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Concert Halls as Nearly Adaptive Spaces

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Abstract: Concert halls have led to increasingly complex spaces that cannot be thought of as static 'containers' anymore. This complexity makes them viable to be launched towards industry 4.0 and to be considered a function of the activities that they can provide during their life cycle. They are characterized by dynamic objects that contain sophisticated sub-systems and add to the capability to influence both environmental variables and user behavior. This article explains an adaptive concert hall at an early stage, in which a network of sensors that gather real-time data on environmental factors such as temperature, air humidity and air velocity are considered, focusing on their direct and indirect intercorrelations with the acoustic quantities to optimize the room acoustic response. The proposed methodology is controlled by a digital twin (DT) based on building information modeling (BIM), integrated with sensors, actuators, and acoustic measurements and algorithms. By analyzing the data, algorithms identify patterns, and an autonomous fine-tune setting is achieved, including the novelty for which a natural variable acoustic field becomes possible during a musical execution without the use of any electroacoustic system support. The hall becomes a natural active instrument to be included in the composer's score. A case study is presented.

Keywords: digital twin; air quality; architectural acoustics; variability of room acoustic parameters; acoustic automation

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1. Introduction

Adaptive buildings refer to spaces designed to adapt to their environments, their inhabitants or users, and their intended activities, as well as to buildings that are entirely driven by internal data.

Adaptive buildings bring together several different concerns from a wide variety of disciplines, spanning architecture, music, computer science and engineering, among others. Buildings in this context are described as flexible, interactive, and dynamic, and they embrace the notion of architecture being adaptive rather than a static artefact, often with an emphasis on computer-supported adaptation [1].

Adaptive spaces for cultural production have a long history. Concert halls have long incorporated technologies that allow them to be used in events [2]. Complex technologies, such as stage systems, lighting systems, and more modern multimedia systems, help a concert to happen, while other equipment, such as air heating and ventilation systems (HVACs), allow for the audience to participate in good environmental conditions.

Adaptive concert halls (ACHs) are considered to have specific acoustic characteristics, which are defined by the absorption surfaces' properties, the volume, and the shape of the hall in the design phase, and they must deal with changing circumstances [3] during their life cycle. For example, hall occupation changes happen at different time scales: there is rapid change through different activities throughout a single day (rehearsals activities instead of concerts), medium-term change that occurs as result of re-organizations (concert for chamber orchestras instead of for big orchestras), and longer-term changes that might impact on their environmental and acoustic conditions.

Concert halls are designed and managed to be adapted for concerts. Their natural acoustic quality is a passive property of the hall that can vary only if some variable volumes or variable acoustic surfaces are modified to control the hall setup before the beginning of the concert. In most cases, when the hall is not designed as a multipurpose space [4], only curtains are introduced to act as variable acoustic elements.

Variable acoustic elements are thought of as adaptation components that directly influence the natural room acoustic response, as well as the number of spectators and their percentage of occupancy [5], but the intercorrelation between the acoustic qualities and the commonly overlooked thermo-hygrometric parameters also plays an important role [6]. In particular, to optimize the acoustic response, it is necessary to consider the influence of temperature, humidity, and air velocity on acoustic parameters [7].

This means that temperature- and air humidity-related factors, such as occupancy and overheating of lighting equipment, can also indirectly influence the natural acoustic response (Figure 1).

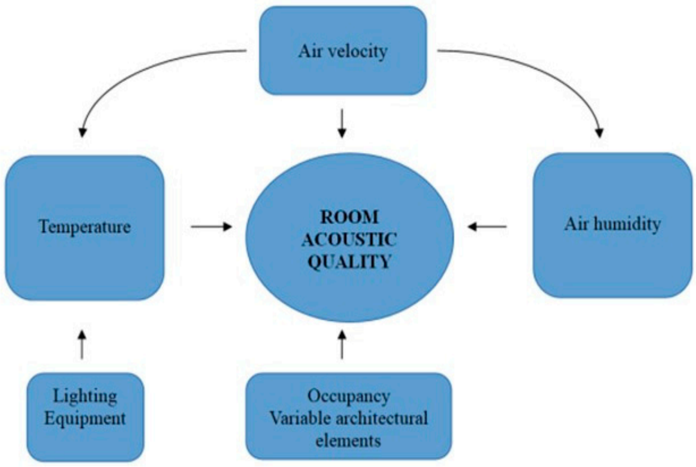

Figure 1. Main factors that directly and indirectly influence the room acoustic response.

Considering the digital transformation era operating in the architecture, engineering, and construction (AEC) industry [8], this paper introduces adaptive concert halls through digital twins (DTs) as part of the automation and control process towards Construction 4.0 in order to optimize their acoustic quality through the main factors that directly and indirectly have influence, transforming the room's acoustic response into an active property of the hall.

Great advantages are achieved when developments of the different interconnections converge to create new and exciting acoustic fields such as experiences and lived-in sound, which, as a further step, transform the hall acoustics into an instrument that acts during a concert without the use of any electroacoustic equipment.

This possibility represents a novelty in the musical field since, although the variability in the reverberation time can be included during the performance of a piece of contemporary music, it is nowadays still left only to the electroacoustic system.

In contemporary music, in fact, the variable acoustic effects included in a score are obtained only through electro-equipment support, while, through a DT including sensors and actuators, a new natural dynamic response becomes possible.

