6	Vinyl Flooring	0.30	0.40	0.40	5.20
7	Cotton Carpet	0.49	0.81	0.66	8.50
8	Polyester Carpet Tiles	0.43	0.27	0.35	10.60
9	Solid Wood Flooring	0.07	0.06	0.06	30.00
10	Cork Flooring	0.15	0.15	0.25	36.13
	Ceiling				
0	Acoustic Plasterboards	0.70	0.60	0.55	1.80
1	Polyester Acoustic Ceiling Panels	0.88	0.98	0.99	3.20
2	Acoustic Ceiling Panels	0.81	0.93	0.71	4.50
3	Bonded Acoustical Cotton Ceiling Panels	0.79	1.01	1.00	5.20
4	Microperforated Acoustical Ceiling Panels	0.45	0.55	0.65	10.00
5	Melamine Foam Acoustical Ceiling Panels	0.81	1.24	1.30	12.10
6	Curved Acoustic Ceiling Panels	0.85	1.05	1.09	22.00
7	PET Acoustic Ceiling Baffle	0.94	1.33	2.15	25.00
8	Grid Panel Suspended Ceiling Acoustic Panels	1.00	0.96	1.00	25.00
9	Acoustic Slatted Timber Ceiling	1.05	0.82	0.48	25.98

The GD tool in Dynamo is used for multi-objective optimization with the following settings: Variables include materials for wall surfaces 1 to 8, floor, ceiling surfaces, and ceiling height. Wall materials range from 0 to 12, floor materials from 0 to 10, ceiling materials from 0 to 9, and ceiling height from 2.6 to 3.8. The goals are to minimize RT, minimize finished material cost, and maximize ceiling height. The population size is 48, the generation count is 50, and the seed count is 1.

Results of the Case Study

The GD tool was run five times with different goal constraints to explore a range of outcomes for the scatter plot and Pareto frontier calculation. Figure 8 shows the results of the first attempt, focusing on RT at 500 Hz, selected as the mid-frequency for optimizing the Pareto frontier. RT values at 1000 Hz and 2000 Hz were calculated based on the material selections for the walls, floor, and ceiling from the Pareto frontier outcomes.

In the first attempt, the RT maximum constraint was set to 0.7, while the finished material cost and ceiling height were unconstrained. The results showed a wide range, with the finished material cost potentially below 1,000 USD and RT under 0.4. However, further improvements could help achieve a finished material cost lower than 1,000 USD.

In the second attempt, the maximum constraints were set to 0.7 for RT and 1,000 USD for the finished material cost. The results revealed new possibilities, with costs potentially under 500 USD and RT above 0.3.

In the third attempt, the maximum RT constraint was set to 0.7, the minimum to 0.3, and the finished material cost to 500 USD. The results stabilized at the lowest cost of 220 USD with an RT of 0.314. It was believed that increasing RT towards 0.7 could allow a further cost reduction.

In the fourth attempt, the maximum RT constraint was set to 0.7, the minimum to 0.4, and the finished material cost to 200 USD. The results remained static, with the highest RT at 0.48 and the lowest finish material cost at 164.43 USD.

In the fifth attempt, the maximum RT constraint was set to 0.7, the minimum to 0.5, and the maximum finished material cost to 150 USD. The results showed the lowest finished material cost at 157.52 USD, with an RT of 0.428.

The results from all five attempts were combined, and the Pareto frontier was calculated using Excel. Figure 9 shows the scatter plot of these results, with the Y-axis representing the finished material cost (0–1,000 USD) and the X-axis representing RT at 500 Hz (0.13–0.53). The orange line represents the Pareto frontier, illustrating the trade-offs between the finished material cost and RT. It shows how improving one objective can worsen the other.

