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Wooden Rehearsal Rooms from the Construction Process to the Musical Performance

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Abstract: Rehearsal rooms play an important role in musicians' activities to obtain the best results during a performance in front of an audience. Numerous rehearsal rooms are located in complex buildings, such as opera houses and cultural centers, where new research outcomes have led to increasingly complex projects and construction phases. Furthermore, technical complexity has also increased due to the large quantity of used materials and the innovation level of the process. In this context, a new methodology becomes mandatory to control the indoor air quality and the acoustic quality in rehearsal rooms. This paper aims to offer a procedure for rehearsal rooms for large ensembles during the construction and life cycle phases to optimize the indoor environmental quality according to different types of ensembles and repertoires. In particular, rehearsal rooms with wood panel cladding are considered. The proposed methodology is controlled by a digital twin (DT) based on building information modeling (BIM), integrated with acoustic measurements, sensors and actuators aimed at implementing the database in real time. A case study is presented, in which the cladding system is described, the new methodology is applied, and the results are compared with the criteria suggested in the standard ISO 23591.

Keywords: digital twin; room acoustics; acoustic materials

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1. Introduction

As happens to most people, nowadays, musicians spend the majority of the day in an indoor environment (about 80–90%) [1]. They frequent buildings like theaters, complex cultural centers, etc., not only during the musical performance on stage in the main hall, but also to practice music in specific spaces, such as rehearsal rooms, recording rooms, teaching rooms, etc., located in the same context. Therefore, the air conditions inside those rooms become an important aspect, together with the indoor space's acoustic behavior [2,3], which is considered a significant factor for the comfort, together with a healthy environment.

Building projects have started to study indoor air and acoustic comfort in the design and construction stages since it is more difficult to achieve high standards when considering these aspects after construction is complete and because implementation of acoustic specifications at the end of the project is more complex to achieve than if they had been controlled in the beginning phase of the project [4,5].

In complex buildings, such as cultural centers and opera houses, a large amount of space is designed to support the activities of the main hall. Many areas are useful for preparing the show, the scenography or the concert. For musicians' practice in particular, many rehearsal rooms with different volumes, shapes and cladding materials are included. They differ from each other not only because of their dimensions and geometrical properties, but also because of their acoustic response, according to the type of ensemble (number of musicians) and repertoire.

In opera houses in particular, rehearsal rooms for choirs are recommended. In an opera piece, in fact, in addition to the presence of the main and secondary characters, that of the choir is expected. The choir can have different dramaturgical functions, representing the community, a group of priests, farmers, woodland nymphs, etc., and they comment on the actions of the protagonists or create the social frame for the setting of the events narrated. Choristers may sing in unison or split into two, three or often four different vocal parts. The classical division of voices is characterized by the registers of soprano, alto, tenor and bass.

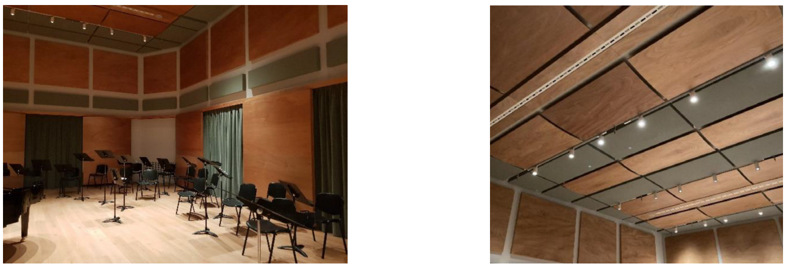
Considering the ISO 23591 [6], rehearsal rooms are subdivided according to the music type (amplified, loud acoustic or quiet acoustic music) and ensemble type (according to the number of musicians). The division defines individual practice rooms and small, medium and large ensemble rooms. These rooms are grouped according to evaluations of different requirements, such as room dimensions (room geometry, volume, area, room height), room acoustic quantities (sound absorption, reverberation time, etc.) and other necessities, which characterize the type of music. The subdivision considers the musicians that play or sing alone (individual rehearsal or teaching rooms), that stay in small groups (both with the same instruments, voices and in ensembles of three to six) or assembled in large groups (choir, big band, orchestra, etc.) [7].

This categorization has proven to be useful and sufficient after the Norwegian NS 8178 Standard [7,8] was applied for 7 years. It has been proven that these three main categories divide the music groups and music practice in an appropriate way: acoustic soft music and ensembles, acoustic loud music and ensembles (and extra loud groups) and amplified music and ensembles.

The reported room division, according to the room dimensions, can be easily recognized, for example, in the "Auditorium Parco della Musica Ennio Morricone"(Rome). The auditorium was designed by Renzo Piano and is managed by the Musica per Roma Foundation, giving the National Academy of Santa Cecilia its own home. It has become one of the biggest performing arts and cultural centers in Europe. On 21 April 2002, the Petrassi and Sinopoli concert halls, with 1133 and 673 seats, respectively, were opened to the public, while the Santa Cecilia hall, with 2756 seats, was inaugurated on 21 December in the same year. The complex of the auditorium was completed in early 2003, including four main rehearsal rooms for large groups (Figures 1 and 2), three rehearsals for small groups and eleven individual rehearsal rooms.

(**a**) (**b**)

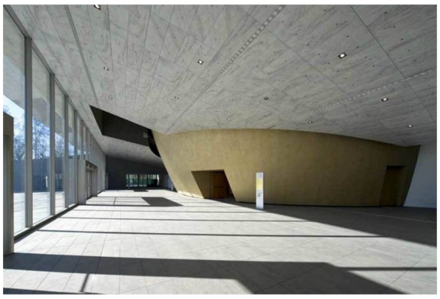
Figure 1. The Auditorium Parco della Musica Ennio Morricone (**a**) and its rehearsal room for orchestra (**b**).



(**a**) (**b**)

Figure 2. "Nuovo Teatro dell'Opera" (Florence): rehearsal room for choir sections (**a**,**b**).

A similar division has been applied to the "Nuovo Teatro dell'Opera" (Florence) (Figures 3 and 4), which is characterized by an opera house hall for 1800 people and a multi-purpose theatre for 1000 people, with the main function being that of a concert hall. Designed by ABDR, the opera house was created to give a new permanent location to the Maggio Musicale Fiorentino and has become one of the largest opera houses in Europe. It includes an outdoor auditorium with over 2000 seats, all services for welcoming the public, rehearsals for orchestra, choir and dance, laboratories, dressing rooms, offices, restaurants, parking and everything else necessary for artistic production.


(**a**)

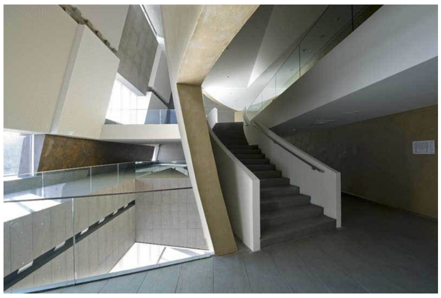

(**b**)

Figure 3. The main entrance (**a**) and the foyer (**b**) in the Nuovo Teatro dell'Opera.


