

Article

Development of a BIM-Based Framework Using Reverberation Time (BFRT) as a Tool for Assessing and Improving Building Acoustic Environment

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Abstract: Both the building design and the construction process determine the indoor acoustic quality of enclosures. A suitable indoor acoustic environment is crucial for the productivity and well-being of users. For this purpose, Reverberation Time (RT) is often calculated or measured in situ. Recently, Building Information Modelling (BIM) has provided a new paradigm to face building projects. Nevertheless, little research has been conducted on the optimisation of indoor acoustics using BIM methodology. In this context, the objective of this work is to propose and develop a BIM-based framework for the analysis, evaluation and optimization of the RT. The proposed procedure allows designers to explore alternatives in order to achieve an adequate acoustic performance without any further needs of specific software. This proposal is devised to consider some important characteristics of the project, such as its location, applicable regulations, room uses, materials and costs. This framework calculates the solution set that meets the requirements, showing the set of optimal solutions according to the minimization of both the cost and the optimum absorbent surface area. BFRT contributes by offering a tool to support the decision making process of designers during the initial design phase in the field of acoustic conditioning of buildings.

Keywords: acoustic performance; building; Building Information Modelling (BIM); built environment; optimization algorithms; reverberation time



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1. Introduction

Between an 80 and 90% of the urban population spends most of its living time in interior spaces [1]. In this sense, the conditions of the indoor environment in buildings represent an important factor in the quality of life for occupants/users. According to the ISO 16814:2008 standard, indoor environment includes thermal, acoustic and lighting conditions, as well as indoor air quality (IAQ). All these elements taken altogether have been already identified and taken into account in different studies [2,3] as relevant aspects that will determine the environmental quality of interior spaces. Focusing specifically in the acoustic conditions, the acoustic behaviour inside rooms in a building is conditioned not only by external noise sources, but also by domestic sources and the characteristics of other adjacent spaces [4,5]. If such behaviour was not appropriate, the normal performance of human activities would be affected, and may even result in an increased risk of diseases related to exposure to noise [3].

In this sense, an appropriate acoustic behaviour for a given indoor space should be already guaranteed from the early design phase, working with some potential available objective parameters to allow evaluating the acoustic characteristics of a room [6–8]. Among these parameters this work focus in the reverberation time, denoted as RT, which is certainly one of the most important variables or physical factors considered by experts in the design

of interior spaces [9]. In fact, the RT is used as the key parameter in the acoustic assessment of enclosures. RT is defined as the time required by the sound to “fade away” or decay in a given closed space. Specifically, it is the time taken from the sound pressure level to decrease 60 dB after ceasing the emission of a sound source in a room or closed space, or equivalently, the time needed for the acoustic intensity to decrease up to a million times its original value when the source is switched on. Its value depends on the constructive elements that make up the room and their fine finishes and coatings, which affect the overall sound absorption [10,11]. Its analysis is important because the presence of reverberant acoustic energy tends to mask the immediate recognition of any new incoming sound and makes it difficult for the speech intelligibility [11]. If the reverb is excessive, the speech intelligibility may be poor and/or the acoustic pressure be high, being able to adversely affect the performance of activities for which these spaces have been designed [12]. In fact, it is confirmed by experimental studies the strong empirical relationship between the characteristics of the RT of a room, its size and the amount of absorbent material of coatings [12]. So, the RT parameter will be optimized to control the main characteristics of the acoustic behaviour inside rooms in a building.

Furthermore, in spite of the great influence that the acoustic behaviour of buildings has on its occupants, it is often not taken into account from the early stages of the project (except in those buildings in which the acoustic requirements are essential, such as theatres and auditoriums). In general, the acoustic behaviour of spaces is analysed later, in an advanced stage in the construction projects when the geometry and configurations of the enclosures have been already set up. Therefore, if designers strive for achieving some minimum acoustic requirements, they realize that it becomes more complicated and expensive than if it had been handled during the design stage of the project [13,14]. What is more, the acoustic simulations are often carried out using specific software (i.e., Odeon, Catt-Acoustic, Ease, Soundplane, etc.) which are not usually integrated with the others used to design the building. In consequence, the use of these tools in later stages of conventional buildings projects involves an additional work that implies further costs in time and resources, but perhaps the most worrying issue is the fact that it not often concludes with an optimal result [13].

Therefore, the purpose of this research is to build an integrated framework in BIM-based software to generate a comprehensive scheme that allows the analysis of room acoustic performance from the early design stages to be included, in the same way as it was performed with other design disciplines in the construction sector (i.e., energy efficiency, sustainability, LCA, facilities, etc.) [15–19]. In this sense, this research assumes and will demonstrate that the use of BIM-based model into a reliable database with the acoustic characteristics of absorbent material of coatings will result in a reduction of the time invested in the definition of the project and, since the number of explored solutions is increased, the achieved acoustic performance is higher than the one obtained without the use of this framework.

This article is structured in five sections: Section 2 establishes the objectives and the methodology followed in this research. In this section it is outlined the problem of acoustic performance in buildings in the early stages of design of the project building using a BIM-based scheme. In Section 3, those parameters and tools that will be used in the subsequent BIM-based methodology development are defined and presented. The proposed framework based on BIM for the assessment of the acoustic performance of rooms in buildings is developed in Section 4, and in Section 5 the proposed scheme is evaluated on a study case of a building for educational uses. Finally, the main findings and conclusions of this research are drawn in Section 6.

2. Objectives and Research Methodology: Problem Identification and the Use of BIM as a Framework to Assess Acoustical Performance of Buildings

In addition to the comments given in the preceding section, it must be also emphasized that the processes of architectural design and construction are currently becoming

increasingly specialized and complex tasks, not only due to the use of new technologies and materials, but also by the specific demands coming from the different regulations (acoustic, thermal, environmental, fire safety, etc.) [20]. In addition, it is quite common that multiple agents to be involved during the life cycle of the project and this fact causes an urgent need for a necessary communication, interaction and collaboration between the different agents from the very early stages of design. For all these reasons, Building Information Modelling (BIM) as a work methodology has attracted a great deal of attention by replacing the traditional methodology based on Computer Aided Design (CAD). The process of generation and data management related to the properties and characteristics of buildings (both geometric and non-geometric data), turns a BIM-based model into a reliable database. This database can be used throughout the whole life-cycle project allowing the effective exchange of information between the different agents involved.

Consequently, the application of the BIM methodology in construction projects offers an exceptional opportunity to assess the building performance from its initial phase [21]. BIM is so useful to test and visualize different scenarios during the process of design, construction and even maintenance; and therefore, it has the potential to improve the design process and to support designers and contractors in the decision-making process concerning the acoustic evaluation [13,22].

On the other hand, the use of BIM-based tools for the assessment of acoustic performance in buildings has been the focus of several studies. Among the most recent ones, it can be highlighted that conducted by Pauwels et al. [20] that proposes a method to analyze the acoustic performance of buildings by translating the design BIM data into ontology data and performing reasoning according to ontology-based rules. For the purposes of this research, it should be note that the BIM-based tool proposed by Wu [13] for the acoustical evaluation of simple rooms during the design stage of the building. The tool is comprised of four modules (BIM data extraction, analysis of frequencies, simulation of sound effects and auralization/visualization). In addition, for simulation purposes, Deng et al. [23] develops in a framework that integrates BIM and 3D-GIS for the assessment of traffic noise in both outdoor and indoor urban environments. This framework is based on four modules that allow calculating noise levels at the outside and the inside and generate output simulation results. As a tool for decision-making based on BIM, the proposal of Hammad et al. [24] allows comparing conventional construction methods and modular ones, considering different factors of sustainability (economic, social and environmental). Among the analysed factors are the study of environmental noise generated by the different processes during the construction process. Finally, Tan et al. [25] proposes an acoustic simulation approach supported by BIM to reduce the impact of noise on offshore platforms in maintenance work. BIM provides the information to configure and prepare the acoustic simulation, this is carried out in Comsol. In this framework, BIM is also used to integrate the obtained information with daily maintenance information. This developed tool can also be implemented in the early stages of design.

The above schemes propose the use of BIM in several acoustic problems but there is a need to develop a complete and fully integrated framework for the assessment of acoustical performance of buildings. For the aforementioned reasons, this work proposes a BIM framework for the assessment and optimisation of the RT in interior spaces. The objective is to propose and develop a framework that allows designers to explore design alternatives in order to achieve a suitable acoustic performance in the early stages of the design of buildings. This framework intends upon completion of the proposed steps to allow the assessment of RT in interior spaces in accordance to the legal regulations of each country or region, and for this commitment, the proposal incorporates an optimization algorithm for the selection of materials to ensure a suitable acoustic behaviour.

With the aim of accomplish the objectives outlined in the preceding paragraph, four consecutive phases were conducted in this research in the following order: (I) Identification of the problem, (II) Statement on Objectives, (III) Proposed Solution and (IV) Evaluation (see Figure 1). In the first phase, literature review allowed defining the context of the

problem, i.e., the main characteristics of the room acoustic behaviour can be achieved by an adjustment of the RT parameter, and this acoustic behaviour should be addressed from the early stages of the building project, BIM methodology being a promising framework to accomplish it. With this starting-point, some evidence-practice gaps coming from RT-based analysis from the early stages of the building project made it possible to identify the needs, and objectives were defined on this basis. Therefore, on the basis of the information obtained from phases I and II, the objective of developing a framework that allows designers to achieve a suitable acoustic performance in initial stages of building design was configured. This framework is called “BIM-based framework for Reverberation Time” (BFRT) and it is developed in Section 4.

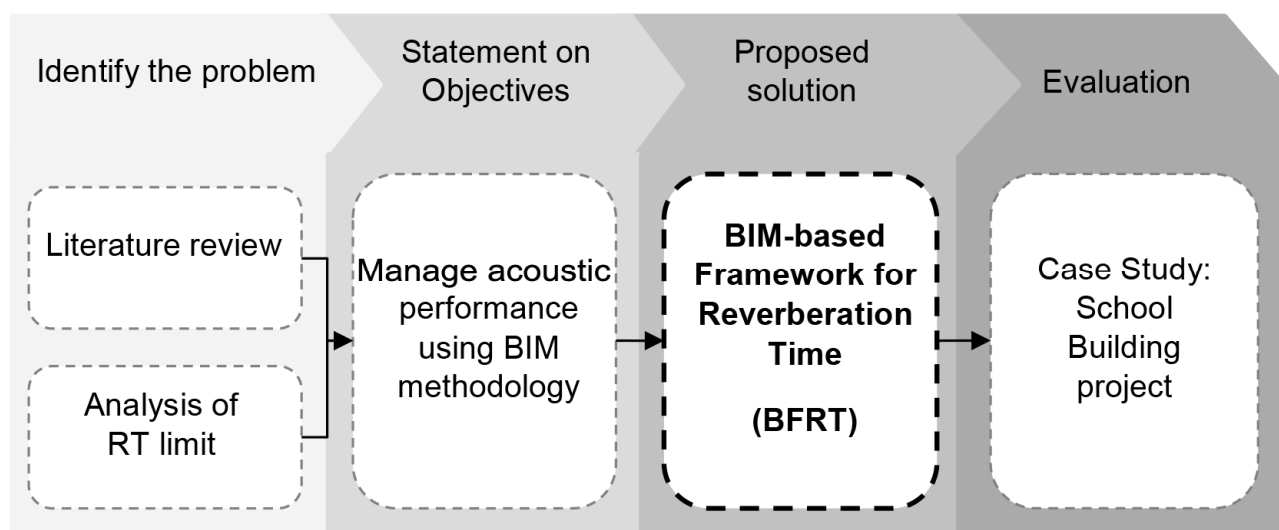


Figure 1. Research method.

