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Analysis of the Development of Acoustic Environment in Chinese Theater Architecture Based on SoundPLAN: A Case Study of the Wuhan Region

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Abstract

Considering that previous literature has focused on the structure, performance space, and acoustic design of ancient and modern theater buildings but neglected the changes, contexts, sound transmission characteristics of performances, and the connections between them, This study aims to investigate the factors that have influenced the evolution of ancient and modern Chinese theater architecture, as well as the changes in the acoustic environment of the performance space during the evolution process. This study uses SoundPLAN acoustic simulation software to simulate the acoustic environments of representative theater buildings in Wuhan in various historical periods and to obtain the sound pressure level distribution of each performance space under different sound sources. It can be found through the analysis that the performance space gradually becomes an independent theater building with the change of history; the theater building gradually evolves from outdoor open type to indoor closed type; the quality of the architectural space and acoustic environment improves with the updating of the structure and the material; different performance sound sources located in different positions on the stage are arranged according to the acoustic characteristics, which will make the quality of the acoustic environment improve. On this basis, the intrinsic relationship between the acoustic environment of theater buildings and musical instruments, the economy, acoustic experience measures, and socio-cultural backgrounds is investigated, and it is concluded that there is a correlation between them. To provide reference value for the restoration and new construction of theater-type buildings in China.

Keywords*:* Brief history of theatre; Viewing space; SoundPLAN; Acoustic Environment; Wuhan.

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1. Introduction

Theatrical buildings have evolved from ancient open-air styles to modern indoor enclosed spaces, integrating functions such as lectures, gatherings, and performances. With increasing attention to architectural form, decoration, and acoustic environments, these aspects have begun to develop in conjunction. Research in these areas not only provides references for the restoration of historical theatrical buildings but also offers new ideas for the integration and construction of modern theaters with regional characteristics.

Recent studies have revealed the development of theatrical buildings and their acoustic characteristics. Acoustic researchers have delved into the acoustic properties of theaters and temples from different historical periods and cultural backgrounds through 3D modeling, acoustic simulation 3D modeling, acoustic simulation, on-site measurements, and digital models. Research has found that the acoustic design of different theaters is suitable for oral and musical performances, and the audience has a significant impact on acoustic characteristics (Tronchin et al., 2020; Tronchin et al., 2023). Acoustic simulation can guide the stage design of theaters (Boa et al., 2015). There are significant differences in the acoustic environments between semi-open and enclosed theaters (Vassilantonopoulos et al., 2009). Additionally, GIRÓN et al. (2020) studied the acoustic characteristics of ancient open-air theaters, and Zhang et al. (2020) measured and simulated the acoustic environment of traditional Han Buddhist temple courtyards (open-air). Moreover, the functions of theatrical buildings are diverse, not only including music performances but also serving as venues for circus performances (Quintana et al., 2022; Bustamante et al., 2014). Some scholars have analyzed the acoustic characteristics of historical theaters (Bevilacqua et al., 2023; Berardi et al., 2020; Ciaburro et al., 2020) and proposed improvements. Other scholars have compared different theaters to analyze the causes of differences in acoustic environments (Kamisiński et al., 2010; Chourmouziadou et al., 2007). Wang et al. (2012) conducted an acoustic survey of traditional Chinese theaters, discussing their architectural forms and acoustic characteristics, deepening the study of the relationship between the acoustic environment and the building itself. Prodi et al. (2016) studied the role of acoustics in the restoration process of historic opera houses.