(**a**)

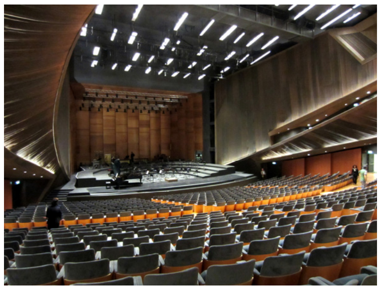

(**b**)

Figure 4. The building of the Nuovo Teatro dell'Opera, Florence (IT) from outside (**a**), and the main hall (**b**) inside.

In these large complexes, large ensemble rooms are suited for different types of music and ensembles, and a system to control and adjust the acoustic response is requested according to different activities. Typical music groups that can occupy the space include, for example, brass bands (25 musicians to 35 musicians), concert bands (35 musicians to 70 musicians), choirs (30 singers to 80 singers) and orchestras (70 musicians to 110 musicians). For these rooms, various purposes shall be clearly defined and prioritized. The main intended use and other activities should be specified and made known to all users in order to avoid conflicts concerning the suitability of the spaces for various applications.

In both the Auditorium Parco della Musica Ennio Morricone and the Nuovo Teatro dell'Opera, as well as in the Astana Opera House [9] (Figure 5) and in many other important musical centers, large ensemble rooms are cladded with wood panels, and the acoustics response is controlled by changing the position of the curtains that come down from the ceiling above the vertical walls.

Figure 5. Astana Opera House (Kz).

In these rehearsal rooms, the optimization of the indoor air quality plays an important role not only for the optimization of the musicians' comfort and the control of the reverberation time, especially at high frequencies, but also for the correct maintenance of the musical instruments and for the proper installation and maintenance of the room cladding. This means that in most cases, rehearsal rooms for large groups, clad by wood panels, require a controlled indoor environmental quality from the beginning of the construction process on-site and throughout their life cycle. The air humidity also affects the panel conditions after a long natural seasoning or a wood-drying cycle because a percentage of water will always remain inside the panel, maintaining dynamic equilibrium with the thermo-hygrometric conditions of the surrounding environment.

If equilibrial humidity is not maintained, effects on the geometry of the panel can appear, changing, for example, its curvature, the fugues' dimensions and the junctions, which can be damaged. Essentially, this means the acoustic properties of the panel are altered, introducing new undesired sound effects, such as some new low frequency absorption and selective absorption frequencies.

In this situation, the building information modeling (BIM) methodology represents a good chance to control the indoor air quality and the acoustic quality from the initial phase of the construction to the management and maintenance of the building during its lifecycle.

The BIM model, which digitally represents all the functional and physical characteristics of the rehearsal room, becomes an information database available throughout the construction phase [10] to control the wood panels' installation and the requested air humidity during the montage. The availability of a single model including all the project information and data contributes to a global vision of the building and improves the process coordination. These are the reasons for which BIM methodology implementation is accelerating as a rapid technological renovation in the architecture, engineering and construction industry (AEC).

Furthermore, BIM implementation in the construction process offers an opportunity to estimate the acoustic quality of the hall from the beginning of the construction phase, as a support for all the involved specialists, architects, engineers and builders making decisions in the acoustic field [4,11], visualizing different scenarios from the commissioning to the management phase.

In this paper, the optimization of the acoustic properties of the room cladding for large rehearsal rooms with benefits on the final room acoustic response, linked to the indoor environmental quality, are considered from the construction to the life cycle of the building using BIM-based technologies through platforms collecting static and dynamic data. This process could be also used to manage the material flows, which are part of the complex organization of a large construction site, such as an opera house.

The proposed methodology connects data from IoT devices, such as sensors and actuators, and it uses visual programming language (VPL) to create interconnections between the collected data and the BIM authoring tool, which becomes the virtual reality for controlling the construction site first, and then of the commissioning and management phases in real time (digital twin).

Furthermore, this paper can be included in a larger research study focused on developing implementation of a digital framework that consists of connecting existing technologies to extend the digital transaction of building data. This includes acoustics and other specific fields in theaters to define a "Theatre Digital Twin" including rehearsal spaces. In particular, in this research, the new acoustics automation field is applied to the building acoustics [12]. Acoustics automation develops a digital platform for monitoring the advanced manufacturing and Industry 4.0, in which the outcome optimizations are guided by acoustic data in real-time. Through DT, customized formats present the data and make them accessible to management operators and customers for decision making [13]. The methodology is detailed in Section 2.

In Section 3, a case study is presented, namely, a large rehearsal room for a choir in the Nuovo Teatro dell'Opera in Florence. Conclusions follow in Section 4.

2. Methodology

The proposed methodology aims to connect data from IoT devices and uses visual programming language (VPL) to realize an interconnection workflow between the data collected and the BIM authoring tool. The application of IoT to the BIM is wide [14]. In this case, data are gathered in the construction, commissioning and management phases through a BIM capable of controlling, enabling and implementing advanced features [15,16].

In this methodology, the BIM becomes the basis for developing a digital twin that simulates the indoor conditions for the rehearsal room. Data about the temperature and relative humidity are gathered by sensors installed inside the space [17] when the wood panels are under construction during the management phase. The sensor installation requires a careful definition of the sensor network with attention to where the sensors are positioned and which protocol needs to be used [18]. Even if temperature and humidity are common choices [19,20], a decision about the communication technology becomes relevant [21]. In the case study, in fact, the data visualization for the involvement of the theater technicians was mandatory.

In the construction phase, the indoor air temperature and relative humidity become the main control parameters, considering specific thresholds. These values were identified to simulate the data collected by the sensors and to verify the indoor conditions.

The considered thresholds are in accordance with the standard (UNI EN ISO 7730) [22] and with respect to the conditions in the case of occupancy during the musicians' activities, with some additional restrictions, including the following: 20 °C < air temperature (T) < 22 °C; 6% < relative humidity (H) < 75%. These ranges represent the correct conditions for the panels' installation and for the different music uses. When the ranges are respected, a specific color code is visualized, while if the values are smaller or larger than the thresholds, the values are plotted as not acceptable and as a result, they are displayed with another color code.

The data are organized in an Excel file considering the specific thresholds related to the adopted parameters.

BIM-based technologies are useful for construction sites phases through platforms collecting data, since they offer the possibility of controlling the overall progress of the project from the design and construction phase, extending it to the entire cycle life, as suggested by the European Directive 2014/24 [23]. The Ministerial Decree 560/2017 has transposed this legislation in Italy, in which the approach for the BIM transition in public procurement is established. This approach suggests a gradual process, starting with the most important and strategic works, to be extended to all the contracts by 2025.