The following section refers to the influence of adaptation elements on acoustics in detail. In Section 3, the methodology used to optimize the acoustic quality of adaptive concert halls is explained.

In Section 4, the methodology is applied to a case study, where a further step is developed to include the natural dynamic response of the hall into a contemporary music score.

The conclusions then follow.

2. Main Adaptive Factors for Room Acoustic Quality in Concert Halls

The main adaptive factors for room acoustic quality, in the operation phase, are linked to complex technologies and are correlated to other equipment, such as heating, ventilation and air conditioning (HVAC) systems, that allow the audience to participate in good environmental conditions, controlling the indoor air quality, the temperature, and the humidity. The occupancy percentage can also be a crucial adaptive factor, according to the seat's absorption coefficient.

2.1. Temperature and Humidity

Thermo-hygrometric conditions play an important role in the variation in indoor acoustic quality. Some acoustic parameters have, in fact, been demonstrated to take influence from temperature, relative humidity, and air velocity (e.g., strength; clarity C_{50} and C_{80}, T_{30}) [7].

Thermo-hygrometric conditions are considered rather infrequently in acoustic analysis. Only a few standards include such conditions in their acoustic measurements. For example, the standard ISO 9613-1 [9] considers the effect of air absorption on the propagation of sound waves and allows for a direct correlation with temperature, relative humidity, and static pressure.

The influences of temperature and humidity have been considered in the field of voice alarm (VA) systems; Gomez-Agustina et al. [10] as well as Yang and Moon [11] have investigated their effects in voice reproduction systems. Research work have = observed that reverberation time increases at high frequencies when temperature and humidity increase.

Changes in air temperature affect the propagation speed of a sound wave, modifying the Sabine equation for reverberation time and having consequences on other correlated acoustic parameters when considering their theoretical basis [12]. One approach has applied the correlation between reverberation time and sound strength by using the method of least squares [13]. Another example is the statistical relationship of reverberation time with the speech transmission index (STI) [14,15].

Theoretical foundations of how air temperature influences the propagation speed of a sound wave, modifying the reverberation time Sabine equation, follow:

$$\mathrm{RT} = \frac{55.3\ \mathrm{V}}{\mathrm{C} * (\mathrm{A} + 4\ \mathrm{mV})} \tag{1}$$

where V [m^3] is the hall volume, the term C is the variable sound speed, and the term (A + 4 mV) is the acoustic absorption of the hall in which the term 4 mV indicates the sound attenuation by the air.

The influence of temperature and relative humidity is included in the formula for the sound speed C and in the m term, and the power attenuation coefficient is calculated according to ISO 9613-1: 1993 [9]. The changes in the air sound attenuation as a function of frequency can be found in the literature [16].

The speed of sound is calculated as follows:

$$\mathrm{C} = 331.4 * \sqrt{1 + \frac{\mathrm{T}}{273}} \tag{2}$$

2.2. Air Velocity and Air Distribution Systems

The thermo-hygrometric variables influence the acoustic parameters, but their effects are commonly neglected. In the case of a highly different distribution of air temperature in the hall, for example, the temperature gradient might cause convective air flows from different seat positions, provoking both an important variation in acoustic parameters and a variation in the tuning of musical instruments. This effect is particularly relevant for musical instruments in which the temperature differences might cause thermal dilatations in their metals' components, and therefore their out-of-tuning.

The influence of thermo-hygrometric conditions on acoustic parameters varies considerably with frequency, but the variation in air velocity in the room represents the most relevant environmental parameter for the change in acoustic quantities [7] inside the space.

To increase air velocity uniformity, under-floor air distribution (UFAD) systems are increasingly used in concert halls. UFAD improve energy savings, indoor air quality, and thermal comfort. In UFAD systems, an underfloor plenum delivers conditioned air to the air supply diffusers (Figure 2), which controls the distribution of internal air velocity and static pressure inside the space and determines the uniformity of the airflow in the stalls. In fact, at the diffusers, the uniformity of the air supply velocity significantly affects the indoor airflow uniformity and thermal comfort environment of the entire concert hall [17].

Figure 2. Santa Cecilia Hall (Rome): plenum construction phase, with completed diffusers' installation (colored red).

In UFAD, air is directly supplied to the occupants' area. Due to thermal stratifications caused by occupants' heat load, it is usually exhausted from the ceiling [18]. UFAD systems achieve good indoor air quality and provide good thermal comfort conditions for occupied halls, reducing the energy supply in comparison with conventional mixing ventilation systems [19]. In halls ventilated with UFAD systems, lower vertical temperature gradients are also verified in comparison with other distributions systems [20]. Compared to mixing ventilation [18,19], UFAD systems are very efficient in concert halls as they only condition the occupied stalls rather than the whole room. Because it is also recommended to limit the background noise in concert halls, noise minimizations must be introduced in the plenum. Since low background noise is, in fact, difficult to achieve with UFAD systems, in which local vortexes appear in the plenum with increasing air velocity. To improve the acoustic performance of UFAD systems, branches extending into the plenum can be added. In this case, outflows become parallel to one another with less interference, reducing local vortexes and increasing the uniformity of air supply (Figure 2).

2.3. Occupancy

In concert halls, the audience area generally represents the most important absorption surface of the room [16]. Therefore, the definition of seating absorption, in the presence and absence of people, becomes one of the main problems in acoustic-architectural design, with the aim of minimizing the differences between the two conditions. In the literature [16], the database describing audience absorption is relevant [21], in which the seats are divided into three macro categories: "slightly padded" (SP), "medium padded" (MP), "very padded" (VP).