Lu, X. D. (2009) analyzed and summarized the development of Chinese theatrical buildings since modern times; Peng et al. (2020) simulated the acoustic environment of the courtyard theater of the Wu Clan Ancestral Hall in Hong'an County; Che, W. M. (2011) conducted measurement research on the stages of the Jin, Yuan, Ming, and Qing dynasties, and discussed the deep development logic of the stages in conjunction with the economic and cultural background of the times and the troupes; Luo, D. Y., & Qin, Y. G. (2002) analyzed and divided the relationship between Chinese opera and the development of ancient theaters; Wang, J. Q. (2002) and Ge, J. (1997), based on the study of ancient theater viewing space literature and on-site measurements, conducted a large number of simulation experiments, analyzing the feasibility of the acoustic design of ancient theater viewing spaces, mainly involving the structural style of the stage and acoustic treatment measures, the reverberation of courtyard theaters, changes in sound field intensity with different viewing space layouts, the acoustic effects produced by changes in the position of the band, and the exploration of ancient historical issues such as the placement of urns and water jars under the stage to assist with sound. In addition, some scholars have analyzed and simulated the viewing spaces of existing ancient theaters and modern theaters, proposing a series of factors that affect the viewing space acoustic environment and conducting simulation experiments to demonstrate (Zhu, X. D., 2020; Cao, X. Z., 1999). Liu, Y. (2018) analyzed and summarized the origin and development of Chinese musical instruments through the dynasties and compared Chinese and Western musical instruments. These studies not only provide valuable information for our understanding of the acoustic characteristics of theatrical buildings but also provide a scientific basis for the design and restoration of modern theaters.

Currently, research on theatrical buildings remains a hot topic. Some studies have explored various aspects of theatrical buildings in different countries and regions, including the structure of the buildings, architectural space forms, construction materials, acoustic structures, and acoustic environments. However, it should be pointed out that these studies are limited to singular research in theory, architectural physics, and acoustics, or they ignore the impact of the construction background of different theatrical buildings on the acoustic environment, or they overlook the impact of building skin materials on sound propagation in acoustic simulation, failing to comprehensively consider regional culture, social background, types of drama, musical instruments, and other factors.

To fill the gap in the aforementioned research and deepen the understanding of the acoustic environment of theatrical buildings, this study, based on a thorough understanding of the background and comprehensive consideration of these influencing factors, uses the architectural acoustic environment simulation software SoundPALN8.2 to simulate the acoustic environment of representative theatrical buildings in Wuhan, Hubei Province, from the Qing Dynasty, modern times, and after the founding of the People's Republic of China, analyzing the sound pressure level distribution in the viewing spaces of these three periods of theatrical buildings, and then discussing whether such an acoustic environment can provide a good listening experience, finally presenting my views on the intrinsic relationship between the acoustic environment of the viewing space of theatrical buildings and musical instruments, economy, acoustic experience measures, and social and cultural background. We summarize the contributions of this study as follows: First, the development of theatrical buildings is greatly related to social policies and culture. The quality of the acoustic environment of theatrical buildings has been continuously improved with the improvement of the social system, construction materials, and architectural structures. Different musical instruments at the same performance position will create different acoustic environment qualities, which will affect the arrangement of the band's position. The rest of the structure of this paper is as follows: The second part introduces the data sources and research methods. The third part studies and summarizes the research on theatrical buildings and the evolution of the viewing and listening environment of Wuhan City before modern times, during modern times, and after the founding of the nation, including society, architectural structure, and acoustics. The fourth part simulates and analyzes the simulation results of representative theaters from three periods in Wuhan City. The fifth part discusses based on the experimental results. The sixth part concludes and looks forward.