In the case study, when the construction phase is completed, static data describing the acoustic quality are implemented in the BIM. These data are collected during the commissioning through acoustic measurements [24] referring to specified curtain positions, the so-called "curtain set". The curtain set used to obtain the designed acoustic parameters, in fact, is identified during the commissioning phase according to the project specifications. The set refers to a finite number of curtain positions, in which all the banner curtains are always at the same distance from the floor (curtain banner random distribution is not considered for the automation process).

Both the room acoustic parameters and the curtain set are visualized in the BIM authoring software (version 2020).

This is a fundamental step in the operative phase for parametrically controlling the project. In fact, the digital model contains not only the main geometrical information but is increased with specific room acoustic information. The BIM model is the repository where the acoustic quantities are stored and extracted for the digital twin simulations according to sensors and actuators used for curtain positioning. In the management phase, when the rehearsal room is available to the musicians, the digital twin simulates the air temperature, the relative humidity, the curtain position among the preset scenarios and two acoustic parameters, the reverberation time (RT) and the strength (G) (Figure 6).

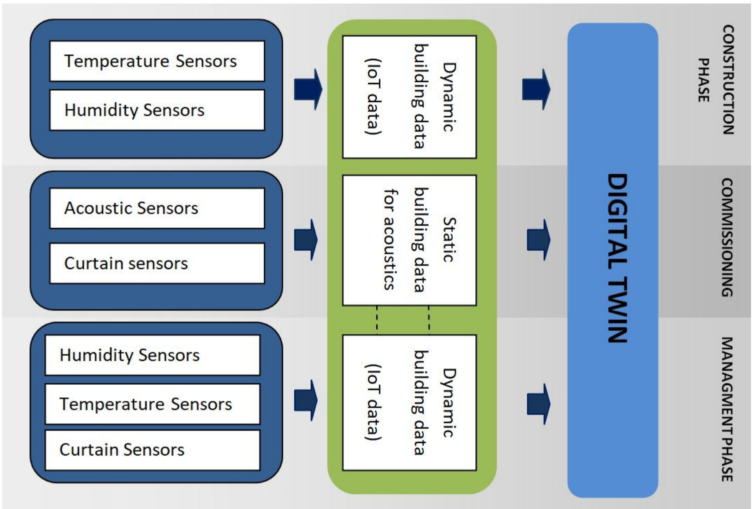


Figure 6. Integrated digital twin framework.

In the methodology, through Java, the sensors' information is exported from the software, which controls the curtain set through actuators. This happens every time a change position is needed to optimize the absorption coefficient of the walls to the acoustic requirements; this means the reverberation time and strength average values are changed. The information is collected in an Excel file. A Dynamo script is executed to read the Excel data virtually, which is derived from the software that controls the curtains' position sensors, visualizing the curtains and the relative information in the DT.

The data flow is automatic in both directions between the digital object and the physical one. In this context, a state variation of the physical object also determines a state variation of the digital model and vice versa.

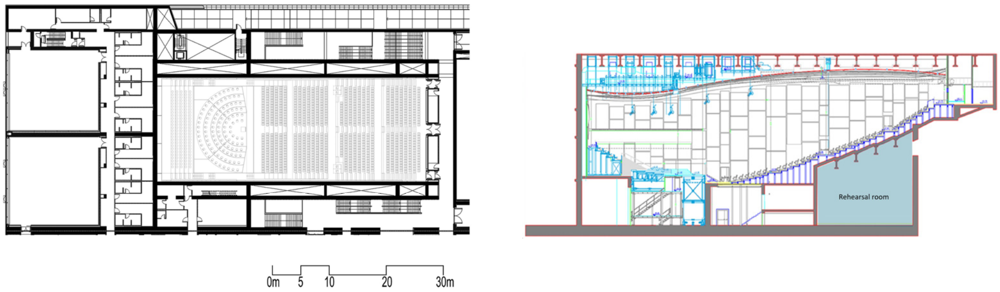
It is noteworthy how the information model should be linked with the organization of the rehearsal activities to avoid unsuitable conditions. If the curtains are moved to a position different from the ones identified during the commissioning, the digital twin displays a warning message "not optimized room acoustics conditions". The visualization of the air quality conditions remains essential in the construction phases.

With this methodology, the advantages of integrating detection technologies (i.e., sensors) are achieved. A project developed with information modeling methodology, in fact, permits both greater control of the works during the construction phase and facilitates the supervision and optimization of the rehearsal room comfort conditions by the operational managers. The digital transition pushed by regulations and organized as described above leads to a combination of a digital project and reality.

The suggested methodology is utilized for the presented case study, in which curtain sensors can detect the curtain position, but not the distance from the floor. This means that no information about the curtains' absorption surface is available to evaluate the reverberation time in real time but is rather determined in a calculation virtual environment (CVE), as explored in previous research [25].

3. The Case Study

The rehearsal room is located in the Nuovo Teatro dell'Opera (Florence), directly under the stalls in the auditorium. It is designed for large groups, especially for the choir, and includes platforms on the floor to allow the singers to sit in classic formation (Figure 7).



(**a**) (**b**)

Figure 7. Auditorium in the "Nuovo Teatro dell'Opera" (Florence) plan (**a**) and a detail of the section including the auditorium and the choir rehearsal room (**b**).

The room plan is rectangular in shape, measuring 14 m × 21.5 m, and is delimited by a sloping, ascending ceiling with an average height of 8.3 m. The effective acoustic volume is equal to ca. 2500 m^3.

This volume is sufficient to accommodate even large ensembles, up to 120 choristers, if a volume of 20 m^3/musician is considered.

The room is clad with wooden panels on the ceiling and on the vertical walls, where sound-absorbing panels with a random distribution are also placed (the blue panels on the vertical walls in the figure below). The absorbing panels cover approx. 35% of the vertical surfaces (Figure 8).

Figure 8. The choir rehearsal room as seen from an entrance door.

Heavy curtain banners lower from boxes under the ceiling to cover up to approximately 50% of the vertical wood panels (Figure 9) to obtain a variable acoustic response, controlling the room acoustic parameters.

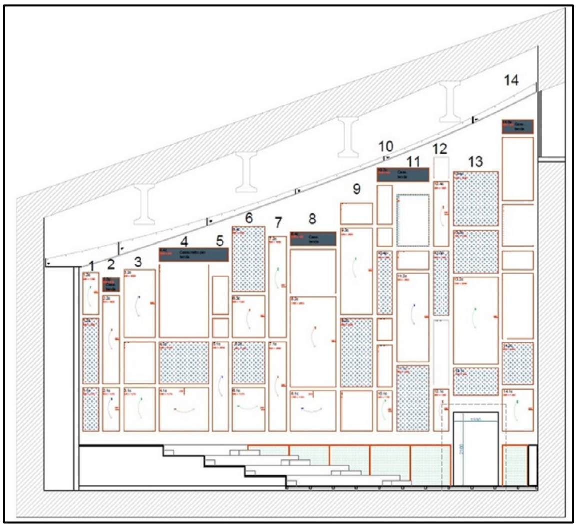


Figure 9. Panel distribution on the same vertical wall seen in Figure 8. The curtain boxes are colored black.