The difference between the sound absorption values of unoccupied armchairs and those with people tends to grow with increasing frequency for medium and highly padded seats. If the armchairs are heavily padded, the difference is reduced to around 10%. Only in the most recent concert halls can padded seats minimize the differences between the sound field of the occupied room and that of the empty room because it is possible to measure their sound absorption coefficients in a reverberant room in the design phase before their installation in the hall [22].

Generally, the influence of seat upholstery is particularly pronounced in concert halls, meaning that all the other surfaces in the hall are reflective. A simplification can be assumed, for which these other surfaces are considered with only one absorption coefficient in octave bands, known as the "residual absorption coefficient". This coefficient represents the total absorption of all walls, ceilings, balcony faces, etc., except for the floor covered by the seats [16].

If differences between the acoustic absorption of armchairs and that of people are not minimized, the occupancy ratio (number of spectators/audience seats) OCA must be specified in the derivative of Equation (1), including both the acoustic absorption of armchairs and that of people.

The A term is better specified as follows:

$$A = \sum_1^n \alpha_i S_i + OC_A \alpha_p S_s + (1 - OC_A)\alpha_s S_s \quad (3)$$

where α_i is the residual absorption coefficient in octave bands of the surface i, from 125 Hz to 4 kHz, referred to as the reflecting surfaces S_i of the hall.

OC_A is the occupancy ratio (number of spectators/audience capacity).

S_s is the audience surface [m^2].

α_p is the absorption coefficient of the people [21].

α_s is the absorption coefficient of the empty seats at a given frequency.

2.4. Curtains' Systems

In concert halls, to adjust the reverberant field when satisfying the need of chamber orchestra music or contemporary electroacoustic music, textile curtains are often hung on the lateral walls of the hall, on the stalls side, as good sound absorbers.

Their acoustic properties depend both on their textile, the drapery fullness, and the backing condition, that is, the spacing between the fabric and a rigid backing wall, or the absence of a backing itself in the case of a freely hanging curtain that reduces the active volume of the hall.

Several prediction models for calculating sound absorption quantities have been developed.

A curtains' acoustic characteristics are usually described by the sound absorption coefficient, the areic mass, the air flow resistance [23], and the thickness of the air cavity between the curtain and the rigid wall, and the classical prediction model considers the thickness of the air cavity between the fabric and a rigid wall as well as the specific airflow resistance of the fabric as input parameters [16].

This model assumes that no sound-induced fabric vibrations occur, which is fulfilled if the fabric is much heavier than the surrounding air layer. For a long time, in fact, only heavy curtains of velvet material were installed to provide the requested absorption.

Recently, new lightweight and translucent textile curtains have been developed that exhibit good absorption properties, in which sound-induced vibrations affect the sound absorption characteristics. New models have been investigated, and several authors have proposed methods that consider these effects [24–26] for evaluating their acoustic properties.

In the prediction phase, testing in a reverberation room can be executed [27], where the edge diffraction at the specimen [28] and the non-uniform intensity distribution of the incident sound are considered even if the absorption coefficient for normal incidence must be validated first in an impedance tube [29]. On site, various measures can be available to quantify the resulting quality of the hall [30].

Considering the reverberation time RT derivative formula (Equation (1)), the walls covered by the curtains cannot be part of the reflective surfaces with Si included in the equivalent absorption area A (Equation (3)) (for which a residual absorption coefficient is referred) because of their higher absorption coefficient, and so they must be specified separately. The walls' surface ratio CLW_c, which is covered by the curtains, is introduced. Equation (1) is then as follows:

$$RT = \frac{55.3\ V}{C * \left(\sum_1^n \alpha_i S_i + OC_A \alpha_p S_s + (1 - OC_A)\alpha_s S_s + CLW_c \alpha_c S_{lw} + (1 - CLW_c)\alpha_i S_{lw} + mV\right)} \quad (4)$$

where α_i is the residual absorption coefficient in octave bands of the surface i, from 125 Hz to 4 kHz, and refers to the reflecting surfaces S_i of the hall, with walls coverable by the curtains S_{lw} excluded.

OC_A is the occupancy ratio (number of spectators/audience capacity).

S_s is the audience surface [m^2].

α_p is the absorption coefficient of the people [21].

α_s is the absorption coefficient of the empty seats at a given frequency.

CLW_c is the curtain ratio referred to the coverable walls (walls' surface covered by curtains/total surface of coverable walls by curtains).

α_c is the curtains absorption coefficient.

2.5. Electroacoustic Systems and Lighting Equipment

Nowadays, concert halls of medium or large size are provided with electroacoustic systems. Whatever their type and purpose is, there is a close interaction between the system and the room, and a concert halls' performance depends on the natural acoustical properties of the enclosure itself. Therefore, the installation and use of such a system requires also a careful acoustic design. Furthermore, without a knowledge of the acoustic factors responsible of sound reflections, reverberation, and other sound effects, it would hardly be possible to plan, install, and operate electroacoustic systems with optimal performance without considering the natural acoustic response of the room.