2. Material (A Brief History of Acoustic Environment Development in Chinese Theatre Architectures)

2.1 A Brief History of the Evolution of the Audiovisual Environment in the Pre-20th Century Theatre

Ancient theatre performance can be traced back to primitive society, at this time the viewing space had not yet been formed, mainly outdoor open-air places, and the conditions were simple, with randomness. At this time there was no division of social classes, and social ideology was not formed, so the performance served everyone. The nature of performances was mainly rituals and exorcisms. The stage and the auditorium were mixed together and were more random. Musical instruments had not yet appeared and could be equated with musical instruments were animal skin drums or shell strings and other simple devices; to the Shang, Zhou, Spring, and Autumn Periods, there were songs and dances, and the viewing space began to depend on the building. Due to the establishment of the dynasty, social hierarchies were beginning to differentiate, performance began to carry the attributes of the aristocracy, and the performances available to commoners were limited by the feudal hierarchy. Outdoor performances were mainly for ceremonial activities and could be played on the hillside, which facilitated the spread of sound. Indoor performances were mostly held in the hall, with guests surrounding the perimeter of the stage, and the stage and auditorium began to be partitioned. At this time, with the emergence of musical instruments such as chimes and chimes, this kind of percussion instrument had a long sustaining time, well adapted to the period of weak enclosure, and weak confinement. Depending on the large viewing space of the hall, the sound could be transmitted to the audience for a long time; After the unification of the state of Qin, the musical performances of other countries were unified, and the development of multiple types of opera performances was limited, but the types of musical instruments at this time were enriched after the unification, and the collection of all the world's musical instruments in one country contributed to the development of acoustic music, with the emergence of plucked and blown wind instruments such as konghou, Chiku, fou, horn, and bili (wind instrument). During the Wei, Jin, and North-South Dynasties, Buddhism was introduced, and with it, Buddhist music. Under the Buddhist law of equality of all beings, nobles, and commoners established ties through Buddhism, and Buddhist cultural performances were geared toward the general public. Bowls and wooden fish were used in the performances. During the Sui and Tang dynasties, the rulers administered benevolent policies and shared their joy with the people. Theatre performances were liberalized and shared by all. At this time, due to the increase in the number of spectators, the theatre stage and the auditorium were partitioned in consideration of sight lines, and there were music shacks on the streets specifically for performances. After the cancellation of the Rifang system in the Song Dynasty (Pan, G. X., 2015), there was an unprecedented development of civic and recreational activities, and the theatre showed diversity and prosperity. Overall, the Song Dynasty period was important in the development of Chinese opera, which not only witnessed the prosperity of court opera but also promoted the popularity and development of traditional music and rap art, laying a solid foundation for the creation and performance of opera for the later generations; the function of the theatre in the Yuan Dynasty became diversified into a performance area in the foreground and a make-up and preparation room in the background. More significant is that the viewing space at this time took into account the architectural physical acoustics of the setup, in front of the stage built a figure-of-eight shaped side wall (Wang, J. Q., 2002), to strengthen the acoustic reflections on the stage, reduce the loss of sound in the front part of the audience area, and to enhance the auditory effect of the audience on the backside.

The three towns of Wuhan during the Ming and Qing dynasties, with their well-developed shipping business, were dominated in this period by guild buildings (the liaison centers of provincial and municipal caravans in

Han), which generally had viewing spaces inside, mainly courtyard and indoor styles. The stage in the courtyard space on one side of the two-story platform, the audience sat in the courtyard. Indoor space is relatively small, with the stage on one side, the audience area set with seven or eight sets of tables and chairs, and benches. In short, theatre performances in Wuhan gradually had fixed venues, attached to temples, ancestral halls, guild halls, and villages also had theatres built. The evolution of traditional Chinese musical instruments was also basically shaped at this time.

2.2 A Brief History of the Evolution of the Audiovisual Environment of Modern Theatre in Wuhan

Wuhan region of modern theatre class building was built in 1861 when the year was the opening of Hankou, commercial prosperity, increasing theatre and entertainment projects, the number of buildings with viewing spaces is also increasing at this time (Guo et al., 2021). At the end of the Qing Dynasty, the more mature theater type of buildings are tea gardens, tea houses, theaters, etc. Dangui Tea Garden, Wuhan's earliest tea garden (Wuhan Local History Compilation Committee., 1998), was built in 1899, singing Peking Opera, according to records, its scale is not very large, simple equipment, belonging to the indoor hall-type performance space, the use of acoustic measures are not advanced. The invasion of foreign barbarians brought Western theatre design principles, these Western theatres from the design principles, and materials to the internal spatial layout of China's traditional theatre building acoustic environment at that time had a great impact, including the transformation of existing theatre buildings and the design and construction of new theatre buildings.