Once the framework is defined and established, the feasibility of its implementation in real cases is tested and its results are evaluated in a study case. The project chosen corresponds to a building for educational purposes. In this study case, the application of the BFRT framework was made taking into account several regulatory requirements in European countries, and the obtained results were further compared each other to identify differences in possible options or solutions according the current different guidelines.

3. Parameters and Tools Used for the Development of the BIM-Based Framework

With the methodology scheme outlined in Figure 1, the following subsections establish the identification problem and the parameters and tools (Phase 2 in Figure 1) within a BIM-based methodology needed to develop the proposed framework scheme in Section 3.

3.1. Using Visual Programming Language in BIM Methodology

The use of the BIM-based methodology in the industry of Architecture, Engineering and Construction (AEC) has aroused a high impact for the last decade. One of the reasons for this growth is that the BIM methodology provides tools to comply with the Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement [23]. This Directive establishes in Article 22. Rules applicable to communication the following: “For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar.”

On the other hand, the ability of BIM to support the decision-making process from the early stages of design has become in an effective tool for building performance modelling. In this sense, researchers have started to use BIM not only as a modelling tool, but also for what it was originally created, i.e., as a critical methodology and technology to achieve

higher levels of performance and automatic simulations (such as predictive analysis of performance, sustainability performance [26], life cycle assessment (LCA) performance [27]).

This progress is accompanied by the appearance of tools based on Visual Programming Language (VPL) that make it easier for the designers, which are not usually programmers, extend the capabilities of BIM without the need for advanced knowledge in programming languages. There are different tools based on VPL for BIM (among the most known ones are Dynamo and Grasshopper). These tools enable us to expand the parametric functionalities of the BIM methodology and its use expands the options of iteration with the model, information extraction and development of tools.

There are many studies that have developed tools or frameworks based on BIM using tools with VPL, such as for example: multi-objective environmental optimization of buildings [28], Building Sustainability Assessment [29], evaluation of BIM-based LCA [30], Safety Analysis [31] or Design for Deconstruction [32].

In this work, VPL is used as a tool for the development of a BIM based-framework that allows designers to evaluate and optimize the acoustic behaviour of a room from an analysis of RT in interior spaces, all integrated into the own BIM software.

3.2. Reverberation Time (RT) for the Assessment of Acoustic Room Behaviour

The standard EN 12345-6:2003 [33] sets the calculation model for the estimation of the RT of enclosed spaces within buildings. Due to the strong dependence of the absorption on frequency, it is necessary to determine the RT for those most representative frequencies. In general, it is calculated as the average of the RT for 500, 1000 and 2000 Hz the frequencies. Equation (1) shows the classical Sabine formula for the calculation of the RT, taking as 345.6 m/s for the speed of sound in air [12]:

$$TR = 0.16 \frac{V}{A} \quad (1)$$

where V is the volume of the room (m^3) and A is the whole room sound absorption (Equation (2)) given by [33]:

$$A = \sum_{i=1}^n \alpha_{s,i} S_i + \sum_{j=1}^o A_{obj,j} + \sum_{k=1}^p \alpha_{s,k} S_k + A_{air} \quad (2)$$

where:

$\alpha_{s,i}$ is the coefficient of acoustic absorption of the i -th room surface.

S_i is the surface area (m^2) of the i -th room surface.

$A_{obj,j}$ is the equivalent sound absorption area of the j -th object (m^2).

$\alpha_{s,k}$ is the coefficient of acoustic absorption of the k -th specific object configuration (for example rows of chairs, people sitting in line or children in a classroom with reflecting furniture).

S_k is the surface area covered by the k -th object configuration (m^2).

A_{air} is the equivalent sound absorption area of the air (m^2).

n is the number of absorbing surfaces in the room (excluding objects).

o is the number of absorbing objects in the room.

p is the number of the configuration of absorbing objects in the room.

The equivalent sound absorption area of the air is given by the Equation (3):

$$A_{air} = 4 m V (1 - \Psi) \quad (3)$$

where

m is the sound attenuation coefficient of the air, in Neper per meter;

V is the volume of the empty closed space (m^3);

Ψ is the object fraction defined as the ratio between the sum of all the volumes of the objects and the volume of the empty space according to the ISO 12354-6:2004 standard (dimensionless).

To ensure a suitable acoustic behaviour, it is required to restrict the reverberating noise inside rooms. If the reverberation is excessive, the audibility may be poor and/or the acoustic pressure be high, which interferes with the appropriate performance of human activities for which these spaces were designed [8]. As a rule, to minimize the effects of an excessive reverberation is desirable to keep RT small. On the other hand, if the sized of the room is large and the sound source power is weak, it is advisable to achieve a higher RT to keep the sound audible at all points in the room. As can be observed, the choice of a suitable RT for a given enclosure depends on the final use of the room and the commitment/criterion to be reached in the design stages [9].

For this reason, in such a case in which rooms have an intended use for spoken word, current regulations of each country sets a maximum value for the RT, which should not be exceeded. In Table 1 it is showed those minimum requirements for the RT in different countries given the different uses of the spaces.

Table 1. RT minimum requirements in different countries.

Country	Type of Room	Requirement RT	Frequency Band	Comment
Spain [34]	classrooms and conference rooms	0.7 s	500–1000–2000 Hz	Unfurnished and unoccupied room. $V \leq 350 \text{ m}^3$
	classrooms and conference rooms	0.5 s	500–1000–2000 Hz	Furnished room. $V \leq 350 \text{ m}^3$
	Restaurants and canteens rooms	0.9 s	500–1000–2000 Hz	Unfurnished and unoccupied room
France [35]	Classrooms and polyvalent rooms	$0.4 \leq RT < 0.8 \text{ s}$	500–1000–2000 Hz	Furnished and unoccupied room. $V \leq 250 \text{ m}^3$
	Classrooms and polyvalent rooms	$0.6 \leq RT < 1.2 \text{ s}$	500–1000–2000 Hz	Furnished and unoccupied room. $V > 250 \text{ m}^3$
	Restaurant (School)	$0.4 \leq RT < 0.8 \text{ s}$	500–1000–2000 Hz	Furnished and unoccupied room. $V \leq 250 \text{ m}^3$
	Restaurant (School)	$0.6 \leq RT < 1.2 \text{ s}$	500–1000–2000 Hz	Furnished and unoccupied room. $V > 250 \text{ m}^3$. Special study required
	Sport	0.6 s	500–1000–2000 Hz	Furnished and unoccupied room. $V \leq 250 \text{ m}^3$
Portugal [36]	Sport	$RT \leq 0.15\sqrt[3]{V}$	500–1000–2000 Hz	Furnished and unoccupied room.
	Sport	$RT \leq 0.12\sqrt[3]{V}$	500–1000–2000 Hz	Furnished and unoccupied room. With Public address
	Auditory, conference and polyvalent rooms	$RT \leq 0.12\sqrt[3]{V}$	500–1000–2000 Hz	Furnished and unoccupied room. if $V < 250 \text{ m}^3$.
	Auditory, conference and polyvalent rooms	$RT \leq 0.32 + 0.17 \log V$	500–1000–2000 Hz	Furnished and unoccupied room. if $250 \leq V < 9000 \text{ m}^3$.
	Auditory, conference and polyvalent rooms	$RT \leq 0.05\sqrt[3]{V}$	500–1000–2000 Hz	Furnished and unoccupied room. Furnished $\geq 9000 \text{ m}^3$.
Belgium [37]	classrooms and conference rooms	$0.35 \log(1.25V)$	500–1000–2000 Hz	Unfurnished and unoccupied room.
	Sport	$\log(V/50)$	500–1000–2000 Hz	Unfurnished and unoccupied room.
	Restaurant (School)	1.0 s	500–1000–2000 Hz	Unfurnished and unoccupied room.

Table 1. Cont.

Country	Type of Room	Requirement RT	Frequency Band	Comment
United Kingdom [38]	Classrooms (primary school)	$RT \leq 0.6 s^1$ $RT \leq 0.8 s^2$	500–1000–2000 Hz	Furnished and unoccupied room.
	Classrooms (secondary school)	$RT \leq 0.8 s^1$ $RT \leq 1.0 s^2$	500–1000–2000 Hz	Furnished and unoccupied room.
	Lecture rooms	$RT \leq 0.8 s^1$ $RT \leq 1.0 s^2$	500–1000–2000 Hz	Furnished and unoccupied room. Fewer than 50 people
	Lecture rooms	$RT \leq 1.0 s^1$ $RT \leq 1.0 s^2$	500–1000–2000 Hz	Furnished and unoccupied room. More than 50 people
	Gymnasium/activity studio	$RT \leq 1.5 s^1$ $RT \leq 2.0 s^2$	500–1000–2000 Hz	Furnished and unoccupied room.

As can be observed in Table 1, in some country regulations there is some limit values for not occupied enclosures, furnished or unfurnished, or depending on the room volume. These considerations inherent in the regulations of each country will be taken into account in the proposed tool to define minimum and maximum values of RT.

Finally, in the design phase of the project these values will be used to define the range that allows us to check if the RT in a room will be acceptable or not, in accordance with its characteristics. In addition, the definition of an upper limit of RT will ensure the information coming from the sound source is intelligible inside the room. Furthermore, the establishment of a lower limit will ensure a suitable room acoustic performance.

4. Proposed BIM Framework for Acoustic RT-Based Design in Indoor Areas (BFRT)

The proposed BIM Framework based on RT (denoted as BFRT) is developed as an integrated tool for the assessment and optimisation of RT of interior spaces in buildings. The proposed tool generates a set of possible solutions from an extensive search for possible combinations of existing materials for the different surfaces of the room (wall, floor and ceiling) included in a database, so that the RT becomes suitable for the prescribed uses of the room. For this purpose, this work develops an optimization algorithm using combinations of finishing materials to propose alternatives of constructive design but always fulfilling the regulatory limits. The aim of this proposal is to help designers in the decision-making process in the initial stages of design.