Often, this equipment is installed in concert halls as a support for speech and electroacoustic music. Originating around the middle of the 20th century, electroacoustic music was followed by the incorporation of electric sound production into compositional practice. The initial developments in electroacoustic music composition to fixed media during the 20th century are associated with the activities of the Groupe de Recherche's musicales at the ORTF in Paris, the home of musique concrète; the Studio for Electronic Music in Cologne, where the focus was on the composition of elektronische Musik; and the Columbia–Princeton Electronic Music Center in New York City, where tape music, electronic music, and computer music were all explored. Practical electronic music instruments began to appear in the early 20th century, followed by "immersive audio systems" which were designed to produce a fully immersive experience wherein the sound is perceived as coming from all around the audience seats. Electroacoustic music may require a shorter reverberation time than natural classical music.

In the early 20th century, new lighting systems also began to appear, which used the new LED lamp technology. Because of their low operating temperature, LED lamps do not lose as much heat as previous lamp systems, reducing their effects on the thermo-hygrometric conditions, especially when on stage for illuminating musician scores during concerts, a scenario that cannot be neglected in any case.

3. Methodology

In the digital transformation era, adaptive concert halls (ACHs) were introduced through digital twins in the architecture, engineering, and construction (AEC) industry as part of the level of process automation and control towards Construction 4.0. The proposed methodology allows for adaptive concert halls to incorporate the ability to detect and control all the main factors (explained in the previous section) that directly or indirectly influence the room acoustic quality. A dynamic process optimization to support the building lifecycle management (BLM) is applied, which is especially useful before and during a concert.

Computerization and digitization are introduced in the presented methodology as they begin to have a significant impact on how physical/engineering properties can be handled during the life cycle of the building [31,32]. The acquisition, exchange, use, and control of data and information throughout an asset's entire life are, in fact, considered to be among the most challenging aspects of implementing building information modelling, so-called BIM, in asset management [33]. Digital twins (DTs), and the Internet of Things (IoT), on the other hand, have drawn interest because of their synergistic and information-management functionalities [34].

In this methodology, it is assumed that the passive room acoustic quality of the physical space of the ACH is already defined in the design and construction phase according to the intended use, i.e., mainly for concerts requiring an almost natural acoustic response, while the DT is developed for visualization, modelling, simulation, and optimization of the room acoustic quality during the management phase, including concert execution.

The DT contains three main components to create a practical loop: a physical entity, a virtual entity, and a data link [35].

For the dynamic mapping in the DT, temperature, humidity, and air velocity data are gathered in the physical world and subsequently transmitted to the virtual world for further analysis. Optimization controls are achieved in the virtual model by learning data from the multiple sensors.

Acoustic parameters are collected through measurements in the commissioning phase; algorithms are implemented to offer prompt solutions to guide actual hall configurations in adaptation to changing contexts, including dynamic curtain positions and different occupancy rates.

The first algorithm calculates the curtains' area in real time and the CLW coefficient, knowing the curtains' position and their banner length (information coming from the sensors) and the curtain width (input value). In the second algorithm, Equation (3) is solved, and is included in the estimation of m as an interpolation of the data from the literature, with air humidity conditions coming from specific sensors.

The DT gathers and presents real-time data on the physical assets, utilizes these data to run various data-driven simulations, visualizes the 3D BIM, and introduces automation.

Through the use of sensors, encoders, actuators, and software of the curtain system which lowers the drapes from above, the position and stop level of the curtain can be known in real time, allowing for the relative absorption area to be calculated immediately through the first simple algorithm. A bidirectional system that manages the behavior of physical assets becomes possible in the DT, following the musicians' requests and visualizing the reverberation time.

The novelty of adaptive concert halls lies in that the DT allows for curtains to be moved during a performance, according to the composer's indications included in the score, introducing a natural dynamic acoustic response to the hall, which actively affects the performance of the music.

A previous necessary technical requirement for the engine that moves the curtains was that its noise must be minimized. Another necessary technical requirement was that the engine velocity had to be fast enough to create variable acoustic effects suitable for the composer's needs.

A third condition is the development of a notation that describes the adaptive hall as an active instrument included in the music score, as is analyzed in the following case study (Section 3).

The proposed methodology connects data coming from IoT devices and uses a visual programming language (VPL) to realize an interconnection workflow between the data collected and BIM authoring tools, including algorithms. BIM is used as the basis of a digital twin, which simulates the indoor conditions.

Data about indoor air temperature, relative humidity, and air velocity are gathered by sensors installed carefully inside the hall in order to evaluate the reverberation. These data are monitored, through specific thresholds, to verify indoor conditions. Specifically, the data are collected and organized in an excel file whilst considering specific thresholds related to the adopted parameters.

These thresholds comply with the standard (UNI EN ISO 7730) [36]. When the ranges are respected, a specific color code is displayed in the DT visualization; otherwise, if values are lower or higher than the thresholds, the values are reported as noncompliant and, consequently, they are displayed with another color code (Figure 3).