In the socio-political background of the fierce battle between the old and the new, the advanced people advocated the abolition of the old culture, and the traditional theatre was also involved, which led to the improvement of the traditional interpretation venues, and the introduction of the "advanced knowledge and technology" from the West. In the theatre category, mainly theatre design, construction techniques, new materials, stage sets, lighting effects, etc. were introduced. To make profits, businessmen arbitrarily piled up Western theatre technology.

In terms of the stage, the framed stage has been evolving ever since it was introduced to China, and if you describe it in terms of the modern cinema experience, the Western framed stage gives a "2D" perspective, whereas traditional theatre performances are more suited to creating "3D" special effects. Traditional theatre performances are more suitable for creating "3D" special effects. Therefore, part of the frame stage began to localize, to meet the needs of the performance, and the lip of the stage will be picked out, to expand the scope of the performance space. Later, in order not to pick out too long lips, the stage looked more abrupt, It reduced the amount of lip picking, on the side of the stage to increase the small stage, some increase one, some of the viewing space area is large, it increased the symmetry of the double side of the small stage, according to the needs of the performance of the choice of whether or not to use the side of the stage.

In the section of the auditorium, the seats were changed from teahouses to rows of seats, and some theaters eliminated the pedestal columns in order not to block the view and to facilitate the propagation of sound (Guo, T. K., 2013); The theater has been renovated with two levels, upstairs and downstairs, with raised seating. In the audience area, tables may no longer be placed, and private booths upstairs may be removed to increase seating capacity. The stage has been equipped with additional technical features such as curtains and lighting, and backstage storage rooms have been added. The audio-visual environment has been enhanced compared to before. However, being profit-oriented, the management hasn't effectively controlled the proportion of seats to the overall space, resulting in some seats still having subpar audio-visual effects. In newly constructed large theaters, a Western-style proscenium stage has been introduced, replacing the traditional three-sided stage. Audience seating is concentrated directly in front of the stage, with curtains and side walls added to aid sound dispersion towards the audience, reducing early sound energy loss to the sides. However, these features may seem redundant in relatively small traditional Chinese theaters and performance spaces, with maximum spans of only 12m. The proscenium stage treatment makes the space appear isolated, losing its three-dimensional effect and obstructing the view of side spectators. It also limits performers' ability to extend performance space and the audience's imagination.

In terms of architectural structure, influenced by Western theater design principles and materials, newly constructed theater buildings often use reinforced concrete, significantly increasing spans compared to traditional wooden structures, thereby enlarging the internal performance space. The structural requirements for cantilevered balconies are met without the need for bottom pillars, improving the acoustic environment quality for audience seating on the lower levels.

In terms of functionality, theaters are no longer solely dedicated to one purpose. With the introduction of movies and the need for various indoor lecture halls, theaters now often serve multiple functions, including drama performances, movie screenings, and lectures. This multipurpose usage can create a blend of requirements, leading to certain incompatibilities in the audio-visual environment between the different functions. At the time, there weren't advanced technological measures to address these drawbacks, resulting in a diminished audience experience.

2.3 A Brief History of the Evolution of the Audio-visual Environment in Wuhan Theatres after the Founding of the People's Republic of China

After the founding of the People's Republic of China, the nature of theaters underwent a significant transformation. Before the founding of the nation, theaters were primarily driven by commercial interests, but afterward, with the shift in societal values, theaters assumed a more political role, oriented towards serving the people. This led to a wave of renovations aimed at rectifying numerous infrastructural deficiencies inherited from the previous era of profit-driven operations. The renovations involved removing seats located outside the optimal viewing angles, installing sound reflective panels, adding auxiliary service rooms, and overall, enhancing the audiovisual environment of the theaters. Regarding improvements in acoustic technology, they were influenced by Western innovations while incorporating local expertise. However, the acoustic design process remained in a stage of emulation, unable to fully address certain underlying acoustic shortcomings at the time.