The proposed framework is composed of 3 stages as shown in Figure 2. In the **Stage 1—BIM Modelling**, the building under consideration is designed and modelled using BIM, with special emphasis in including the information of constructive elements, materials, etc. In this stage, this modelling must ensure that all the necessary information (geometric and not geometric) of the project is available, accurate and reliable. After that, it is performed the zoning of the model and allocation of final uses for the building rooms. The **Stage 1** was developed using Autodesk Revit software [39], which is based on the building parametric information modelling.

In the **Stage 2—Data extraction and RT calculation**, the extraction of geometric data (dimensions of the enclosures, volume, areas of surfaces, etc.) and non-geometric data (item type, materials, etc.) from the BIM model is performed. This stage was developed using the Dynamo software [40] (as it is shown in Figure 3). At this stage, a connection with an external database of materials is made to gain access to absorption coefficients and price of the materials used in the model. From the data obtained from the BIM model and database, it is calculated the current RT and the targeted or desired RT (RT objective) is established, as well as the range of acceptance for each room according to their use and regulations in the specific country where the project is run.

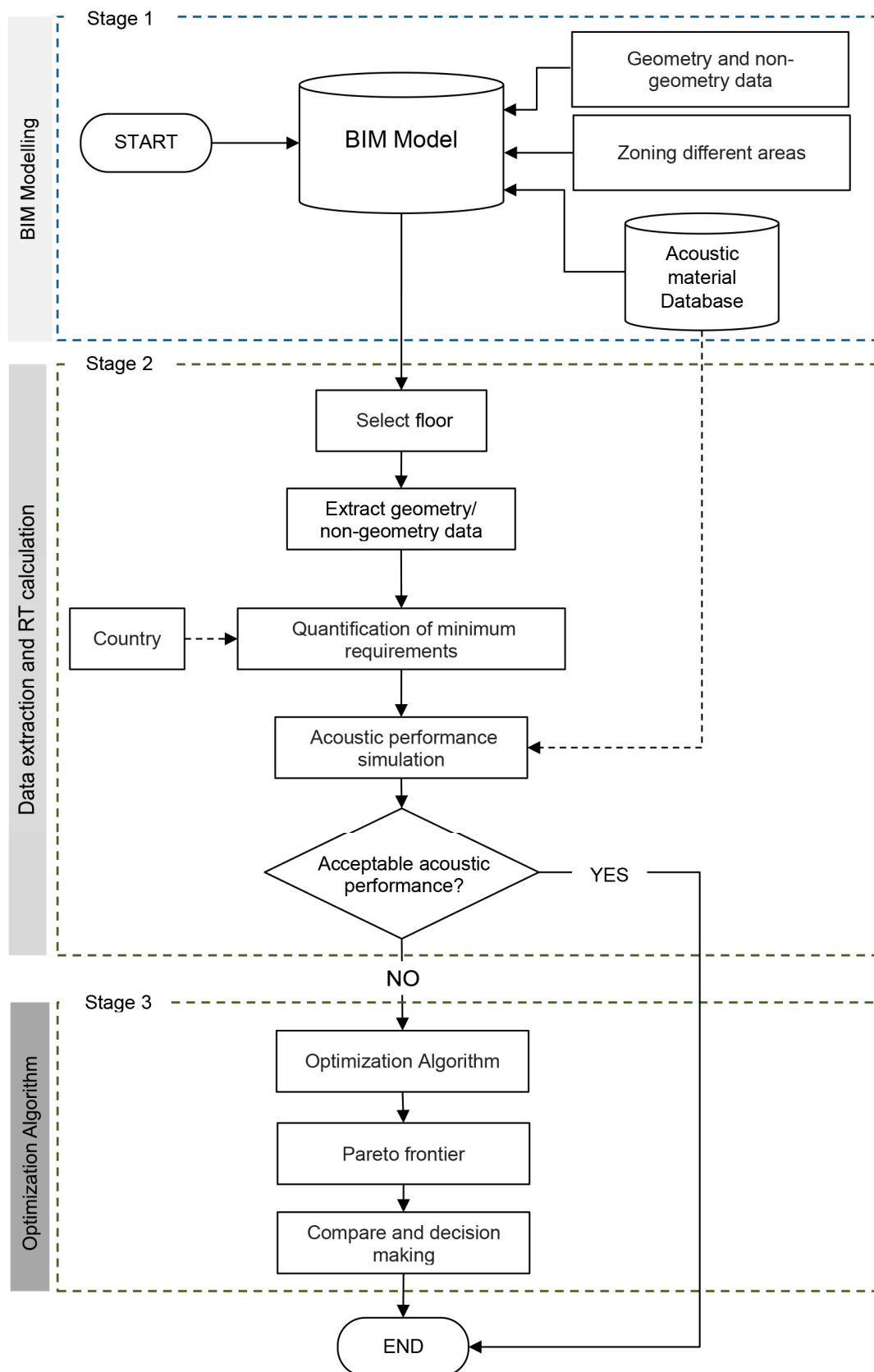


Figure 2. Proposed acoustic BIM framework.

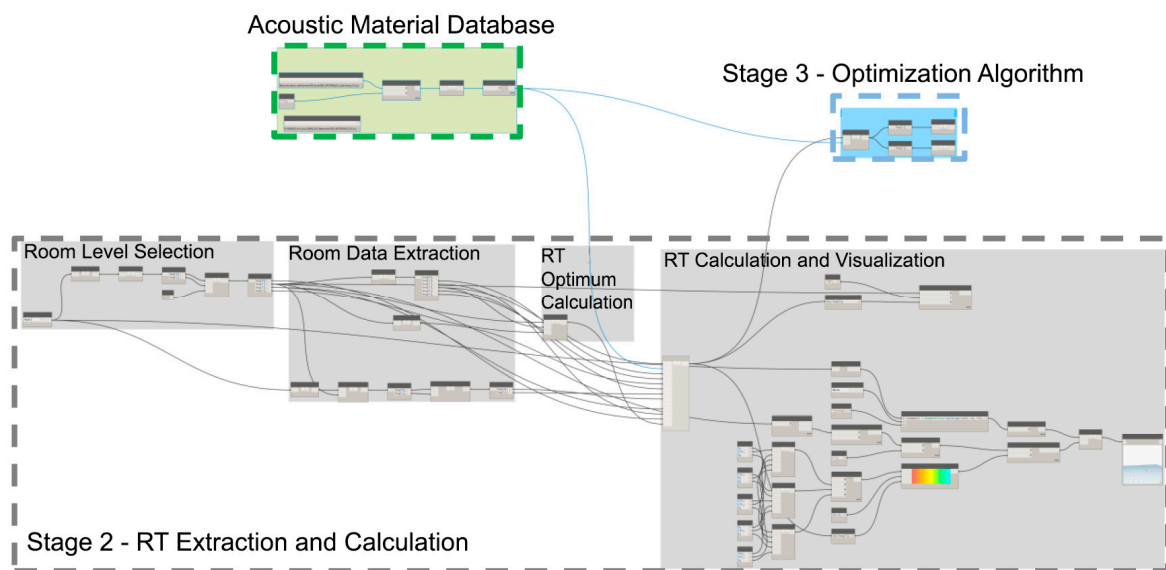


Figure 3. BFRT system in Dynamo (Stages 2 and 3).

Just in the case that the initial RT of the room (calculated from the original design) becomes unacceptable, it is undertaken the application of the optimization algorithm defined in Stage 3. If the initial RT were acceptable, the proposed procedure ends at this point. In any case, once the calculations are finished, the results are displayed in the Dynamo interface.

In those cases, in which the RT is not acceptable, the **Stage 3—Optimization Algorithm** starts. Now, these cases are evaluated using an algorithm that performs the search for the optimal solution of the RT using a branch and bound algorithm [41]. This stage is carried out using Dynamo software (Figure 3). The optimization is based on the search for all the appropriate combinations of existing materials in the database that can be used in the different surfaces of the room (wall, floor and ceiling) to accomplish the targeted RT. After performing this search, the algorithm shows a set of optimal solutions by the Pareto frontier. These stages are described in detail in the following Sections 4.1–4.3 of this work.

4.1. Stage 1—BIM Modelling

Prior to the design process of the building in BIM, it is necessary to define several multiple shared parameters (Figure 4) with that serve to save and communicate information about the BIM model components. The advantage of the shared parameters is that they can be used in other projects or ensembles of projects without the need to re-create them, as they are stored in different files separated from the main project files.

The above-mentioned shared parameters are required for the subsequent process of calculation and optimization of the acoustic room behaviour. In this case, it will be necessary to generate four shared parameters associated with the different components of the model. Table 2 shows the parameters used for the development of the BFRT.

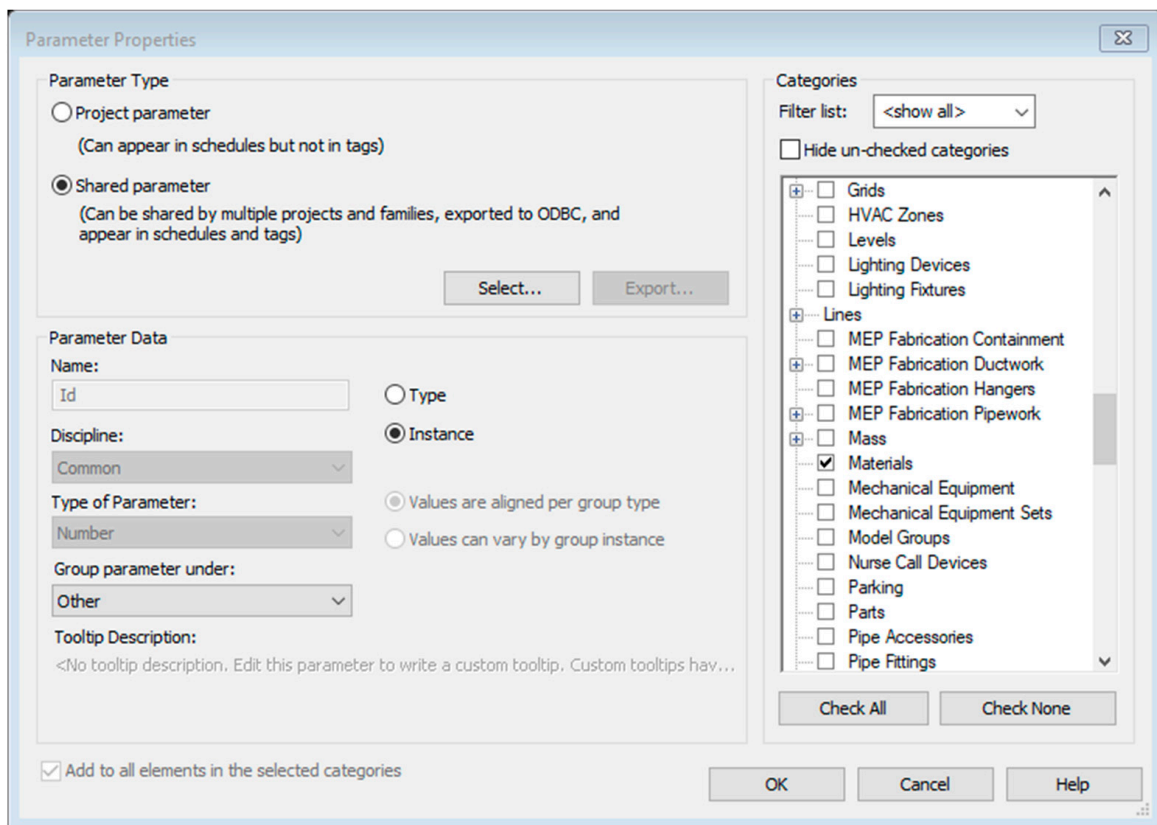


Figure 4. Example of creating shared parameters for its further use in BIM.