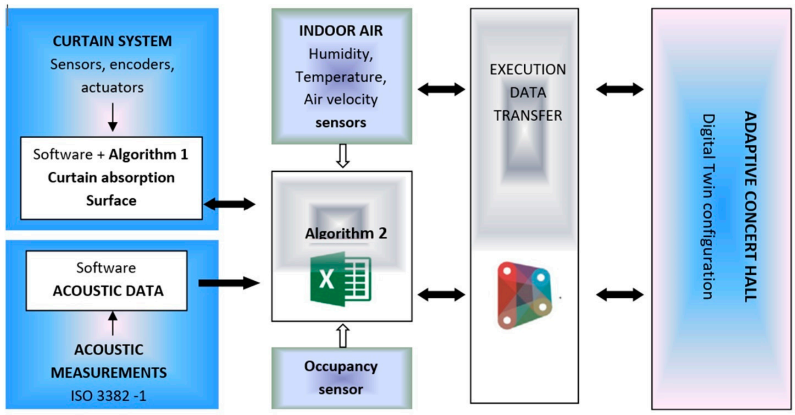

Figure 3. Integrated digital twin framework (VPL Dynamo version 2018, Excel version 2016).

The DT controls the project and the physical space in the operative phase. The digital model, in fact, contains both the main geometrical information and is also enriched with specific room acoustic and indoor air quality information. In the management phase, when the hall is available to concerts, the digital twin will simulate the air temperature, relative humidity, and curtain movements according to the requested dynamic or static acoustic response.

4. The Case Study

This case study refers to an auditorium for 1000 people, with its main use as concert hall, which is located inside the "Nuovo Teatro dell'Opera" in Florence (Italy). Designed by ABDR, the opera house was created to give a new permanent location to the Maggio Musicale Fiorentino, and it has become one of the largest opera houses in Europe, including a main hall for 1800 people and an outdoor auditorium with over 2000 seats. All its services include welcoming the public; rehearsals for orchestra, choir and dance; laboratories; dressing rooms; offices; restaurants; parking; and everything else necessary for artistic production.

The auditorium plan is rectangular in shape, measuring 20 m × 54 m ca. and is delimited by a sloping ceiling with an average height of 8.3 m. The effective acoustic volume is equal to ca. 11,800 m^3 (Figures 4–6).

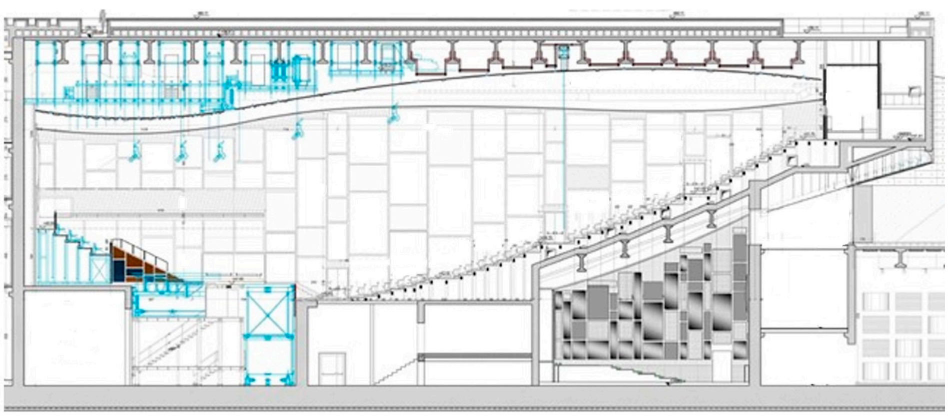

Figure 4. Auditorium longitudinal section.

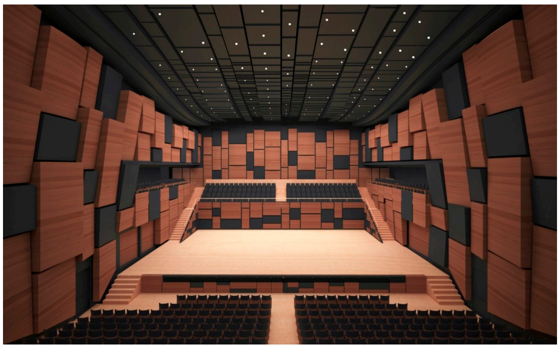

Figure 5. The auditorium stage.

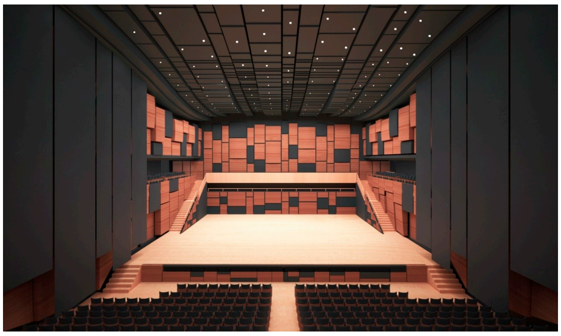

Figure 6. The auditorium curtains.

The space is surrounded by wood panel cladding and insertions of absorbing panels (35% ca. of the total vertical surfaces). On the lateral wall side, heavy curtains can come down to reduce the reverberation time according to an event's requests.

4.1. Acoustic Measurements

Acoustic measurements of the main acoustic parameters, including the strength G, were carried out following ISO UNI 3382-1 [30] during both a concert hall configuration and in empty conditions by using an omnidirectional source and a sine sweep signal. From the microphone and the analyzer, the signal was imported for real-time analysis and was utilized using post-processing noise and vibration software.

The omnidirectional source was put in two different positions and eight microphones were used (Figure 7).