In this kind of rehearsal room, the optimization of the indoor air quality plays an important role, not only for the optimization of the musicians' comfort and the control of the reverberation time (especially at high frequencies), but also for the correct maintenance of the musical instruments and for the proper installation and maintenance of the room cladding.

3.1. Construction Phase

From the beginning of the construction phase to hang the wood panels, air humidity and temperature sensors were in position, ensuring the optimal installation conditions through the digital twin (Figure 10).

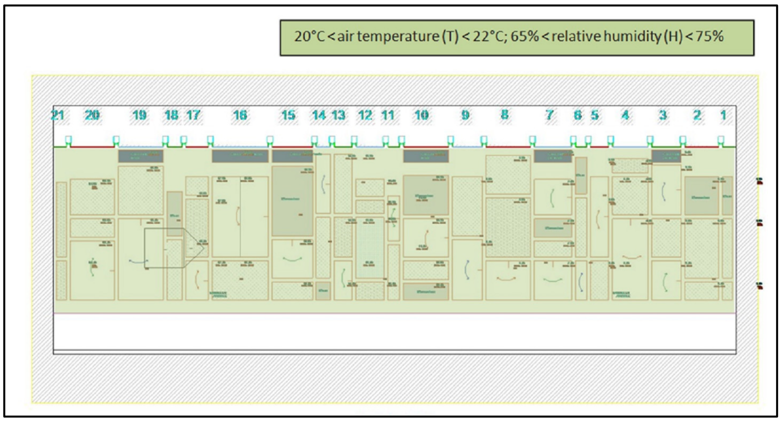


Figure 10. Digital twin visualization (21 panel columns are considered).

To install the wood layer on the walls and on the ceiling of the concrete box (Figure 11), a time schedule was organized.

With the beginning of the cladding installation, the visualization of the DT simulation was controlled to ensure the required comfort for the wooden panels throughout the installation period. The temperature and the humidity were maintained in the same conditions that would be necessary during the musicians' activities.

Throughout the installation phase, in fact, the temperature and the air humidity were quite constant: T 21.2 °C, humidity equal to 67% ca, respectively.

Figure 11. Rehearsal room concrete box.

First, frames to hang the panels were put in position (Figure 12), followed by the installation of the panel surfaces (Figure 13) and the curtain boxes to complete the room (Figure 14).

Figure 12. Panel frame installation.

Figure 13. Panel surface installation.

Figure 14. Rehearsal room completed.

3.2. Commissioning

During the commissioning phase, the air humidity and temperature were controlled through digital twin simulations to ensure optimal environmental and acoustic conditions. Some acoustic parameters have been demonstrated, in fact, to be influenced by temperature, relative humidity and air velocity (e.g., strength; clarity C50 and C80, T30) [26].

The measured air humidity and temperature were equal to 67% and T 21.6 °C, respectively.

The acoustic measurements followed the ISO UNI 3382-1 [24]. An omnidirectional source and a sine sweep signal were used. The signal, coming from the microphone and the analyzer, was imported into software for real-time analysis and post-processing noise and vibration.

The omnidirectional source was put in two different positions, and seven microphones were used (Figure 15).

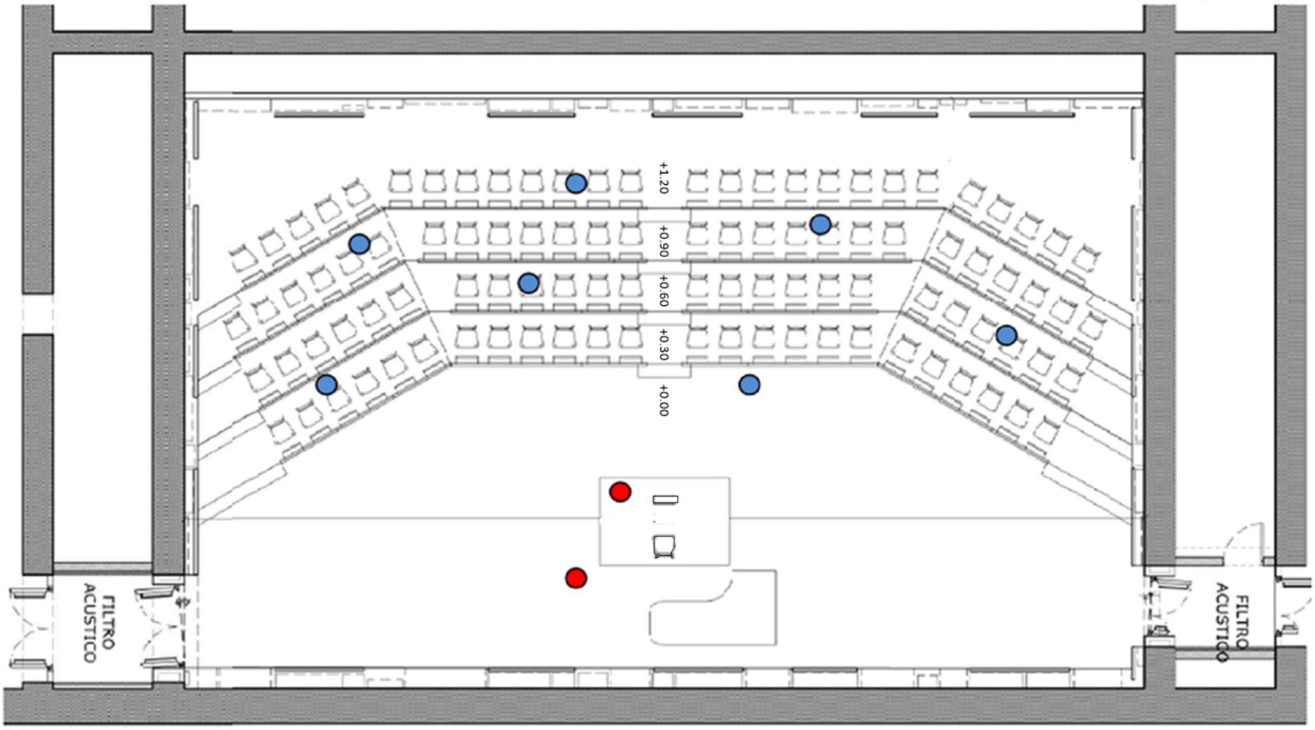


Figure 15. Source (red dots) and microphone positions (blue dots).

The equivalent background noise L_{eq} was equal to 23 dB.