In terms of stage design, there was a significant influence from the advanced technology of German mechanical stages. The layout shifted from the traditional "品" character-shaped arrangement to a completely symmetrical stage, with spatial constraints and on-demand usage. This design, combined with the use of mirror-framed stages, aligned with the formal requirements of socialism and demonstrated solidarity with the friendly alliance with the Soviet Union. Later, influenced by North Korean theaters, the stage area was enlarged, leading to increased absorption of sound, which was not conducive to audiovisual experiences for the audience area. Subsequently, adjustments were made to reduce the stage size to an appropriate dimension (Lu, X. D., 2009).

At this point, theaters have evolved into multipurpose venues catering to theater performances, movie screenings, and lectures. The design of new theaters now requires simultaneous consideration of acoustic, lighting, projection room, and advanced stage equipment layout factors. To meet the diverse needs of these functions, the approach at the time was to compromise by designing and constructing with intermediate values for various indicators. This approach generally met the overall usage requirements.

The theatre incorporates traditional Chinese elements into the general layout design, adding courtyards and other elements to enhance the sense of visual experience and not make the theatre building look so rigid.

In the Wuhan region, several theaters have been constructed, with the most notable being the Wuhan Theater completed in 1959, which has undergone multiple renovations over the past sixty years and remains in use today. Another prominent example is the Victory Theater of Rehe Military District, established in 1945, and renamed Wuhan People's Art Theatre in 2012. These theaters represent mature cases, with ongoing upgrades to their internal facilities. As of today, the audio-visual environments have reached a stable stage.

3. Methods (Data sources and research methods)

The drawings and other information about the theater building were obtained from the field survey and the archives of the theater building. Firstly, CAD software was used to make the necessary drawings for the simulation and then imported into SoundPLAN software for modeling. For the open-air performance space, the outdoor modeling section was selected. For an enclosed indoor performance space, the indoor modeling section was selected. Based on the collected information, the acoustic parameters of the building materials are imported into the database and the acoustic parameters of the building components are set in the model. Finally, the analysis interface is selected as needed, and the experimental results can be obtained after the analysis, which include: a two-dimensional plan view, three-dimensional stereo view, and sectional view. The results include a 2D plan view, 3D stereo view, and profile view. This kind of result illustration can observe the sound pressure level of each sound source receiving point in an all-around way (Figure 1).

SoundPLAN is a professional acoustic modeling and noise simulation software designed to provide engineers, planners, and environmental scientists with powerful tools for evaluating and dealing with sound and vibration problems. soundPLAN's modeling, calculations, and evaluations are based on ISO and other standards and transform real-life environments into abstract mathematical models, which are automatically calculated, with the types of calculations selected according to the user's needs. The types of calculations are chosen according to the user's needs, including sound perimeter maps, color gradient maps, sound pressure level distribution on the surface of buildings, sound calculations at specific points, etc., which satisfy the requirements of various indicators of the EIA. Users can create scenarios with real terrain and buildings in the virtual environment to accurately simulate the propagation path of sound waves.