Table 2. Shared parameters of the BIM model.

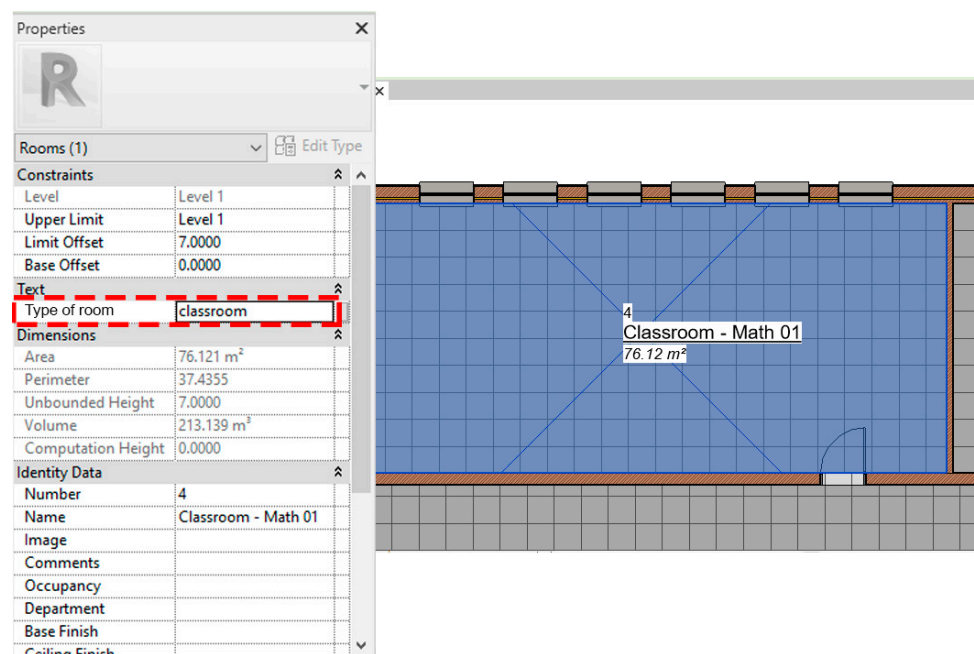
Shared Parameter	Definition	Type Parameter	Caegory
RT	Reverberation time of room	Number	Room
Type room	Type of room	String	Room
Id	Identification number of material with Acoustic material Database	Number	Material/Door/Window
A_{furn}	Equivalent sound absorption area of furniture	Number	Room

Once the parameters are defined, it is accomplished the design and construction of the BIM model of the building (it would be also possible to use an already developed model and import the shared parameters, if it were the case). A minimum Level of Development (LOD) 300 is required for the analysis. Then, it should subsequently be defined the different constructive elements (walls, floors, ceilings, doors, windows, etc.) to be used in the rooms under analysis and the *Id* parameter is assigned to each material comprising the components. This parameter is used to properly relate the materials of the model with the external database of acoustic parameters of construction materials (AM database). This database must be defined and set up at this stage, and it is connected with the BFRT system. The AM database is composed of different fields (see Table 3), and it contains all the necessary information on materials for the making of calculations and the subsequent optimization. Its content and information have been obtained after a review of the currently materials available in the market and the information provided by the manufacturers. Users can easily modify the database manually, which may be broaden with new materials.

Table 3. Basic information scheme of the AM database for each material.

Element	Data-Type	Description
Name	String	Name or description of the construction material
Id	Number	Identification number of the acoustic material
α	Number	Absorption coefficient in the 125–250–500–1000–2000–4000 Hz frequency band.
Location	Number	Each finish material has a specific type of location (wall or/and ceiling or/and floor).
Cost	Number	Cost of material (€/m ²)

The next step is the zoning of the building. To accomplish this, it will be required the identification and definition of the use of each enclosure using the shared parameter Type room (Figure 5). In addition, in the event of the regulations of the country specify that the RT must be calculated considering that the room is furnished, the parameter A_{furn} must be fulfilled with the quantity corresponding to the amount of equivalent sound absorption area of the furniture that the designer should consider.

**Figure 5.** Example of Type room shared parameter setup.

4.2. Stage 2—Data Extraction and RT Calculation

This stage is composed of 4 groups of nodes developed using Dynamo, which will be defined in the following sections (Figure 3) i.e., Room Level Selection, Room Data Extraction, RT Optimum Calculation and RT Calculation and Visualization. Some of the used nodes are included in the basic library of Dynamo, while the more complex functions have been developed as nodes in a Python script to avoid the limitations from the basic nodes.

4.2.1. First Node Group—Stage 2: Room Level Selection

This first group is composed of 3 nodes. For RT assessment is necessary to gather some data from the BIM model. To accomplish this, firstly it will be necessary to choose the model floor for which the assessment is going to be performed. The levels node is used from the bookstore of Dynamo to select the corresponding plant model. Once the floor is selected, using the Room at level node it is performed a filtering process of the rooms classifying them by its floor (Figure 6). At this point, the Filter Room Regulation node makes a selection of rooms depending on the country where the project is located and the

final intended use. In this node, only those rooms with a prescribed RT value addressed in regulations will only be selected for its subsequent evaluation.

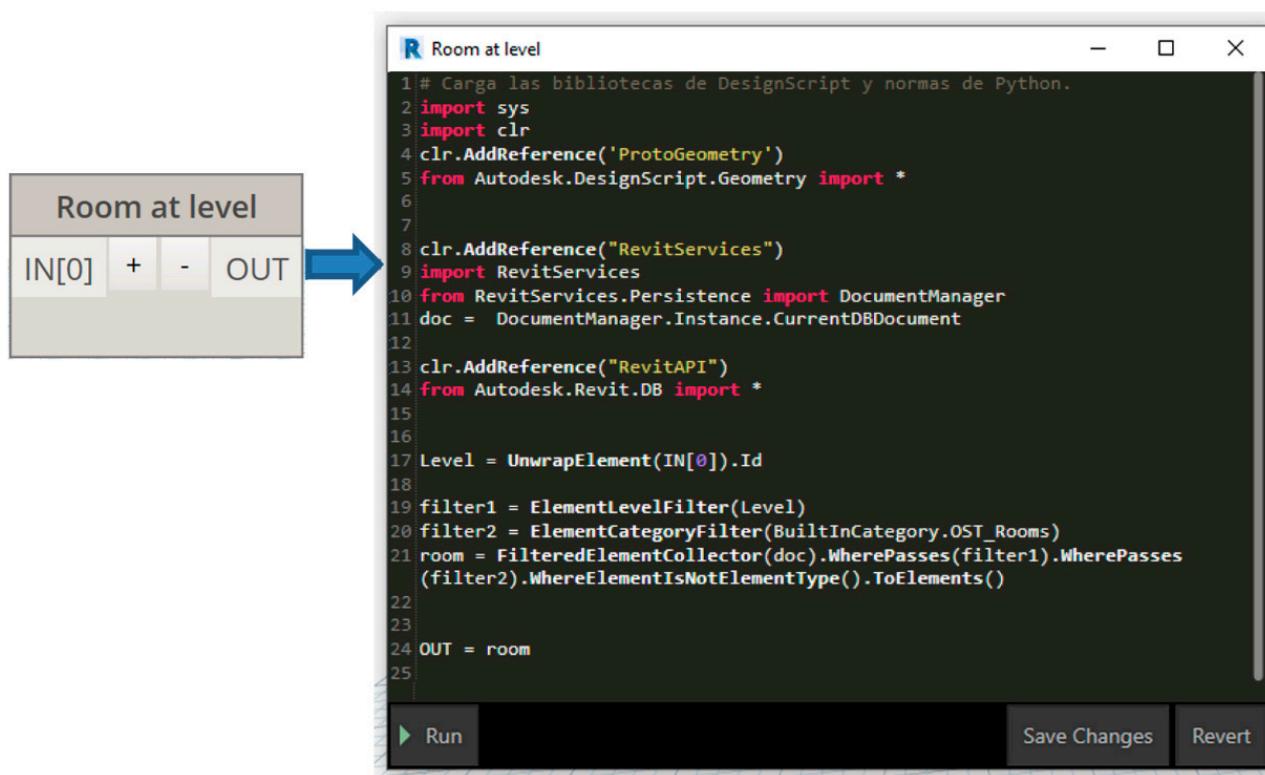


Figure 6. Room at Level Node.

4.2.2. Second Node Group—Stage 2: Room Data Extraction

The second group of nodes is comprised of 4 nodes. They extract information such as geometric data (dimensions, area, and volume) and non-geometric data (finishing materials, Id of the materials, element type, location, and the A_{furn} parameter) from the elements of the BIM model. Data Room and Element Room nodes extract the information related to the rooms selected by the First Node Group, while the Door/Window at Level and Door/Window Released nodes extract the information related to the doors and windows. To accomplish this, the Door/Window at room node filters out doors and windows of the model and then they associate them to the room where they are located. Finally, the Door/Window Released node obtains the necessary information for performing the calculation process.

4.2.3. Third Node Group—Stage 2: RT Optimum Calculation

Once data from the model have been extracted in the preceding sub-stages, it is calculated the minimum RT requirements demanded by regulations. For this task Regulation RT node has been developed. This node assigns the limit RT value depending on the country in which the project is going to be implemented and the room use, obtaining as output the maximum values that each of the rooms should meet. In a first approach of this framework, it has been implemented the limit or recommended values from the regulations of the following countries: Spain, Portugal, Belgium, Denmark and the United Kingdom. If new country regulations are required for RT assessment in other countries than the pre-set ones, the designers can add their own restrictions by editing de Regulation RT node. For this purpose, the code of the Regulation RT node must be edited, simply adding the new country, the types of room and the associated RT requirement values.