The curtains were put in three different set positions: two curtain limit positions, firstly when the curtains are totally inside the box at their upper level (UL C), and secondly when they are totally out of the box in their lower level (LL C), as well as with their half height position (1/2 C). During measurements of every single set, both empty (E. s.) and fully occupied (O. s.) spaces (120 singers) were included.

The RT results, as average values of the two source positions and of the seven microphones, are plotted in octave bands in the following figure (Figure 16).

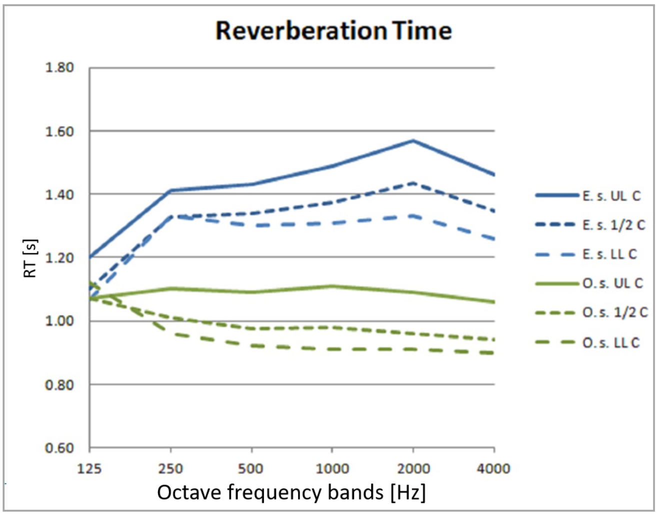


Figure 16. Measured RT in octave bands (from 125 to 4000 Hz) for 6 different conditions. Curtains at upper level (UL C), curtains at half height position (1/2 C), curtains at lower level (LL C), both in empty (E. s.) and occupied (O. s.) space.

In the DT, the visualized $T_{mid(500–1000Hz)}$ comes from both the measurements and an interpolation to obtain values referring to the room in a half-occupied condition (HO) (Figure 17).

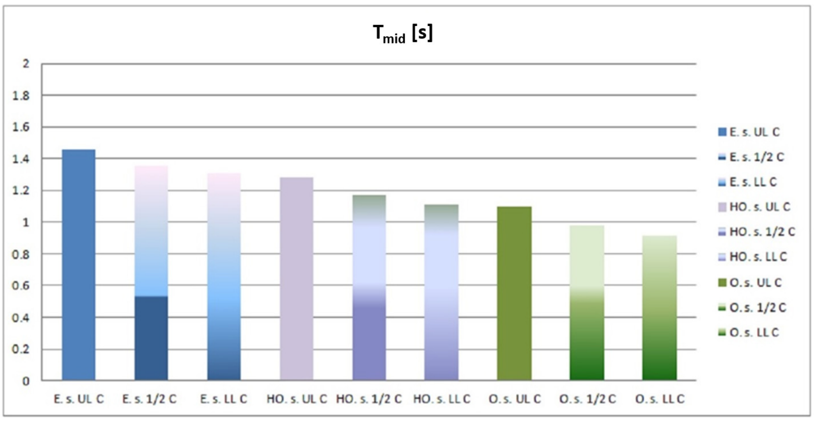


Figure 17. Rehearsal room T_{mid} in 9 different conditions. Curtains at upper level (UL C), curtains at half height position (1/2 C), curtains at lower level (LL C), both in empty (E. s.) half occupied (HO. s) and occupied (O. s.) space.

As suggested by the standard [6], the values of strength G, the other main acoustic parameter to be considered in rehearsal rooms and C_{80}, at mid-frequencies (Figures 18 and 19) follow.

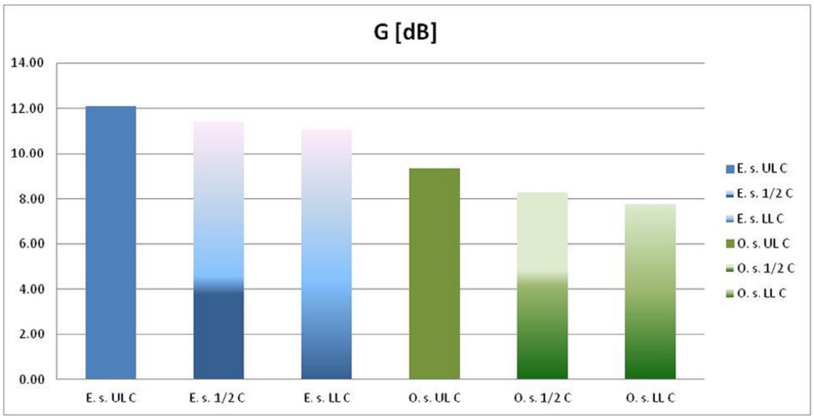


Figure 18. Strength G at mid-frequencies of 500 and 1000 Hz in 6 different conditions. Curtains at upper level (UL C), curtains at half height position (1/2 C), curtains at lower level (LL C), both in empty (E. s.) and occupied (O. s.) space.