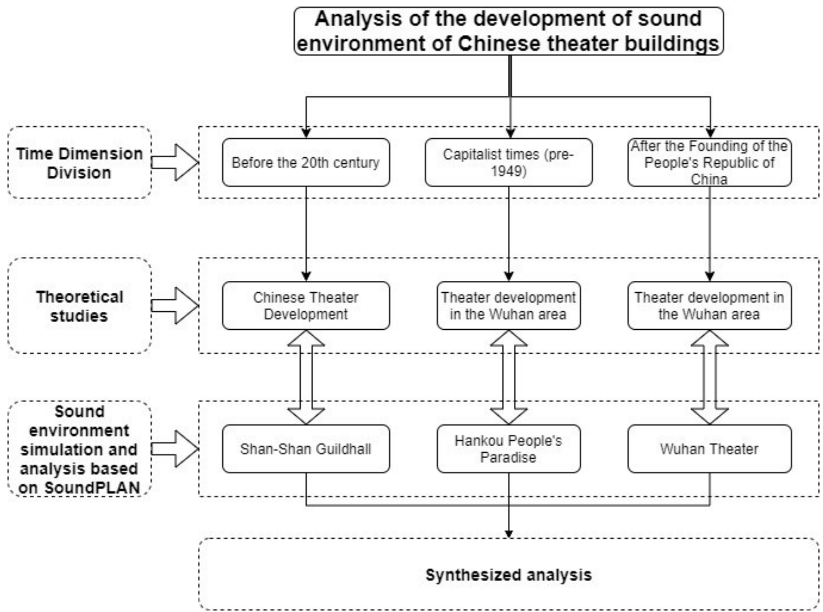


Figure 1. The research framework of this paper.

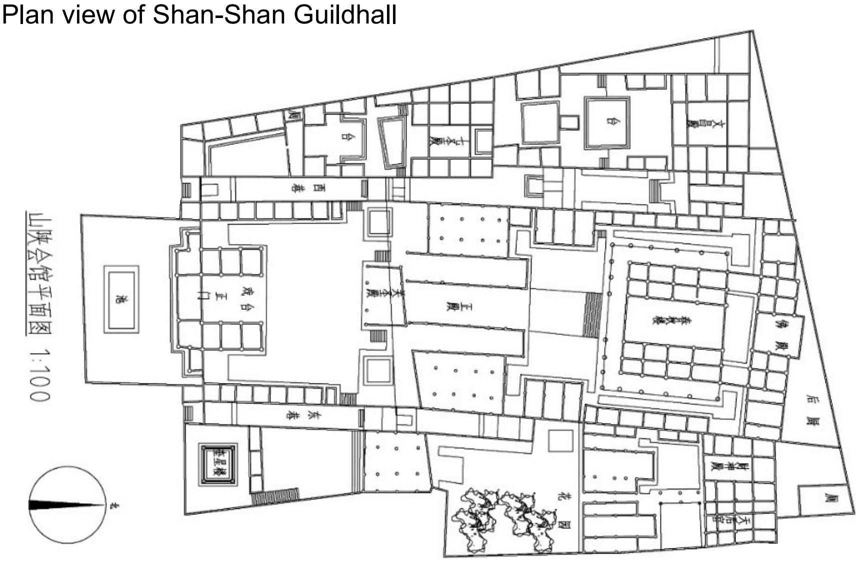
3.1. SoundPLAN-based Simulation of Wuhan Theatre Acoustic Environments in Various Periods of Time

3.1.1 Example of simulation of the acoustic environment of the pre-20th century theatre

a) Introduction to the Hankou Shan-Shaan Guildhall

The Shan-Shan Guildhall was completed in the 22nd year of the Kangxi Emperor (1683 AD) and was damaged during the Taiping Rebellion. After 25 years of reconstruction, it was completed in the 21st year of the Guangxu Emperor (1895 AD). Based on the surviving illustrations in the " Shan-Shan Guildhall Chronicle," a floor plan of the Shanxi Guild Hall can be drawn (Figure 2a). Additionally, modeling and simulating the central theater space for performances (Tian, L. S., 2016) (Figure 2b) can be conducted.

a) Plan view of Shan-Shan Guildhall



b) Central courtyard-style performance space of Shan-Shan Guildhall.