Figure 8

The Outcome of the First Attempt in the GD Tool

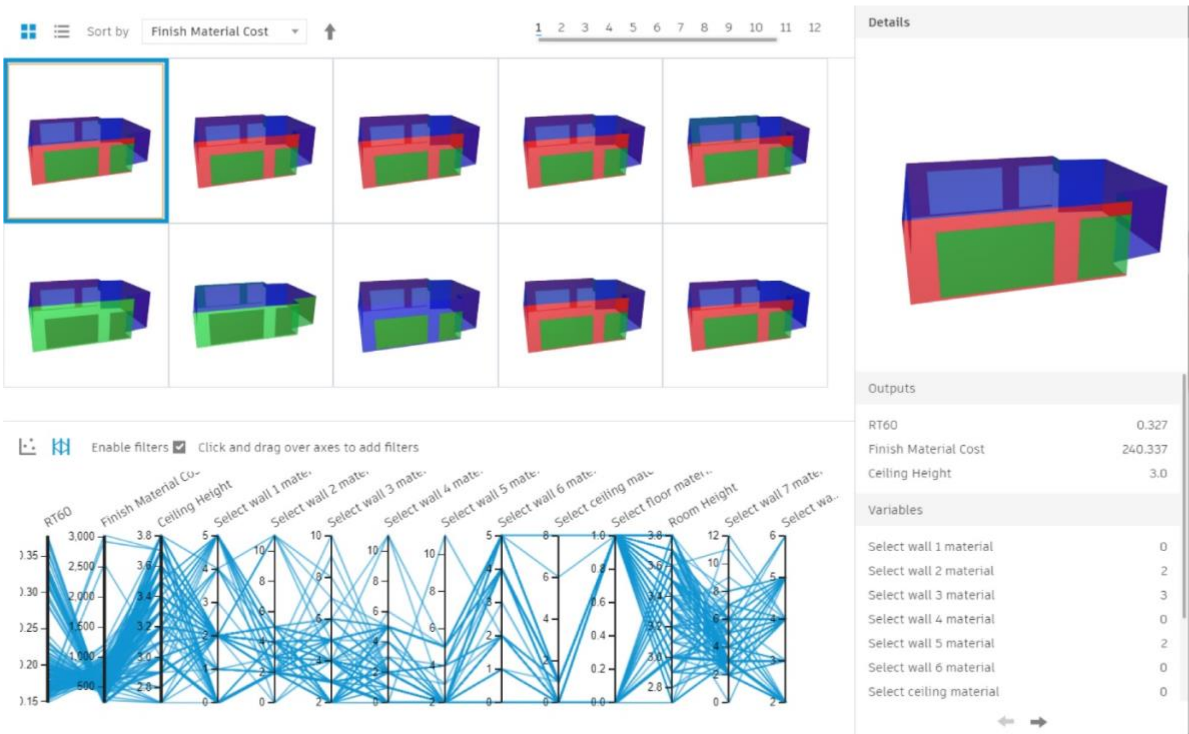


Figure 9

Scatter Plot of the Results and the Pareto Frontier

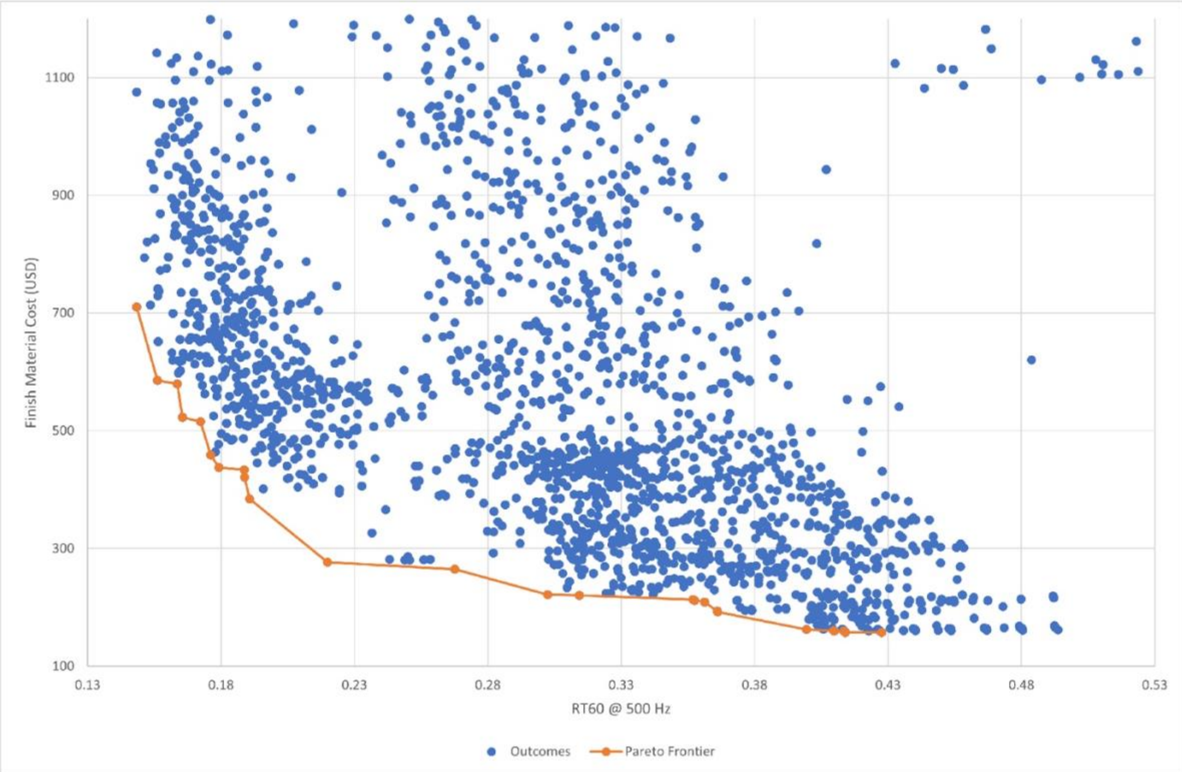


Table 3

Pareto Frontier Outcomes

Out-come No.	RT @ 500Hz	RT @ 1,000 Hz	RT @ 2,000 Hz	Finished Material Cost (USD)	Ceiling Height	Wall 1 Material	Wall 2 Material	Wall 3 Material	Wall 4 Material	Wall 5 Material	Wall 6 Material	Wall 7 Material	Wall 8 material	Floor Material	Ceiling Material
1	0.148	0.127	0.134	710.18	2.70	2	7	7	7	7	6	5	6	1	1
2	0.156	0.132	0.137	585.56	2.70	2	3	9	2	2	6	8	6	1	1
3	0.164	0.135	0.140	579.60	2.70	2	5	5	2	6	2	5	5	1	1
4	0.166	0.138	0.141	522.86	2.70	2	4	1	2	2	1	5	1	1	1
5	0.172	0.146	0.149	515.62	2.90	2	2	1	2	2	1	2	0	1	1
6	0.176	0.153	0.163	458.69	2.70	5	2	6	2	2	6	4	6	1	0
7	0.179	0.158	0.166	437.66	2.80	2	6	7	2	2	1	5	5	1	0
8	0.189	0.166	0.178	433.54	2.90	2	5	8	2	2	0	5	5	1	0
9	0.189	0.165	0.172	421.30	2.90	1	2	2	5	2	2	2	2	1	0
10	0.191	0.170	0.181	384.35	2.90	2	2	5	0	2	0	2	5	1	0
11	0.220	0.189	0.202	276.68	2.80	0	1	0	0	0	0	5	0	1	0
12	0.268	0.231	0.250	264.62	3.40	0	0	0	0	0	0	5	0	1	0
13	0.302	0.312	0.323	221.51	2.60	2	0	0	1	0	0	2	2	0	0
14	0.314	0.318	0.325	220.47	2.60	2	0	0	1	0	0	2	1	0	0

Table 3 (Continued)