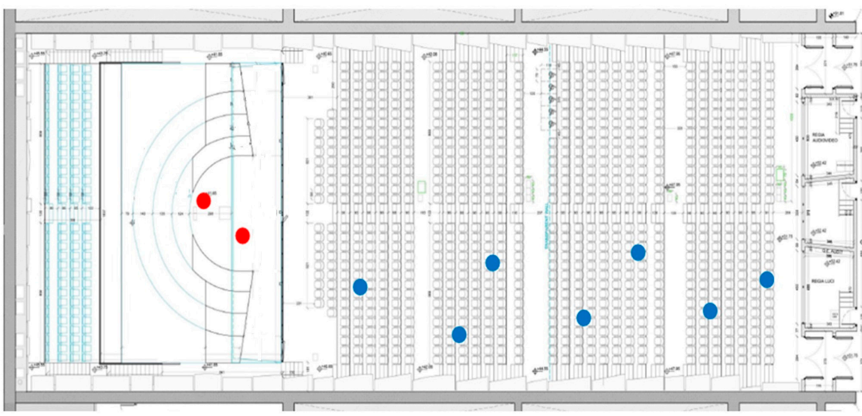

Figure 7. Microphone positions (colored blue) and source positions (colored red).

The equivalent background noise, Leq, was measured as equal to 26 dB(A). The measured air humidly and temperature were equal to 65% and T 22 °C, respectively. The measurement results of considering three curtains' positions are shown in Figures 8–10.

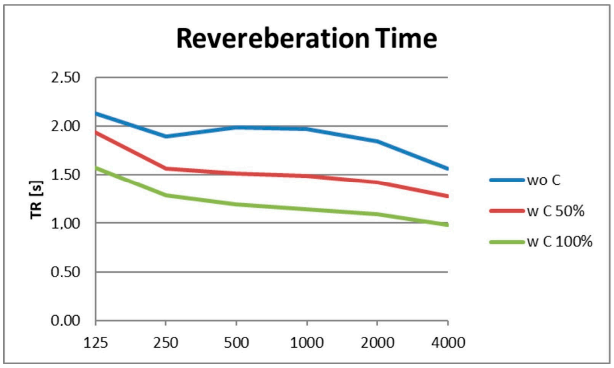

Figure 8. Average reverberation time without curtains (wo C), with 50% curtains (w C 50%), and with 100% curtains (w C 100%) down on the lateral walls, homogeneously distributed.

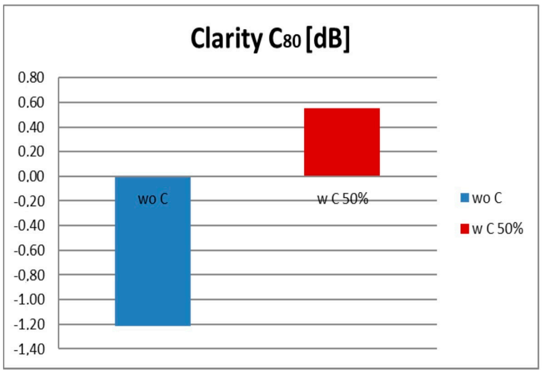

Figure 9. Average clarity index, C_{80}, without curtains (wo C) and with 50% curtains (w C 50%) down on the lateral walls.

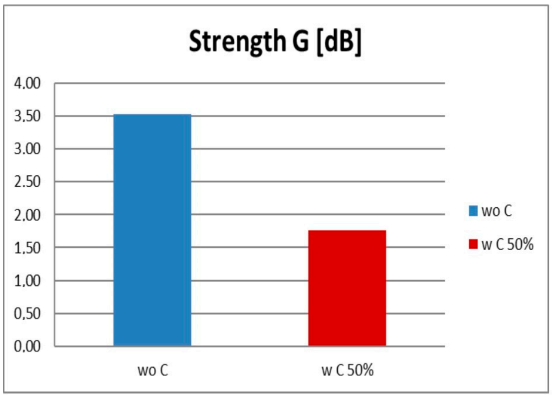

Figure 10. Average strength index, G, without curtains (wo C) and with 50% curtains (w C 50%) down on the lateral walls.

The configuration without curtains is compliant with the optimal range for concert halls as suggested by the literature, and the configuration with 100% curtains is recommended for use in cases of special requests for electroacoustic music. This configuration is not considered for congresses because another configuration of the stage is recommended by the acoustic design for this scope, with the stage of this concert hall being flexible enough to transform the space in a multipurpose room.

4.2. Air Distribution Systems

The entirety of the concert hall is air-conditioned by all-air systems. The air is introduced into the stalls via displacement diffusers integrated into the supports of single seats, with a flow rate of 45 m^3/h each. The connections for the air inlet of the diffusers are connected to two pressurized plenums under the wooden decks of the stalls, and do not communicate with each other. Temperature sensors are installed at different heights, but all are situated at a height no higher than 1.5 m from the floor. CO_2 and relative humidity sensors are also installed within the floor. Based on the signal from the sensors, the variation in the air flow rate, both in intake and exhaust, is determined. These signals also define the maximum air velocity (Figure 11).

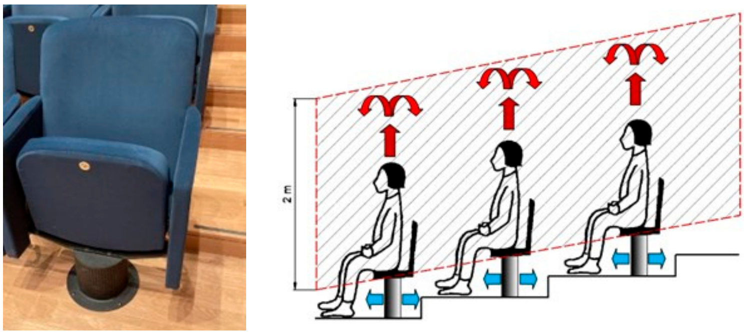

Figure 11. Single seat diffuser and heat load definition by volumetric heat source.