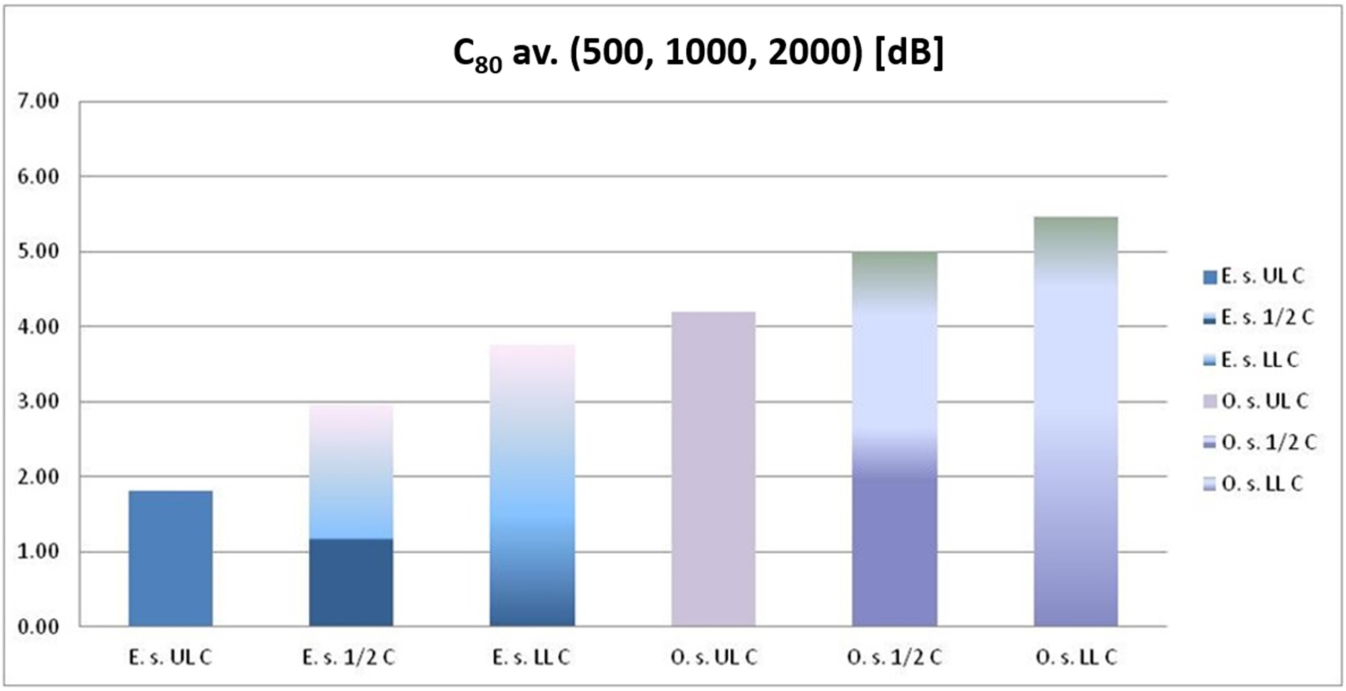


Figure 19. Clarity C_{80} at mid-frequencies in 6 different conditions. Curtains at upper level (UL C), curtains at half height position (1/2 C), curtains at lower level (LL C), both in empty (E. s.) and occupied (O. s.) space.

The acoustic design of the choir rehearsal room was developed before the standard [6] was published. The standard [6] does not consider rehearsal rooms for choirs as a special case and includes them in the "quiet acoustic music" space category. The acoustic quality criteria differentiate, in fact, music rehearsal rooms considering three types of music: amplified music, quiet acoustic music and loud acoustic music. In particular, quiet music refers to music that is played by quiet acoustic musical instruments or singing.

Typically, singing groups are considered to be vocal ensembles, choirs, string quartets, folk groups, string orchestras and groups including string instruments (such as guitars) without amplification.

These groups are estimated to create sound power levels lower than 95 dB at "forte".

In rooms for quiet acoustic music, the standard [6] underlines requirements with the following considerations:

- Adequate room dimensions (net volume and net area);
- Appropriate net room height;
- Reverberation adapted to the goal—the reverberation time does not vary too much with the frequency;
- Control of the reflections, properly inclined surfaces, adjusting the sound diffusion and evaluating the sound-absorbing elements' percentage;
- Avoiding flutter echo;
- Sound strength according to the sound power of the ensemble;
- Low background noise level.

The optimal reverberation time is suggested to be the average value of the octave bands at 500 Hz and 1000 Hz (the mid-frequency range), considering rehearsal rooms with normal furnishing (with or without seats) and without people. It is in accordance with the following formula:

$$T_{mid} = a \log (V) - b \quad (1)$$

where the constants *a* and *b* are given in a table (table 5 in the standard [6]) and *V* is the net room volume. Depending on the net volume, *V* and the type of music, the optimal reverberation time T_{mid} range is also indicated in a figure according to Equation (1), as follows (Figure 20).

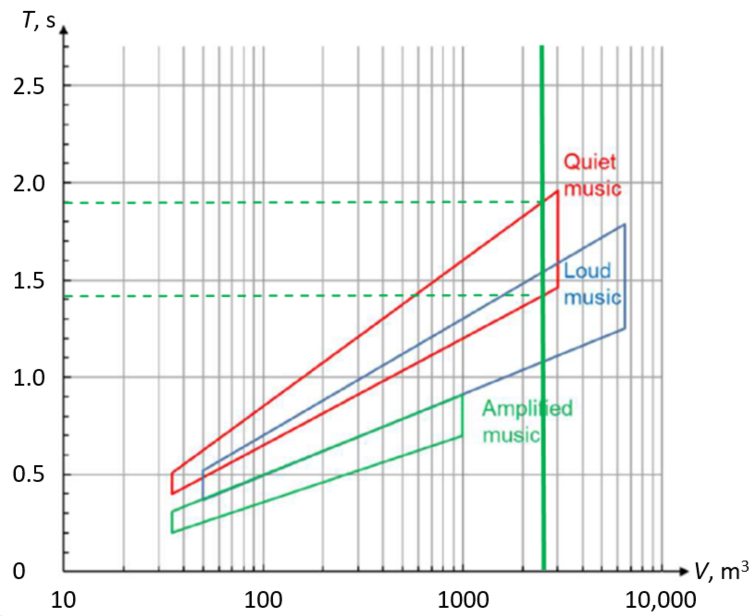


Figure 20. Optimal RT range for quiet and loud music. The green vertical line refers to the case study volume, for which the target is $T_{mid} < 1.9$ and $T_{mid} > 1.4$.

For the case study, the main properties suggested by the standard have also been verified. They refer to large rooms used for quiet acoustic music (Table 1).

The main acoustic parameters used in the standard are the reverberation time and the sound strength (G).

The rehearsal room for singers can be considered as an extension of their voice. For this interdependence between the room and the musicians, the sound strength (G) becomes crucial [27]. Too low a sound strength of the room weakens the music sound; consequently, the musician will try to compensate by forcing the playing, leading to too harsh a sound quality and decreasing the dynamic range of the music [28]. On the contrary, if the sound strength is too intense, the music will be too loud, and the singers will reduce their volume; consequently, the dynamic range of the music will decrease. When the room acoustic response is in accordance with the singers' needs, good rehearsal conditions are guaranteed.

Table 1. Large ensemble rehearsal room properties for quiet acoustic music.

Standard ISO 23591		Case Study	
Property	Large ensemble room	Properties	Verified property
Number of musicians	20 to 35 singers (N) (string orchestras) Ensemble type 30 to 80/100	(Choirs) Ensemble type 30 to 80/100	Yes
Net volume	>25 × N·m^3	>25 × N·m^3 under 100 <25 between 100 and 120 (choirs)	Partially verified
Net average room height	>5 m	>8 m	Yes
Reverberation time, without persons, according to Figure 18	1.4 < T_{mid} < 1.9 (s)	1.3 < T_{mid} < 1.45 (s)	The standard lower limit is achieved only without curtains

The appropriate sound strength G is suggested by the standard, considering the relationship between sound strength, reverberation time and net room volume, as in the figure below (Figure 21).