Out-come No.	RT @ 500Hz	RT @ 1,000 Hz	RT @ 2,000 Hz	Finished Material Cost (USD)	Ceiling Height	Wall 1 Material	Wall 2 Material	Wall 3 Material	Wall 4 Material	Wall 5 Material	Wall 6 Material	Wall 7 Material	Wall 8 material	Floor Material	Ceiling Material
15	0.357	0.356	0.359	213.48	2.80	0	2	1	0	1	0	6	0	0	0
16	0.357	0.351	0.352	211.49	2.70	0	1	2	0	1	0	7	0	0	0
17	0.361	0.353	0.352	209.10	2.70	0	1	1	0	1	0	6	0	0	0
18	0.366	0.363	0.369	193.79	2.70	0	0	1	0	1	0	5	0	0	0
19	0.366	0.363	0.368	192.31	2.70	0	0	1	0	1	0	1	0	0	0
20	0.399	0.410	0.433	162.28	2.90	0	0	1	0	0	0	1	0	0	0
21	0.410	0.422	0.449	160.65	3.00	0	0	0	0	0	0	3	0	0	0
22	0.410	0.423	0.450	160.35	3.00	0	0	2	0	0	0	0	0	0	0
23	0.410	0.423	0.450	160.35	3.00	0	0	0	0	0	0	2	0	0	0
24	0.413	0.425	0.450	160.15	3.00	0	0	1	0	0	0	0	0	0	0
25	0.413	0.425	0.450	160.15	3.00	0	0	0	0	0	0	1	0	0	0
26	0.414	0.427	0.454	157.52	3.00	0	0	0	0	0	0	0	0	0	0
27	0.428	0.441	0.469	157.52	3.10	0	0	0	0	0	0	0	0	0	0

The combined results from the five attempts consist of 12,000 records. Table 3 presents 27 outcomes representing the Pareto frontier, with parameters including RT values at 500Hz, 1,000Hz, and 2,000Hz, the finished material cost in USD, ceiling height, and materials for walls, floor, and ceiling. The material numbers in Table 3 correspond to those in Table 2.