4.3. The Adaptive Concert Hall as an Active Musical Instrument

The auditorium of the "Nuovo Teatro dell'Opera" in Florence is an adaptive concert hall in which the acoustic response can vary rapidly during the execution of a piece of music, without introducing noise; the RT changes seamlessly, and the referred values are known in real time. This means that the concert hall can play an active rule during a music performance without being supported by electroacoustic equipment. The RT can be reduced from a high value, which falls in the optimal acoustic range for concert halls, to a target that usually refers to speech auditoria and vice versa. These characteristics make an adaptive concert hall different from a multipurpose room, in which variable acoustic movements usually increase the background noise at unwanted levels and, in most cases, RT variations are slow and refer only to preset configurations.

In the case study, the curtain movement speed, which changes the reverberation time, is controlled by the DT to ensure that the composer's requests are met as well as to allow for simulations to evaluate the values of RT in real time.

For musical instruments which are not electrically amplified, the sound pressure level in the space is determined by type and number of musical instruments playing at the same time, the style of playing, and the dynamic expression, while the audience's perception of the sound pressure level changes, especially according to the reverberation time of the hall. If the reverberation time is too long, the sound becomes thick and unclear. However, if the reverberation time is too short, the music becomes 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 of a problem for piano and string instruments, which have a built-in sound board.

If the hall is not active, i.e., if it is a passive one, musical instruments can be played at different sound powers during a concert while the reverberation time remains constant for the entire execution of the piece, especially if the concert is not amplified with electroacoustic equipment.

In an orchestra score, the most common instrument dynamic designations for different sound power are indicated. They are pianissimo–piano–mezzoforte–forte–fortissimo (pp–p–mf–f–ff). Pianissimo specifies that the sound is very quiet but still with timbre; fortissimo is very loud, but without the timbre being distorted. There are also ppp (extremely quiet) and fff (extremely loud).

The dynamic range from pp to ff for solo musical instruments is typically around 25 dB(A) to 30 dB(A), somewhat less for the flute and the oboe, and somewhat more for the clarinet and the horn. An orchestra may have a dynamic range between 50 dB and 60 dB. This dynamic range also depends on the musician's proficiency.

In analogy with the dynamics of musical instruments, a new designation is proposed for the reverberation of an active concert hall to be included in the score, as discussed with composers of the Santa Cecilia School in Rome.

The highest reverberation time condition, the target suggested by the literature for concert halls, is indicated with RR, and it usually refers to the highest possible reverberation time of the hall.

In the case study (with the agreement of the composer who will be commissioned to write a new piece that includes the active room response), when the RT is reduced seamlessly achieving the measured value for 50% curtain deployment, the reverberation time is identified as mR and the RT equal to the last measured configuration 100% curtain deployment is indicated as DD.

The designation can be generalized to concert halls in which the acoustic response can vary rapidly without introducing noise during the variable acoustic elements 'movement', the RT can change seamlessly, and the referred values are known in real time from the concert hall range RR to the congress range DD (Table 1). A control through a DT to identify all the RT in between to properly assign the designation (R, mR, D) has to be included (Table 1).

Table 1. Dynamic designations' analogy between musical instruments and active concert halls.

Dynamic Designations' Analogy	
Musical Instruments	**Active Concert Halls**
pp	RR
p	R
mf	mR
f	D
ff	DD

At the beginning of the score, over the treble or bass clef of the pentagram, the composer indicates the initial reverberation condition of the hall; then, under the pentagram, corresponding to the beat in which the reverberation time change happens, the dynamics of the room's response is indicated as happens when the dynamics of musical instruments are specified (Figure 12).

The dynamic designation of the concert is visualized in the DT.

For the composers involved in the designation, the dynamic range of the hall must be big enough to gradually identify the five different steps from RR to DD and vice versa, also considering a precise equal interval from each corresponding RT subdivision (RR, R, mR, D, DD) to be less relevant. To define the hall as an active space, however, the total RT dynamic range has to be estimated at no less than 0.8 s.

For these reasons, the two configurations, characterized by homogeneously distributed curtains equal to the 25% and 75%, were accepted to create the dynamic responses, R and D, of the hall. For the same reasons, and since the measurements determined three main dynamic steps (RR, mR, DD), an interpolation was accepted to discover the corresponding RT values for R and D.

Generally, since evaluation of the RT dynamic range has been considered to be much more important than the precise determination of the RT values of every single dynamic range subdivision, the estimate of the corresponding curtain area % (or vice versa) was considered to be acceptable by applying the Sabine equation in real time via digital twin.

A database with the same information, coming from a room acoustic software prediction, could be also uploaded in the DT architecture [5].