Figure 2. Shan-Shan Guildhall. (Tian, L. S., 2016).

b) Model construction and related parameter settings

The viewing space in the middle of Shan-Shan Guildhall can be qualified as China's traditional open courtyard type, with a fully absorbing roof (Peng et al., 2020), the simulation type of this space is set as outdoor acoustic environment analysis when doing the simulation in SoundPLAN, and the modeling is completed in the Outdoor Module, which is mainly a courtyard surrounded by the stage in the south, the main hall in the north, and two-story compartments on the east and west sides (Figure 6a). The singing voice of the Chinese traditional opera performer is extremely loud, so the sound source parameters are set as a point source (Voice level, very single value), sound power level LwA=89.0dB. According to the traditional Chinese theatrical performance mode, the sound source of performers is generally located at the front and center of the stage. Referring to the average seated height of 1.5 meters for individuals in China, plus the stage structure elevation of 3.5 meters, the total height of the sound source above the ground is 5.0 meters.

This hall was built in the Qing Dynasty when the main frame structure was made of wood and the enclosure was built with brick masonry. Therefore, when building the model in SoundPLAN, the material for the external wall enclosure structure is set to "Brick wall", and the absorption spectrum of the surface of the brick wall is imported.

According to relevant anthropometric principles, the seated height of a person is typically 1/2 to 1/3 of their standing height. Therefore, the height of the sound source-receiver horizontal plane in the courtyard is set at 0.7 meters. Following traditional viewing habits, the height of the sound source-receiver point on the second floor is the height of the second floor (floor height h=3.5 meters) plus the height of the audience leaning against the railing (approximately 1.5 meters), making the sound source-receiver point height set at 5.0 meters.

3.1.2 Example of simulation of the acoustic environment of modern theatres in Wuhan

a) Introduction to the Hankou People's Paradise

According to Wuhan Municipal Records - Cultural, People's Paradise is the largest comprehensive cultural amusement center in Wuhan, built after Shanghai Big World. It is located in the downtown area of Liuduqiao, Zhongshan Road, Jianghan District, Hankou, covering an area of 12,200 square meters and using an area of 17,100 square meters. There are 18 large and small theatres built in the park. According to the drawings drawn by exploration (Jiang et al., 2000) and historical information to model and do simulation analysis of a viewing space in the popular paradise.

b) Model construction and related parameter setting

The viewing space of People's Park is an indoor large space located within a commercial complex building. In SoundPLAN, when conducting simulation analysis, this space is categorized as indoor acoustic environment analysis. A wooden stage is constructed indoors, with several tables, chairs, and benches arranged for the audience. A wide aisle is left in the middle of the audience area as the performers' stage space, with tables, chairs, and benches placed on both sides of the aisle (Figure 8a), the sound source parameters are set as point Sound source (Voice level, very loud-Single value), sound power level LwA = 89.0dB. At this time, the height of the indoor performance stage is only three or five steps high, 0.6m, concerning the average seated height of 1.5 meters for individuals in China, the sound source from the ground for a total height of 2.1m.

This entertainment arcade was built in modern times when the main frame structure was already made of reinforced concrete, the enclosure structure was made of brick or stone masonry with washed and polished stone, and the floor slab was a 120mm thick reinforced concrete layer cast-in-place. When the model is built in Sound PLAN, the material of the floor layer is set as concrete; the material of the enclosing structure of the four external walls is set as Brick wall. According to the relevant content of ergonomics, the height of a person when sitting down is 1/2~1/3 of the height when standing up, so the height of the horizontal plane of the sound source reception in the audience area is 0.7m.

3.1.3 Example of simulation of the acoustic environment of theatres in Wuhan after the founding of the People's Republic of China

a) Introduction to the Wuhan Theater

The Wuhan Theatre blends the style of Soviet architecture with the characteristics of traditional Chinese architecture to build a closed modern architectural theatre (Figure 3a-3b). The building plan highlights the symmetry of the central axis, with the center as the main, the main viewing space is arranged in this center, and various auxiliary spaces are arranged around the center. These auxiliary spaces play a key role in the isolation of external noise. At the same time, the roof is made of cast-in-place reinforced concrete, and the ceiling is elevated (Ding, X. Y., 2021) (Figure 3c). The outdoor noise coming from the top is effectively blocked.