Outcome 1 shows the lowest RT value with the highest finish material cost of 710.18 USD, while outcome 27 has the highest RT value and the lowest cost of 157.52 USD. Outcome 12 has the highest ceiling height at 3.40 m, while outcome 27 has the second-highest at 3.10 m.

Outcomes with low finished material costs show that certain surfaces were left unchanged to save on the budget. For example, outcomes 13 to 27 use an existing floor finish material, and outcomes 26 and 27 retain all existing wall and floor materials. Only the cheapest ceiling material (type 0) was used. As a result, the finished material cost reached the lowest value of 157.52 USD. The ceiling height difference between outcomes 26 and 27 did not affect the cost, as all walls kept their original materials.

DISCUSSION AND LIMITATIONS

The prototype system successfully extracts finish materials and sound absorption coefficients, calculating the RT at 500Hz, 1,000Hz, and 2,000Hz without issues. The sound absorption coefficients are visually represented on the model surfaces using a color gradient from blue to green to red. In this system, red indicates low absorption, green represents moderate absorption, and blue signifies high absorption on the respective surfaces.

The GD tool in Autodesk Revit uses the NSGA-II algorithm, which explores a limited subset of the solution space in each optimization run. Different seeds help explore a broader range of possibilities (Autodesk, 2021a). The case study showed that running the optimization multiple times with different goal constraints enabled exploration of various possibilities, including cost ranges of under 1,000 USD, 500 USD, 200 USD, and 150 USD. However, user fine-tuning in the final stage is necessary to find solutions the GD may not have explored. The RT constraint was set to a maximum of 0.7 seconds to ensure acceptable acoustic quality in all scenarios. Many results fell below this threshold as optimization favored solutions that balanced cost and acoustic quality, yielding lower RT values. For example, in outcome 27, the lowest finished material cost, even with a ceiling height of 3.80 m (the maximum), the RT at 500Hz, 1,000Hz, and 2,000Hz were 0.522, 0.538, and 0.567, respectively, still below 0.7. Thus, ceiling height can be further maximized if prioritized over RT.

The Pareto frontier analysis helps designers understand the optimal trade-offs between different parameters or objectives in the design process. By identifying outcomes on the Pareto frontier, designers gain valuable insights into the best balance among conflicting criteria. In the case of the data from Table 3, the Pareto frontier shows the trade-offs between RT values, the finished material cost, and ceiling height. Designers can use this information to make informed decisions based on priorities and project requirements. For example, if minimizing RT is essential, they can focus on outcomes with lower RT values. However, they should also consider the higher cost, as these outcomes tend to have higher finished material costs. Conversely, if cost efficiency is a priority, they could explore outcomes with lower material costs, understanding that this may lead to higher RT.

Additionally, designers must consider the impact of human occupancy on RT. The proposed method calculates RT for an empty room, which is a typical acoustics approach that provides a conservative baseline as a worst-case scenario. This ensures the design meets minimum acoustic performance across varying occupancy levels. Human presence generally increases absorption, lowering RT in real-world situations. Designers can use this empty-room RT to anticipate acoustical outcomes in all conditions, with the option to make further adjustments for specific occupancy scenarios. This approach balances accuracy and adaptability, making it suitable for diverse design contexts.

Furthermore, the designer may consider the room's appearance alongside the insights from the Pareto frontier analysis. They can explore various design options by swapping or changing finished materials to achieve the desired aesthetic outcome. For example, by selecting outcome number 9 from Table 3, they could swap materials between wall 1 and wall 2, enhancing the room's overall appearance. Similarly, choosing outcome number 24 might lead them to use material 1 on wall 6 instead of wall 3 for a more visually appealing result. It is important to note that altering or swapping materials can impact both cost and RT values. Designers must carefully balance aesthetics, cost, and acoustic performance to ensure that changes align with the project's objectives and constraints. By balancing these factors, the designer can create a visually pleasing room while maintaining the optimized parameters identified in the Pareto frontier analysis.