As noted in Section 3.2, it is necessary to set both the lower and upper limits to evaluate if the RT for a specified room can be acceptable or suitable in the design phase. In this way, if the RT belongs to the interval defined by those limits, it is ensured a correct acoustic behaviour of the room. The upper limit value (RT_{lim_sup}) of the acceptance interval corresponds to that established by the regulations as the value that should not be exceeded (see Table 1). In addition to this upper limit, it is necessary to establish the lower limit of the acceptance range to ensure a minimum suitable RT (RT_{lim_inf}) so that the speech intelligibility is reasonably good at all points in the room.

For this purpose, it has been set by default that the lower RT limit (RT_{lim_inf}) will be a value 20% lower than the upper limit RT_{lim_sup} . In this issue, the recommendation of DIN 18041 standard has been chosen, although the designer could set a different value or other requirement according to his own criterion (see Figure 7). In this sense, the value corresponding to the middle of the interval defined by both limits, RT_{lim_inf} and RT_{lim_sup} , is accordingly denoted as RT_{target} .

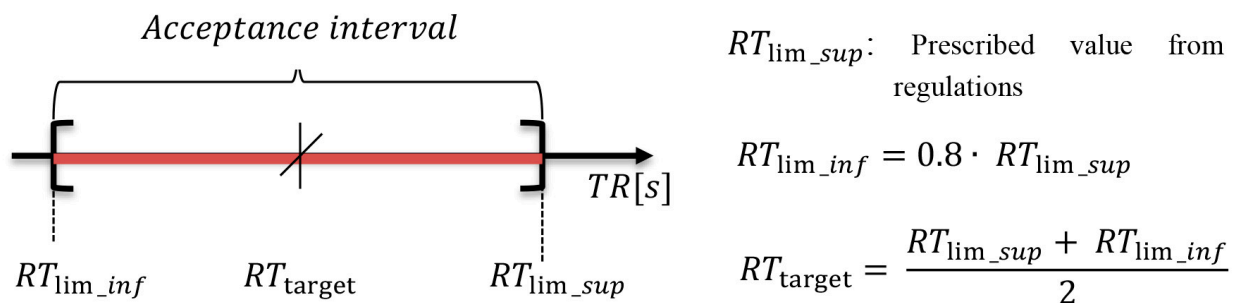


Figure 7. Acceptance interval for the RT from the regulatory limits.

4.2.4. Fourth Node Group—Stage 2: RT Calculation and Visualization

Finally, the last group of nodes needs to perform the calculation of the RT from the data obtained through the previous node groups. The RT will be calculated for each room from the finishing materials defined in the initial design. The calculation is made using the absorption coefficients of materials provided by the AM database for the mid frequencies (500–1000–2000 Hz) and Equation (1) shown in Section 3.2. In those cases, in which regulations would require to consider the room furnished -that is to say, the equivalent sound absorption area of the furniture-, the A_{furn} parameter absorbent characteristic of each room will be added to the total absorption area.

Then, the RT value obtained for each room is checked upon it belongs to the acceptance interval established in the previous phase. At this moment, a preview of the rooms is displayed to the user in the Dynamo environment, so that those rooms marked in green stands for those ones with the value of the RT inside the acceptance interval, being marked in red otherwise. For those enclosures in which the RT value falls in the acceptance interval, the process finishes and this solution is taken as a valid one with the initially defined finishing materials. Lastly, the values of the RT obtained are exported to the model BIM to enrich and complete the information contained in the model database related to the acoustic behaviour of the building.

4.3. Stage 3—Optimization Algorithm

In this Stage 3 the optimization process is performed, in a Dynamo environment. This process is carried out over the rooms whose RT does not belong to the region of acceptance. The objective of this algorithm is twofold, firstly it tries to find out different design solutions to adapt the original RT to the prescribed targeted RT (see Figure 7) and secondly, it looks for minimizing the total cost, by the replacement of finishing materials once the AM database is connected. The information on materials included in the AM database is then used for proposal of new solutions in the optimization process. As a result, different solutions are shown, ordered as their average absorption coefficient increases.

Table 4 shows different types of action made for optimization, according to the replaced materials for the finishings of the room (wall, ceiling or floor) and their possible combinations.

Table 4. Types of optimizations according to the replaced material.

Type	Replaced Material
Type 1	Replace the wall
Type 2	Replace the ceiling
Type 3	Replace the floor
Type 4	Replace the wall-ceiling
Type 5	Replace the wall-floor
Type 6	Replace the ceiling-floor
Type 7	Replace the wall-ceiling-floor

To determine the possible potential solutions that would allow us to adapt the RT of the room, the implemented algorithm uses the branch and bound technique [41]. This technique is frequently used to solve optimization problems through the generation of a space of solutions defined in a tree (Figure 8). The use of this technique has the purpose of searching for a set of solutions that meet one criterion previously established, through a systematic path by the tree of solutions.

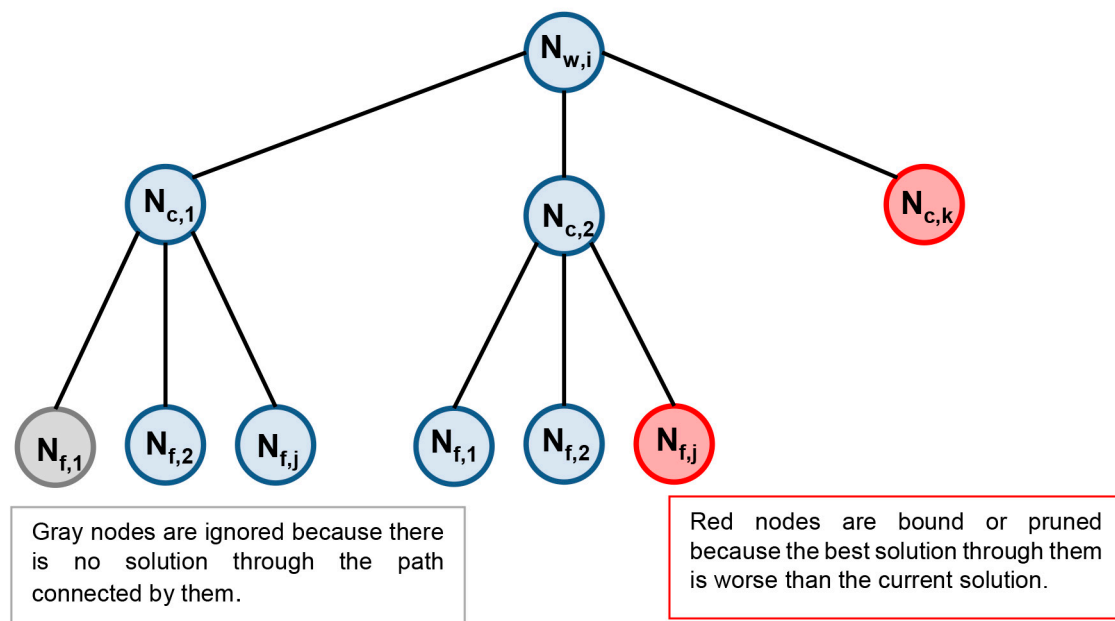


Figure 8. Branch and bound algorithm using to adapt the RT.

So, this procedure discards large subsets of unsuccessful candidates on the basis of the use of upper and lower limits by following different paths. The efficiency of this method depends mainly on the branching procedure of nodes and the strategy of bounding to remove those nodes that are not a feasible solution.

For this study, a FIFO (First In First Out) strategy of branching has been chosen, in which the path through the search space is made in the width of the tree. With regard to the bounding strategy, the range of acceptance interval of the RT is taken into account.

Thus, the procedure in the stage 3 remains as follows:

1. From the TR_{lim_sup} y TR_{lim_inf} limits of the acceptance interval, it is possible to calculate the minimum acoustic absorption surface (A_{lim_inf}) y and the maximum

acoustic surface absorption ($A_{lim\ sup}$) that the room under analysis should have. The bounding strategy is set from the Equations (4) and (5),

$$A_{w,i} + A_{c,k} + A_{f,j} \geq A_{lim\ inf} \quad (4)$$

$$A_{w,i} + A_{c,k} + A_{f,j} \leq A_{lim\ sup} \quad (5)$$

where $A_{w,i}$ is the total absorption surface area corresponding to a wall coated with the i -th material; $A_{c,k}$ is the total absorption surface area corresponding to a ceiling coated with the k -th finishing material; and $A_{f,j}$ is the total absorption surface area corresponding to a floor with the j -th finishing coating material, i.e.:

$$A_{w,i} = \alpha_{w,i} \times S_w \quad (6)$$

$$A_{c,k} = \alpha_{c,k} \times S_c \quad (7)$$

$$A_{f,j} = \alpha_{f,j} \times S_f \quad (8)$$

In the above equations $\alpha_{w,i}$ is the average absorption coefficient of the wall coated with the i -th material; S_w it is the total surface area of the wall; $\alpha_{c,k}$ is the average absorption coefficient of the ceiling coated with the k -th material; S_c is the total surface area of the ceiling; $\alpha_{f,j}$ is the average absorption coefficient of the floor covered with the j -th material; and S_f it is the total surface area of the floor.

- For each individual solution that meets the acceptance criterion, the objective functions are computed. These functions are two: the first one denoted as C_i is the cost of the investment (Equation (9)) and the second one is denoted as D_i (Figure 9) which is the absolute value of the difference between the total absorption surface area that provides such a solution with respect to the optimal absorbent surface area (A_{target}) of the enclosure (Equation (10)).

$$C_{ijk} = p_{w,i} \times S_{w,i} + p_{c,k} \times S_{c,k} + p_{f,j} \times S_{f,j} \quad (9)$$

$$D_{ijk} = |A_{target} - A_{ijk}| \text{ being } A_{ijk} = A_{w,i} + A_{c,k} + A_{f,j} \quad (10)$$

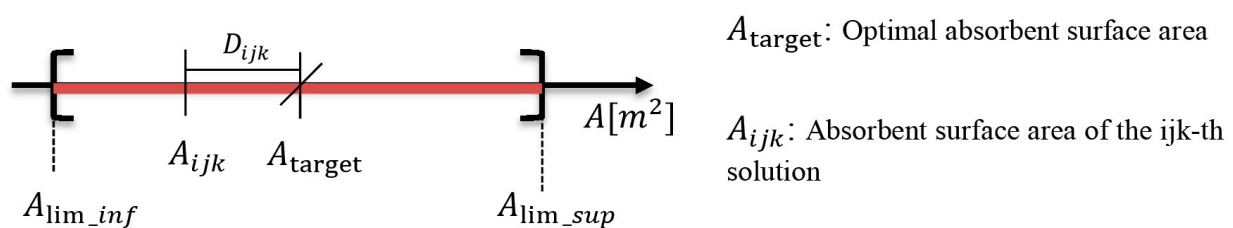


Figure 9. Calculation of D_{ijk} objective function.