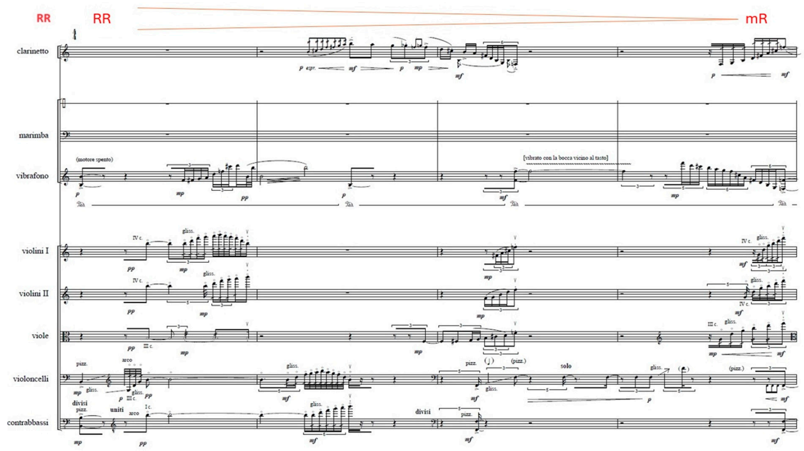

Figure 12. Included in a score; an example of dynamic designations for an active concert hall are indicated in red.

Computer simulations could be especially useful in spaces characterized by complex geometry, such as vineyard concert halls, to optimize the RT homogeneity based on a curtain's location and possible asymmetric distributions. Considering that the hall dynamic plays a 'role in a score', composers have considered the study of other acoustic parameters to be secondary and have confirmed the use of the Sabine equation as sufficient for their purpose.

Whether using computer simulations or simplified algorithms to control the dynamics of the hall, specific encoders need to be installed to read the curtains' banner length. In fact, curtain control systems usually memorize a layout, but they are not able to read the curtain dimensions unrolled in the hall.

These specific encoders are absolute encoders that generate unique position values, and they work like "lap counters" of the curtain bar. Information about the number of revolutions of the bar on specific the curtain unrolls, the position, the angle of rotation, or the speed can all be derived.

Sensors can communicate with a programmable logic controller, which is part of the curtain control system. Their information is exported to be part of the DT process and visualization.

Curtain movements are recorded by the control system from a starting point to a stopping point. A preset time (subject to maximum speed) and a preset speed, with a default acceleration or deceleration towards a registered profile (using joystick or gear wheel), are included.

During a concert, the selected and recorded positions are recalled by an operator who then follows the conductor's indications to ensure that the same effects obtained during the rehearsals are repeated according to the hall dynamics in the score.

The methodology opens infinite possible scenarios and does not exclude the use of the active dynamics of the hall in combination with electroacoustic equipment.

In many concert halls, in fact, to obtain special effects, an immersive sound system is installed (which is also able to reintroduce the dynamic from DD to RR in the hall).

Composers that study electroacoustic composition appreciate a multi-speaker setup and electroacoustic diffusion techniques, but they agree that an active hall does not have to be excluded because of the different natures of acoustic response and the interesting new combinations to introduce into a score.

Electroacoustic systems become irreplaceable if the natural acoustic quality is lacking. An example of this is the Sphere in Las Vegas, where an electroacoustics immersive sound system has been installed.

Using a DT to collect data arriving from different equipment, such as audiovisual technologies, LED systems, and stage craft systems, could be useful in extending the immersive experience to all the senses. Audiovisual technology (audio, still picture, video, animation), for example, has increased quickly in the last decade and is rapidly converging to integrated multimedia [37].

Furthermore, an alternative method of data representation could be developed in DTs, for example, a visual video overlay showing the sound reflections [38].

The development of algorithms could help to transform adaptive concert halls in cognitive buildings for both music and sensorial experiences in general, whilst also controlling the air quality and the energy saving.

5. Conclusions

The adaptive concert hall (ACH) is a model realized through DTs for visualization, simulation, analysis, prediction, and optimization of the room acoustic quality during the operation and maintenance phases to transform a static hall space into an active musical instrument that interacts with the orchestra without any electroacoustic equipment support, whilst also optimizing the indoor air quality.

DTs contain information on the physical entity for which the main acoustic properties are defined during the design, construction, and commissioning phases; a virtual entity; and data links. Temperature, humidity, and air velocity data are gathered in the physical world and subsequently transmitted to the virtual world for further analysis to ensure that the target environmental conditions are met and that adequate intercorrelations with the acoustic parameters when the concert hall is put into operation occur before and during the concerts.

Simulation, prediction, and properties' optimization are achieved in the virtual model by learning data from acoustic measurements and curtain systems that control these positions, and also by using algorithms which offer prompt solutions to guide a room's acoustic response for adaptation in the changing contexts of musical execution as indicated by the composer's score.

An ACH shares common characteristics with other buildings involved in the architecture, engineering, and construction industry (AEC); its features can be enlarged, gathering and presenting much of the real-time data on physical assets through continuous analytics from historical data, providing helpful insight. Visualization could be improved (live 3D BIM models, videos of the physical asset, and immersive visualizations), and automation could increase the bidirectional system that manages the behavior of all the technological equipment during concert and rehearsal activities.

Virtualization in a dynamic, run-time process allows for a digital counterpart's behavioral model to be constantly modified, thus emulating the physical element's actions and perhaps becoming a support for a composer's creativity during the writing of a new score.

Further research could be developed on using DTs for ACHs, including on cognitive abilities, with detection of anomalies and behavioral learning, and on the definition of physical twin actions, to improve measures, defining their states or functions to know the room acoustic quality in every possible curtain layout and occupancy condition. The cognitive digital twin (CDT) could represent an evolution of the DT concept that is better standardized and improved.

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