The proposed BIM-based approach for RT evaluation and optimization builds on recent research using BIM and VP for acoustic analysis, such as Nik-Bakht et al. (2021) and Sušnik et al. (2021), which focus on automating RT calculations. However, these methods lack an optimization framework for design decisions. This study fills that gap by integrating multi-objective optimization to balance RT performance and material costs. By incorporating GD and VP, this method provides a more flexible and comprehensive solution for acoustical design in classrooms.

The novelty of this work lies in integrating multi-objective optimization with BIM and VP, creating a more dynamic tool for acoustical design decisions. Using Pareto frontier analysis, it balances acoustic performance with cost efficiency, allowing greater design exploration. Future research could enhance optimization algorithms, incorporate subjective factors like client preferences, or extend the method to more complex spaces.

However, the proposed method and the prototype system have limitations and remarks. First, the proposed method assumes that the design changes the entire material on each surface, whereas in reality, designers often modify only parts of a surface (e.g., acoustic panels on half a wall or mixed materials). Secondly, the prototype system does not support complex designs. It has restrictions on the number of wall (8), floor (1), and ceiling (1) surfaces. Additionally, since it uses a Room object in Autodesk Revit for boundaries, rooms with sloped or stepped floors/ceilings are not supported. Air absorption was not included due to its minimal impact on this research, but future work could address it to further refine the model. Regarding the remarks, the method's effectiveness also depends on the availability and accuracy of material data, as incomplete or outdated information can reduce reliability. Furthermore, the system doesn't account for subjective design factors like client preferences or the desired ambiance, which are crucial for design decisions. Ultimately, the designers must make the final decisions.

CONCLUSION

This study aimed to address the challenges associated with calculating RT in room design and provide an automated solution using BIM and VP. Calculating RT using Sabine's formula can be time-consuming and error-prone due to the manual extraction of room volume and the surface areas of materials, encompassing walls, floors, ceilings, and furniture. Additionally, the complex trade-offs between RT, material costs, and design aesthetics further complicate the decision-making process for designers.

To address these challenges, the proposed method used BIM and VP to automate RT calculation and optimization. By assigning sound absorption coefficients to BIM material properties, algorithms extracted room geometries, materials, and coefficients to compute RT and material costs, which were then optimized using a multi-objective algorithm.

The prototype system effectively validated the proposed method by extracting finish materials, calculating RT at various frequencies, and visually mapping sound absorption coefficients on model surfaces. This provided designers with a fast and efficient way to evaluate and analyze acoustic quality in indoor spaces.

A classroom case study validated the proposed method and prototype system, demonstrating its ability to optimize room design by selecting materials and room height to achieve the desired RT within cost constraints. The results offered insights into trade-offs between RT, material costs, and ceiling height.

The intended achievement of this research is to provide an automated method for optimizing room acoustics while balancing material costs. By integrating BIM and VP, it offers a streamlined solution to support designers in making informed decisions early in the design process.

This research significantly contributes to room acoustics by tackling RT calculation challenges and optimizing room design early in the process. Integrating BIM and VP automates RT calculations and room parameter optimization. The key contribution lies in developing an automated method and prototype system that streamlines this traditionally time-consuming, error-prone task. By leveraging BIM and VP, designers gain a fast, accurate tool for acoustic analysis, enhancing speech intelligibility and sound quality. Additionally, the multi-objective optimization algorithm and Pareto frontier analysis offer insights into trade-offs between RT, material cost, and ceiling height, helping designers balance acoustic performance, cost efficiency, and aesthetics.

While the proposed method and prototype system demonstrated promising results, they do have limitations. One limitation is that the system was designed under the assumption of changing the entire material on each surface, whereas in reality, designers may only modify specific parts of a surface. Additionally, the system restricts the number of wall, floor, and ceiling surfaces, making it less suitable for complex designs. Furthermore, the system's reliance on accurate material properties and costs, as well as its limited consideration of subjective design factors, were identified as areas for improvement.

Future work could refine the system to support partial material changes and complex designs. Improving sound absorption coefficient data accuracy would enhance reliability. Developing automated scripts to integrate GD with Pareto frontier analysis and optimization would streamline workflows, enabling real-time adjustments and quicker design evaluations. Moreover, incorporating subjective factors, like client preferences and ambiance, into the optimization process would provide a more comprehensive design solution that balances functionality and aesthetics.

In conclusion, this study contributes to the field of room acoustics by providing an automated solution for calculating RT and optimizing room design using BIM and VP. The proposed method and prototype provide a faster, more accurate approach to acoustic analysis, helping designers achieve optimal performance while considering cost efficiency. The findings open the door for future advancements in integrating more complex design considerations and further refining optimization algorithms.

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