In the above equation $p_{w,i}$ is the cost of the i -th finishing material covering the wall surface, $S_{w,i}$ being the total surface area of the walls coated with the i -th finishing material. $p_{c,k}$ is the cost of the k -th finishing material that coats the ceiling surface. $S_{c,k}$ is the total surface area of the ceiling coated with the k -th finishing material. $p_{f,j}$ is the cost of the j -th finishing material that covers the floor surface and $S_{w,j}$ is the total surface area of the floor covered with the j -th finishing material.

- Once obtained the set of solutions for the studied problem, the optimum solutions are calculated using of the Pareto front or frontier. The criterion of optimization has been the minimization of the cost and the difference between the absorbent surface area of the solution and the optimum absorbent surface area. The Pareto front is the set of possible solutions of optimization that are not dominated; a non-dominated solution being a solution that is not dominated by any other solution. The optimal

Pareto solution will be that solution P_i such that there is no other solution P_j that will improve in a goal without becoming worse at least one of the other ones.

- This algorithm ends by showing the solutions that belong to the Pareto fronts corresponding to each one of the 7 types of actions proposed in Table 3. Thus, the designer will be able to choose between the proposed solutions, as they all fulfil the criterion of a suitable RT.

5. Results: Case Study

In this section, the application of the proposed methodology is illustrated, using a study case. This example aims to show the type of solutions found and the potential of the proposed methodology to be applied in the design process.

5.1. Building for the Case Study

The proposed framework (BFRT) was applied to a building to be used for educational purposes. The building has a design area of 2500 m² with two floors (Figure 10), and is located in the city of Granada in Spain. The building comprises of different rooms for different uses (classrooms, laboratories, offices, conference rooms, library, dining, warehouses and facilities). Table 5 shows a summary of the materials used in the different rooms.

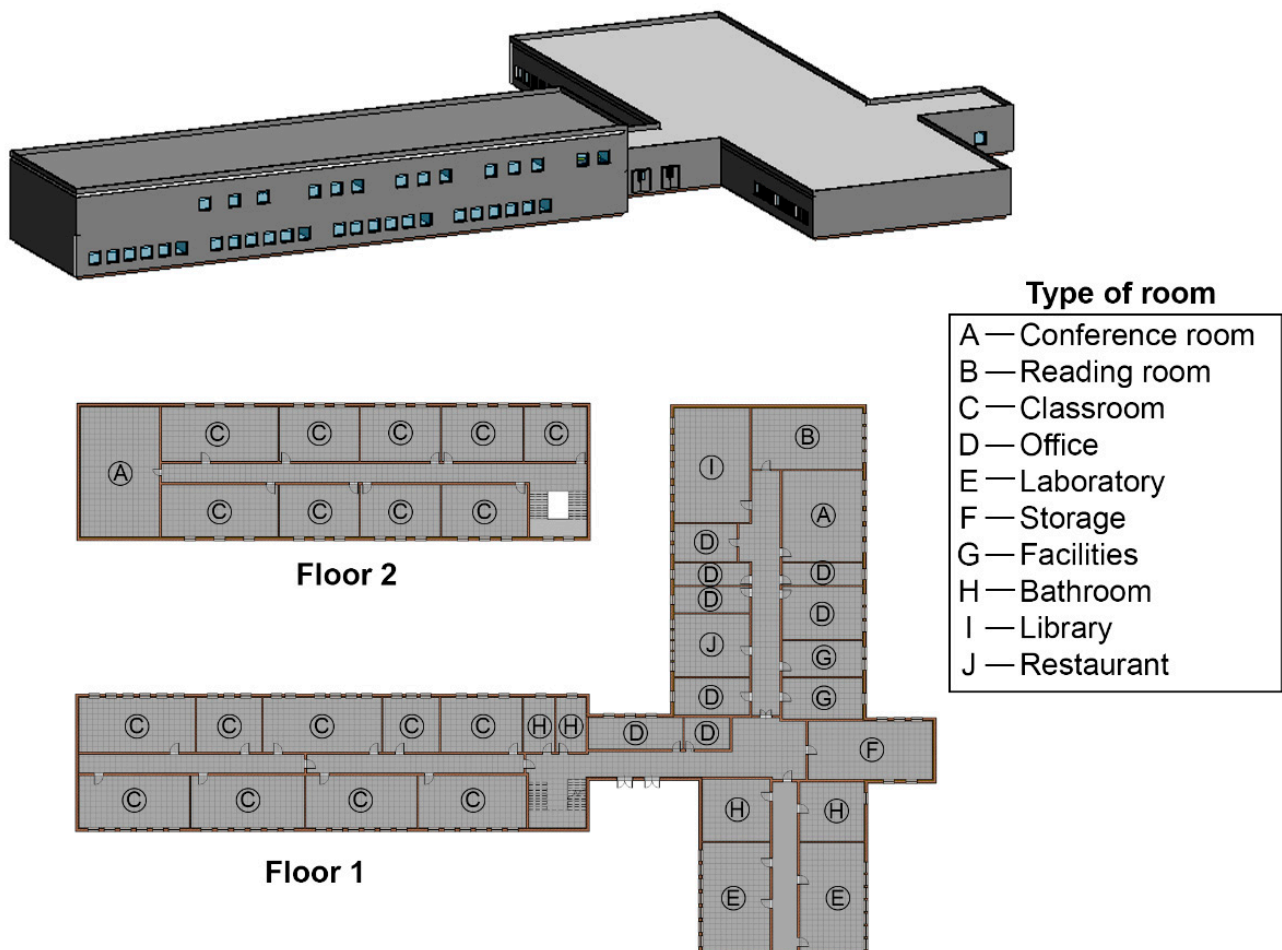


Figure 10. BIM 3D model of the educational building taken as a study case.

Table 5. Finishing materials according to the type of room.

Type of Room	Element	Finishing Material
Classroom/Reading room/Office/Laboratory	Wall	Plaster
	Ceiling	15 mm gypsum board
	Floor	Ceramics
Storage/Facilities/Bathroom	Wall	Tile
	Ceiling	Ceiling
	Floor	Terrazzo
Library/Conference room	Wall	15 mm gypsum board
	Ceiling	Drop ceiling
	Floor	Parquet

The windows are composed of glazed surface area in the 90% of its surface, while the doors are made entirely of wood. The height of the rooms is 3.00 m. The 3D BIM model was created using Autodesk Revit 2021 and Dynamo 2.1.

5.2. Data Extraction and RT Calculation (Application of the Stage 2 of the Proposed Procedure)

Once the building is modelled, the package of nodes developed in Dynamo extracts the geometric and non-geometric data (related to its Node Group). Firstly, it performs a filtering of the rooms that have a regulatory requirement to fulfil. Given that this building is located in Spain, in accordance with the applicable regulations, only those rooms with a declared use of classroom, conference room and restaurant (see Table 1) must meet the prescribed limits. On the basis of these data, the RT is computed. Figure 11 shows the calculated values for the RT in the different selected rooms, as well as its use. Figure 12 shows the display of the RT fulfilment according to the Spanish regulation in the different floors of the BIM model. As shown in Figure 12 only the room with the use of dining room/cafeteria meets the criteria for acceptance of the RT.

A	B	C	D	E	F
Name	Level	Ud	Type of room	RT	Volume
A01	Level 1	Ud_1	classroom	0.76	120.26 m ³
A02	Level 1	Ud_2	classroom	0.79	217.80 m ³
A03	Level 1	Ud_3	classroom	0.75	103.59 m ³
A04	Level 1	Ud_4	classroom	0.77	149.67 m ³
A05	Level 1	Ud_5	classroom	0.78	194.87 m ³
A06	Level 1	Ud_6	classroom	0.78	200.34 m ³
A07	Level 1	Ud_7	classroom	0.78	196.52 m ³
A08	Level 1	Ud_8	classroom	0.78	190.18 m ³
A09	Level 1	Ud_9	classroom	0.87	213.14 m ³
TEC	Level 1	Ud_12	classroom	0.88	249.21 m ³
TECFP	Level 1	Ud_13	classroom	0.88	237.93 m ³
Laboratory	Level 1	Ud_15	classroom	0.8	244.88 m ³
Conference room 01	Level 1	Ud_20	conference	0.81	247.51 m ³
Cafeteria	Level 1	Ud_23	restaurant	0.78	158.66 m ³
Reading room	Level 1	Ud_30	classroom	0.8	229.43 m ³
A10	Level 2	Ud_31	classroom	0.79	214.06 m ³
A15	Level 2	Ud_32	classroom	0.79	205.55 m ³
A16	Level 2	Ud_33	classroom	0.77	141.03 m ³
A11	Level 2	Ud_34	classroom	0.77	146.87 m ³
A12	Level 2	Ud_35	classroom	0.77	146.87 m ³
A17	Level 2	Ud_36	classroom	0.77	141.03 m ³
A18	Level 2	Ud_37	classroom	0.77	150.82 m ³
A13	Level 2	Ud_38	classroom	0.77	149.67 m ³
A14	Level 2	Ud_39	classroom	0.76	114.51 m ³
Conference room 02	Level 2	Ud_40	conference	0.74	346.95 m ³

Figure 11. Room schedule in the BIM model with RT calculated values.

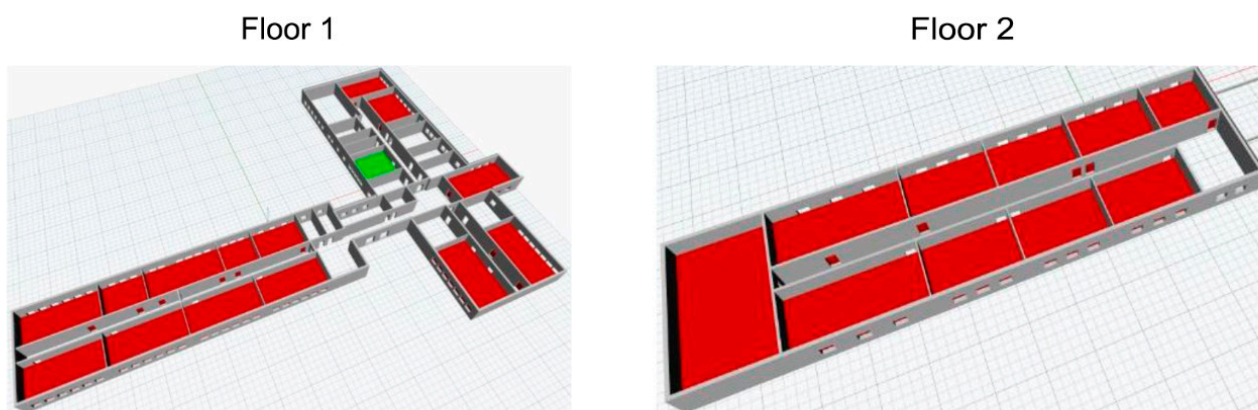


Figure 12. Visualization of the compliance with the RT limit values according to the type of room on the ground floor (project located in Spain).