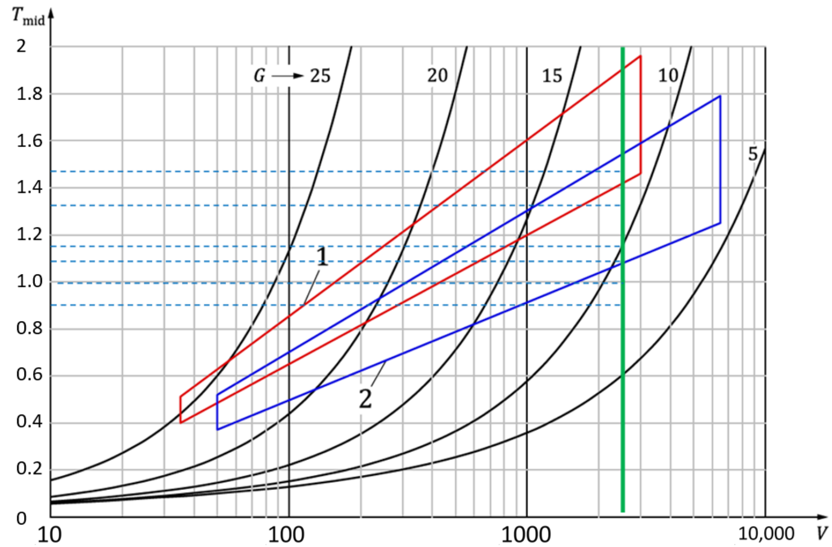


Figure 21. The red line (1) represents the target range for T_{mid} for quiet acoustic music. The vertical green line refers to the case study's volume. The dotted blue lines represent the different measured reverberation times of the case study. The blue line (2) represents the target range for T_{mid} for loud acoustic music.

Looking at the figure above, in particular at the red frame that refers to the quiet acoustic music, it seems that, in the case study, the optimal value for G is achieved only in the empty configuration, with curtains in the boxes, when the T_{mid} results equal 1.46 s. With active curtains, in fact, the measured T_{mid} and G are out of the red frame (Table 2). Even though they are outside the red range, the other two results were considered acceptable by the singers because they are similar to those of the main hall of an opera house. In fact, they fall inside the reference range for opera houses, in which the RT values are lower than those found in concert halls, improving the voice intelligibility.

Table 2. Measured acoustic parameters T_{mid} and G in three different curtain positions. The standard values of G are included.

Configuration	T_{mid}	Measured G	G Suggested by the Standard (V 2500 m^3)
E. s. UL C	1.46	12.10	11.5
E. s. 1/2 C	1.35485	11.40	10.4
E. s. LL C	1.305	11.07	10.3

To evaluate if the configurations E. s. 1/2 C and E. s. LL C can be considered to have a good acoustic quality, the sound level at forte has been evaluated according to the standard.

When calculating an ensemble sound level, the number and type of singers are first determined. The data are given in the following table (Table 3).

Table 3. Sound characteristics of a singer's voice [6].

Source	Sound Power Level dB re 1 pW	Reference	Sound Power P mW
Singer, adult	96	[6]	4.0
Singer, boy	88	[6]	0.6
Singer, soprano	97	[6]	5.0
Singer, alto	93	[6]	2.0
Singer, tenor	95	[6]	3.2
Singer, bass	96	[6]	4.0

In the room, the sound level of the ensemble at forte is calculated with the following formula:

$$L_p = G + 59 + 10lg\frac{\sum n_i P_i}{(mW)} \quad (2)$$

where G is the sound strength; n_i is the number of instruments of type i; and P_i is the sound power for instrument type i.

According to the standard, the sound strength of the space can be considered suitable for the ensemble if the sound level at forte is in the range of 85 dB to 95 dB, the upper limit of quiet acoustic music.

In the case study, to evaluate the sound level at forte, an ensemble with all four voices, soprano, alto, tenor and bass, is considered, gradually increasing the number of singers equally for every voice type (Figure 22 and Table 4).

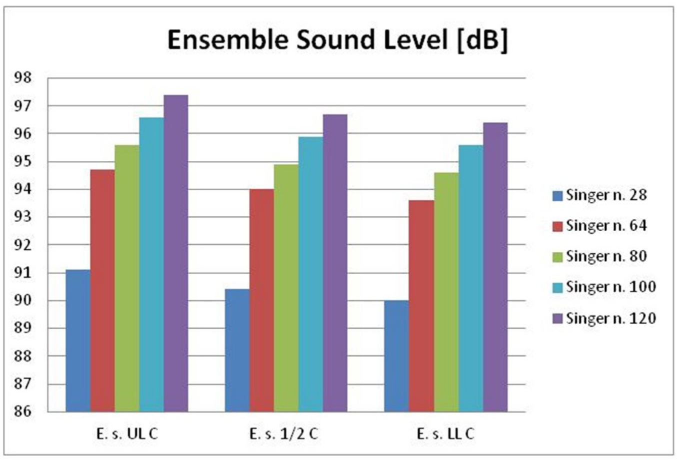


Figure 22. Sound level at forte. An ensemble with all four voices, soprano, alto, tenor and bass, gradually increasing the number of singers.

Table 4. Sound level at forte, gradually increasing the number of singers.

Room Configuration	Singer Quantity	n.Measured G (dB)	Total Sound Power P	Sound Level of the Ensemble
E. s. UL C		12.1		91.1
E. s. 1/2 C	28	11.4	99.4	90.4
E. s. LL C		11.07		90.0
E. s. UL C		12.1		94.7
E. s. 1/2 C	64	11.4	227.2	94.0
E. s. LL C		11.07		93.6
E. s. UL C		12.1		95.6
E. s. 1/2 C	80	11.4	284.0	94.9
E. s. LL C		11.07		94.6
E. s. UL C		12.1		96.6
E. s. 1/2 C	100	11.4	426.0	95.9
E. s. LL C		11.07		95.6
E. s. UL C		12.1		97.4
E. s. 1/2 C	120	11.4	426.0	96.7
E. s. LL C		11.07		96.4

The calculated ensemble sound level shows that large choirs are much more similar to loud instrumental groups that can achieve sound power levels above 97 dB. The big difference between the two groups is that a large choir always requires good comprehension of the voice, which means the clarity index and/or the definition could be verified even if not requested by the standard. If a large choir is considered to be a loud group, the measured reverberation times lie properly within the blue frame suggested by the standard (Figure 19). However, the volume does not comply with the values suggested by the standard for loud acoustic music and large ensemble groups ($V < 50 \times N$ m^3).

The volume and the reverberation time values have to be optimized according to the type of music. If the reverberation time is over the target, the sound can be thick and unclear. However, if the reverberation time is under the target, the music can be dry, and the tones lose some of their timbre and brilliance. This is most significant for vocals, woodwind instruments and brass instruments, while it is less problematic for piano and string instruments, which have a built-in sound board.

If the room is too small and its reverberation time is over the referred optimal range, the resulting sound will be too powerful, becoming unpleasant or damaging to the voices and the hearing. If the room is too large and its reverberation time is under the referred optimal range, the resulting sound will be too quiet. In the first case, experienced musicians can compensate to a certain degree by playing quieter than normal, but this compromises the dynamic range and musical expression, especially for the singers. In the second case, most musicians will try to compensate by playing louder than normal, but this compromises the voice timbre, damaging it.