5.3. Optimization (Application of Stage 3 of the Proposed Procedure)

Once it has been identified those rooms whose RT is not appropriate, a further analysis is performed applying the “Optimization Algorithm” node developed in Stage 3. The calculation is made automatically for all the on the same floor rooms that do not comply with the predefined criteria, in accordance with the acceptance interval based on the Spanish regulations.

An example of the results obtained through the optimization process is shown in Figure 13 for the “A” room whose use is classroom. The Branch and Bound technique is used to determine all the possible potential solutions. Every solution A_{ijk} providing a total absorption surface area contained in the interval $[A_{lim,inf}, A_{lim,sup}]$ is stored and classified according to the replaced material (i.e., Type 1, . . . , Type 8). Based on this set of solutions classified for each typology, the optimum solutions are then calculated by making use of the Pareto frontier. In this sense, in this study case a database was used containing $i = 81$ wall materials, $k = 207$ ceiling coated materials and $k = 25$ floor materials. In fact, these numbers depend on the number of materials used by the design team. Accordingly, the size of the solution space is $n = 419,175$ cases. The algorithm has generated 46,437 feasible solutions. From these solutions and in different colour Figure 13 shows the Pareto fronts for each of the types of intervention defined in Table 4, based on the criteria of minimizing total cost and difference of absorption. In this figure, it can be also observed the results obtained for the different choices of elements for optimization: Wall (w), Ceiling (c) and Floor (f), as well as their diverse combinations. In type 1 (only wall) there are no solutions starting from the existing database. For the rest of elements (see Table 4) two sets of Pareto fronts can be identified.

According to the Pareto fronts obtained for the different elements, the different types can be grouped into two sets. The first set comprises the types 3, 2 and 6, in which all the solutions have a cost equal to or greater than 4000 €. The second set comprises the types 4, 5 and 7. In this set, the solutions provide values near to the optimal absorbent acoustic performance, but with a total cost less than the Pareto fronts in the first set.

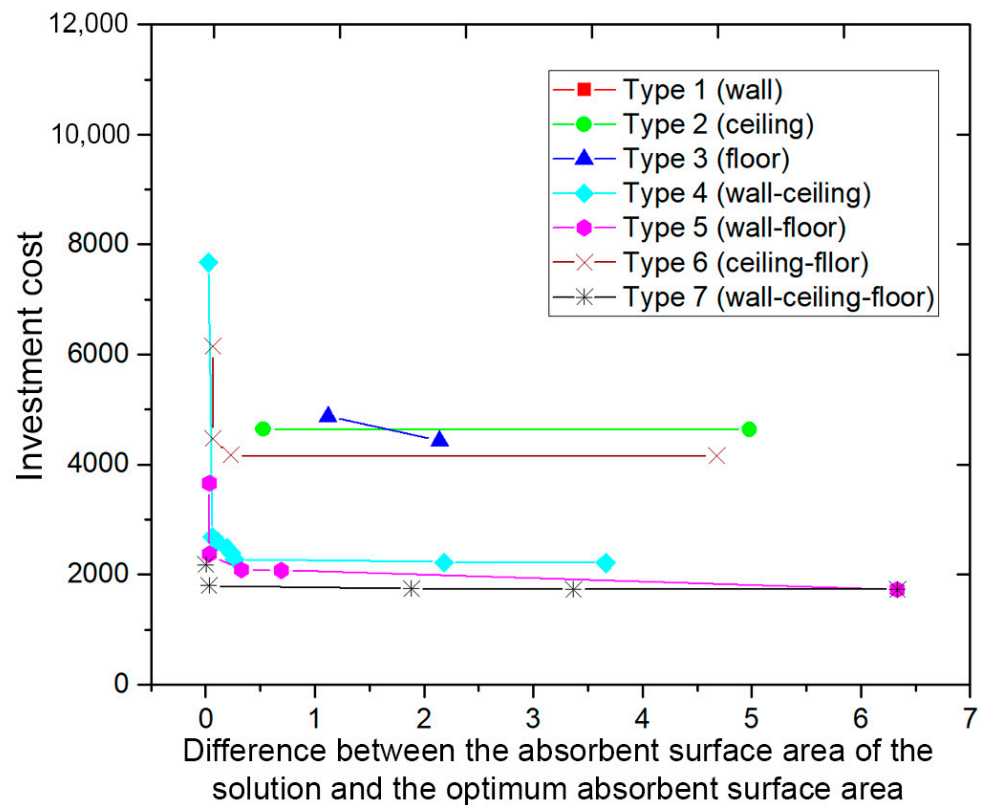


Figure 13. Results obtained from the Pareto frontiers calculation in Stage 3 for the optimization based on the acoustic absorption of materials and their investment cost. Red square—Pareto front type 1. Green dot—Pareto front type 2. Blue Triangle—Pareto front type 3. Cyan rhombus—Pareto front type 4. Purple hexagon—Pareto front type 5. Wine cross—Pareto front type 6. Black Cross—Pareto front type 7.

It is interesting to note that the use of the information provided by the stage 3 of the proposed procedure through the Pareto frontiers can be helpful to the designer/researcher in order to make a final decision by selecting a specific proposal. On the basis on these results, the designer could choose from several solutions depending on the preference for one criterion or another. Thus, the designer could prioritize whether to minimize the cost of the intervention, or minimize the difference between the optimal absorbent area and those provided by the tool, or the number of surfaces to adapt, or the material of the elements to be used in the project. The designer, depending on the level of requirement for acoustic comfort and other specific features or needs of the project, can thus implement this tool to make the final decision.

5.4. Solutions for the Study Case in Different Locations: Comparison of Results

As has been mentioned before, the regulatory requirements of RT vary by country (see Table 1). To assess the versatility of the proposed BFRT framework, the analysis of the same project of the case study has been performed, maintaining the initial configuration but changing the country of location of the building. For this, three different countries with different regulations were chosen and, accordingly, the results obtained are different depending on the selected country, since the regulatory limits established by each country are different. Figure 14 shows the results obtained following the implementation of the Stage 2 of the proposed BFRT to three different locations. It should be noted that the results differ from those previously obtained when the location was set in Spain (see Figure 12).

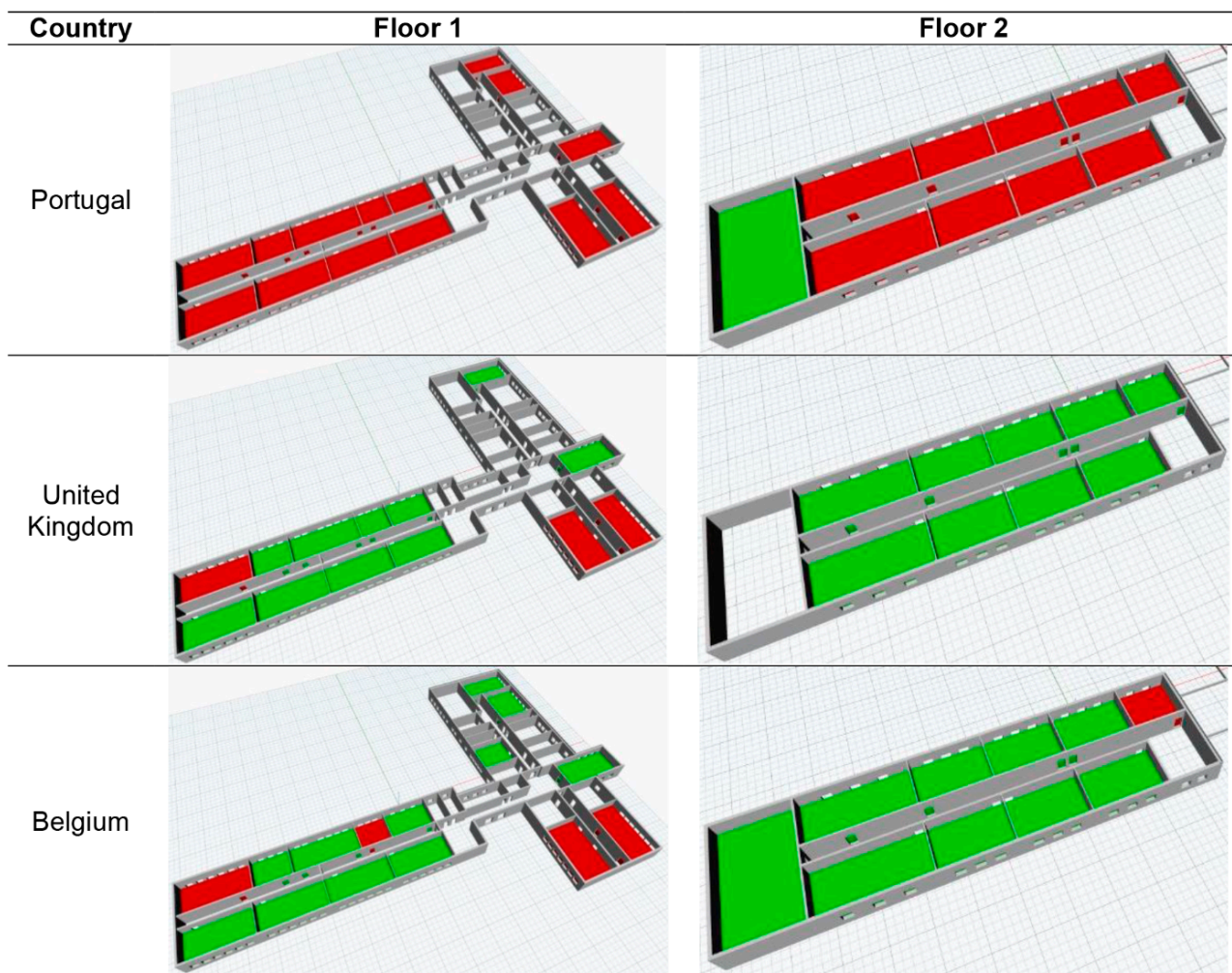


Figure 14. Compliance with the RT limit values by room type and floor for different locations of the study case.

Subsequently, it is interesting to make a comparison of the results obtained in Stage 3. To accomplish it, it has been selected the room of the study case (“A” room whose use is classroom). Figure 15 shows the Pareto fronts after the optimization process performed for this room.

For the case of the optimization of the room case study (classroom) located in Portugal, the algorithm generated 35,211 feasible solutions. If the classroom was located in United Kingdom, 25,642 solutions were obtained and 12,605 ones for the case of Belgium. The number of solutions obtained for each country is different because the RT limits are different for each country: the RT regulatory limits for Portugal is 0.76 s, being 0.8 s in the case of United Kingdom and 0.87 s in the case of Belgium. In this sense, the number of feasible solutions provided by the proposed optimization algorithm is going to depend on the RT regulatory limit established by each region or state, and of the initial finishing materials and the configuration of the rooms in the buildings.

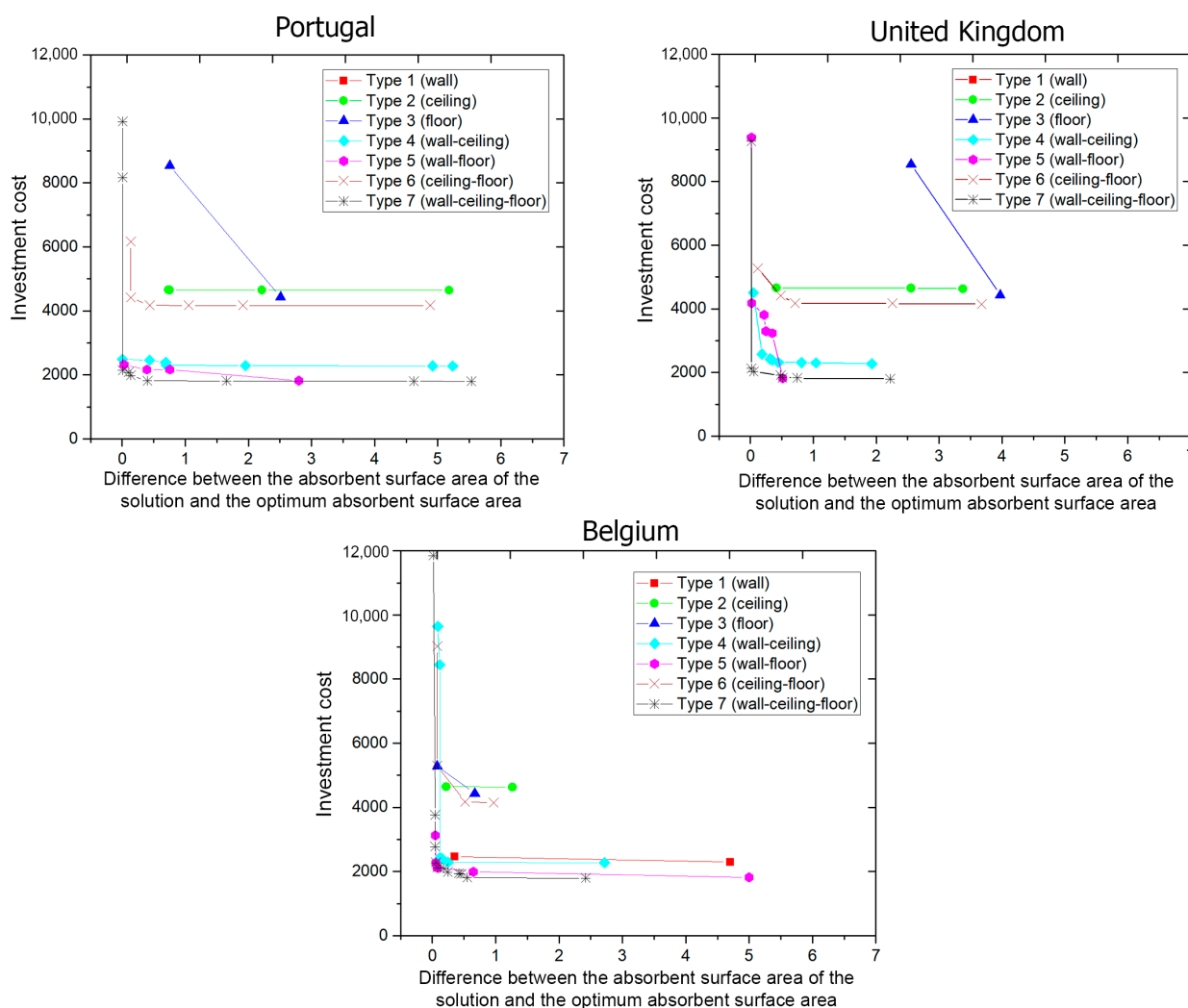


Figure 15. Results obtained from the Pareto frontiers calculation in Stage 3 for the optimisation based on the acoustic absorption of materials and their investment cost for the countries of Portugal, United Kingdom and Belgium. Red square—Pareto front type 1. Green dot—Pareto front type 2. Blue triangle—Pareto front type 3. Cyan rhombus—Pareto front type 4. Purple hexagon—Pareto front type 5. Wine cross—Pareto front type 6. Black cross—Pareto front type 7.

5.5. Discussion

The BFRT proposed framework implements a workflow based on BIM for the assessment and optimisation of RT in buildings. The BFRT framework allows to develop the acoustic analysis of spaces in the BIM design software itself, without having to resort to a specific acoustic software outside of the own BIM frame. This is an important advantage in contrast to other research approaches proposed in other studies which require the use of additional software, such as GIS [23] or Comsol [25].

Therefore, the scientific contribution of this research is the development of a framework for the integration of acoustic analysis in BIM-based software. This framework is developed in Section 4 (Proposed BIM framework for acoustic RT-based design in indoor areas: BFRT). The relevance of the proposed BFRT is that it contributes to solving the current problem of defining the design of spaces with a suitable acoustics according to their prescribed use with two important features: (1) it is carried out during the design stage and (2) it performs a systematic search for a large number of possibilities with a reduced time for analysis.

The BFRT allows the compliance with the limit values of RT depending on the country and its specific regulations to be analysed. The implemented procedure is based on the RT calculation, which is automatically computed for the different rooms of each floor

of a building. In those cases where the value of the RT of the room does not belong to the acceptance interval, the optimization process provides solutions based on changing finishing materials of different surfaces of the walls, floors and ceilings. The design of the interior spaces is essential for a good acoustic conditioning. The selection of materials and composition of the constructive elements in the design phase allows us to anticipate the solution of arguments arising from a poor acoustic behaviour already in the initial design phases of building projects. Consequently, cost savings and better acoustic performance can be provided to building inhabitants compared to addressing the issue in subsequent phases.

The BFRT offers the possibility to evaluate the behaviour of the RT depending on the location of the project since the limit values of the regulations can be included in the optimization process. In this first stage of development of this framework, the designer can supply other limits coming from specific regulations or requirements. This process requires editing the code of the Regulation RT node and a minimum knowledge of VPL and Python scripting in Dynamo is advisable. Results are displayed by using colours in the same interface of the BIM software, which greatly facilitates the visualization of the assessment in the same design interface.

In the proposed framework it has been chosen the optimization algorithm based on the technique of branching and bound since it is a flexible tool for calculating all possible solutions. It should be noted that the application of this procedure for optimization differentiates this research from other proposals that only evaluate the initial design solution and do not provide alternative design options [13,24]. Other multi-objective optimization tools could have been chosen at this stage, but results do not differ mainly from the proposed one, since the objective is that the algorithm does not calculate all possible scenarios for interventions in the rooms. In fact, the results obtained for the study case in the classroom, considering the location of the project in different countries (Spain, Portugal, United Kingdom and Belgium), shows that of the total number of combinations chosen by the branching and bound tool lies between 9% and 33% of the total (Spain: 33%, UK: 16%, Portugal: 23% and Belgium: 9%). So, the algorithm has discarded approximately a 67 to 91% of possible combinations without need to be computed, saving computational time. In this regard, the computation time needed by the proposed algorithm to obtain the results of the floor where the room study case is located (15 rooms) is 117 s and it obtained 639,647 workable solutions for all the different rooms. For the second floor (10 rooms), the computing time was 44 s obtaining 419,441 feasible solutions. The calculations were carried out with an Intel Core i7-9750H computer.

In summary, the main advantages and contributions offered by the application of BFRT in the field of acoustic engineering are: (1) it allows incorporating information related to the acoustic behavior of interior spaces and so the further enhancement of BIM model. In addition, the proposal allows for efficient connection with AM databases; (2) BFRT provides an automatic calculation of RT in all the rooms of the studied floor of a building (no need to re-enter data in other software); (3) Visualization of the fulfilment of the RT requirements in the design software allows the designer to work with a friendly tool for helping in decision-making process in the early design phase; (4) The proposed algorithm based on the technique of branching and bounding allows selecting the combination of finishing materials to obtain an optimal value of the RT without the need to evaluate all possible solutions. This implies a significant saving on computation time in the calculation process; and (5) the framework is flexible, i.e., it allows the user to add easily new RT limits according to the regulations of different countries in the code.

Finally, among the limitations presented by this study, it should be noted that the calculation of RT is based on Sabine's formula. Nevertheless, this formula has been implemented in the framework because national regulations in European countries state that it should be used to assess RT. In further research, complementary methods for the calculation of RT other acoustic parameters will be incorporated into the system.

6. Conclusions

This research develops a framework for the analysis of acoustic behaviour of rooms based on RT parameter (BFRT). Using both a BIM-based methodology and a graphical programming software (Dynamo) it has been developed a framework to support the decision-making process of designers during the early design phase in the field of acoustic conditioning of buildings. The proposed framework is embedded itself in the design software, so facilitating the evaluation of the RT without the need to use other specialized software. This is quite relevant since working time is saved and errors arising from manual data entry of a software to another are avoided. In addition, it allows an easy and automatic evaluation of the RT each time that a modification of the 3D BIM model is considered, showing a display of the results on the same interface design which is really comfortable for the designer.

The BFRT provides a framework for the integration of information on acoustic parameters within the building BIM model. The inclusion of parameters relating to the acoustic behaviour of the building allows additional features of the building to be taken into account and adds new information to the database so that it can be performed the analysis of the acoustic behaviour from the early stages of design in many ways. In this sense, the integration of the proposed BFRT into BIM design software simplifies the process, avoiding further rework and it reduces the time spent in RT assessment. Furthermore, it provides key information to designers for the decision-making process and improves the acoustic performance in buildings construction, which are key aspects in practical work. Finally, the automation of the assessment procedure encourages designers for optimisation of the building acoustic behaviour in their projects from the early stage of design, with the important fact that the acoustic data and parameters become integrated in the BIM model.

Finally, the management and consideration of the acoustic behaviour in the interior spaces from the initial stages ensures a further appropriate acoustic performance of the different rooms. This is an important issue since providing acoustic comfort and ensuring the correct performance of the activities that can be carried out according to its use without the need of subsequent costly and complicated actions in other phases of the project results in relevant time and economical savings and better final performances.

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