During the measurements, the singers were asked if they would like to move into a bigger rehearsal room. The answer was negative in most cases.

In the case study, analyzing the evaluated ensemble sound level at forte, it does not always seem appropriate to consider a large choir as a group for quiet acoustic music. It is also true that not all the properties of rehearsal rooms for loud acoustic music can be suitable for choir music, especially the volume dimensions.

Further research is suggested, in which another music type could evaluated to be implemented in the standard, namely, "the choir music", which would allow for a better definition of the necessary room properties and constants a and b [6] to evaluate the optimal reverberation time range. The biggest acoustic challenge in choir rehearsal rooms remains the balance between the reverberation time and the sound strength, but because of the nature of the voice, further research including the clarity index is also suggested.

Rehearsal properties for choir music could be extended to medium ensemble rooms. In large complexes of opera houses, in fact, near the rehearsal room for the entire choir, there are at least two other rehearsal rooms for the choir sections that also require acoustic criteria definitions [29].

3.3. The Management Phase

At the end of the commissioning phase, the three main curtains' positioning, UL C, 1/2 C, and LL C, are preset in the software to allow them to be controlled remotely during the musicians' activities.

In the management phase, the digital twin is used to virtually replicate the static and dynamic characteristics of the rehearsal room, realizing a real-time connectivity between the physical and virtual entities.

The virtual copy of the physical rehearsal room is leveraged to monitor the current state, the temperature and air humidity and the curtain set; this means the room acoustic conditions are linked to the curtains' position (Figure 23).

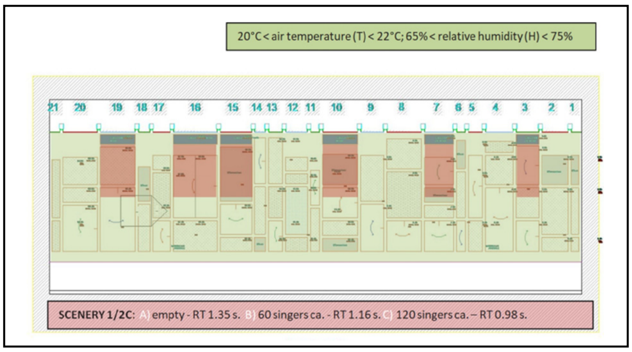


Figure 23. A digital twin simulation in the management phase (curtain position is colored red).

The digital twin is characterized by three main components: the physical counterpart, the virtual counterpart and the bidirectional connectivity between the physical and the virtual entities. Despite its potential, this research applied to a rehearsal room is at an early stage because the curtain sensors are not able to read the curtains' distance from the floor when the banners come down. This means it is not possible to quantify the curtain absorption surface in real time. To improve the capability of the digital twin to virtually replicate information about the room acoustics in real time, new sensors, actuators and an acoustic algorithm should be added to the digital twin architecture.

However, in the management phase of the case study, it remains possible to set other fixed curtain positions according to the musicians' needs; related acoustic measurements could follow.

4. Conclusions

Numerous rehearsal rooms are located in complex buildings, such as opera houses and cultural centers, where new research outcomes have led to increasingly complex projects, construction processes and management phases. In particular, the rehearsal room indoor environment, the air conditions and the room's acoustic behavior have to be considered critical factors for the musicians' comfort, as they spend the majority of the day in those spaces.

To achieve the desired room acoustic response, the recent ISO 23591 [6] has been proved to be very helpful, indicating the main acoustic quality criteria to be followed in the design stage and to be verified in the commissioning and management phases.

This standard subdivides the rehearsal room spaces by music type (quiet or loud acoustic music) and ensemble type (musicians' number) in accordance with different requirements: individual practice rooms and small, medium and large ensemble rooms. The subdivision refers to individual rehearsal or teaching if musicians play or sing alone, to small groups with the same instruments, voices or in ensemble (from three to six musicians) or to large groups, such as choir, big band, orchestra, etc.

The presented case study, the rehearsal room located in the Nuovo Teatro dell'Opera (Florence), is a space specifically for large choir groups. Even though it was designed before the introduction of the standard ISO 23591, singers describe the room as a space with high acoustic quality. They consider the space to be an extension of their voice.

In the standard, the suggested acoustic criteria referring to a space for large choir groups are the ones to be applied to large rooms for quiet acoustic music. By analyzing the case study and verifying the acoustic range of the main acoustic parameters, the reverberation time and the strength, it has been observed that their trend is much more similar to that for loud music. The geometric properties are in the range of quiet music, instead.

This is justified by the fact that, according to the room acoustic response, the capability of the voice to compensate for the dynamic range of the music without being damaged is lower than that of the other instruments (even if their sound power at forte, when in large groups, can achieve the values of loud instruments).

For these reasons, further research is suggested to better classify the acoustic criteria for choir ensembles, evaluating the introduction of a new type of music, the "choir music", in the standard.

In the Nuovo Teatro dell'Opera, the choir rehearsal room is also appreciated by the musicians because it is clad with wooden panels. Wooden panels, in fact, are used in most cases both for large choir groups and for large orchestras' rehearsal rooms. To contribute to the room's acoustic quality, wooden cladding requires an air- and temperature-controlled space from the beginning of the installation process on site throughout its life cycle to maintain both the wood's properties and the room's acoustic response. To ensure these conditions, the digital twin has proved to be very useful both in the construction phase and in managing the rehearsal room set according to the musicians' activities.

Building information modeling data have provided precise information regarding the geometric, semantic and spatial elements of the building throughout the construction and management phases. Furthermore, Internet of Things (IoT) technology has provided real-time and dynamic operational data during the same process steps. Consequently, integrating data from heterogeneous data sources and different cross domains, such as BIm and IoT, is considered to be one of the most important steps to develop DT architecture. Possible further implementations have been identified to improve the DT performance:

- Acoustic algorithms should be included in the DT platform to control the room's acoustic properties for different rehearsal rooms, starting from the design phase, according to ISO 23591.
- Sensors and acoustic algorithms should be added to evaluate the sound power of the instruments that enters the room in real time to optimize the curtain set according to the ensemble configuration.
- The control schedule costs should include 4D and 5D simulations to optimize the building process for wooden cladding in rehearsal rooms.

Another contribution of the used method is that it can be applied to rehearsal rooms characterized by other cladding materials. The limitations of this study are given by the necessity to collect data from other rehearsal rooms for choirs to define the criteria for properly verifying all the optimal acoustic parameters and geometrical characteristics.

This paper can be considered a part of research that focuses on the development of a proof-of-concept implementation of a digital framework that is based on the connection of existing technologies for helping the digital transaction of building data for acoustics and other specific fields in theaters and cultural public spaces to define a "Theatre Digital Twin", including rehearsal spaces.

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