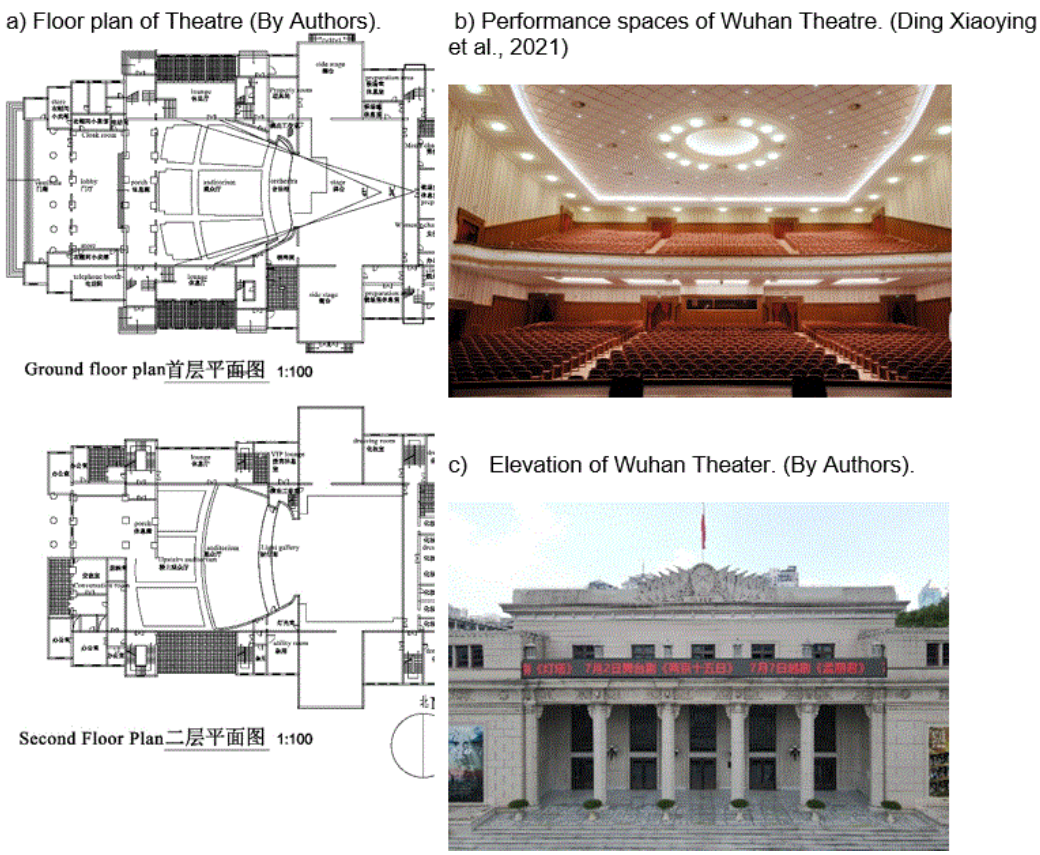


Figure 3. Wuhan Theater.

b) Model construction and related parameter setting

The viewing space of the Wuhan Theatre is a large indoor space within a commercial complex, categorized as an indoor acoustic environment analysis when simulating in SoundPLAN. Following the relevant drawings and documents, it is modelled as an indoor space (Figure 4). The stage space of the Wuhan Theatre is modelled after foreign designs and can be divided into two main parts. The first part is the sunken orchestra pit in front of the stage. The second part is the stage itself, with side stages on the left and right for preparation. Behind these are a series of ancillary rooms. For this simulation, the sound source chosen is a Western instrument, the violin, placed in the orchestra pit, with sound source parameters set as a point source (Violin Single value) with a sound power level of Lw=85.0dB.

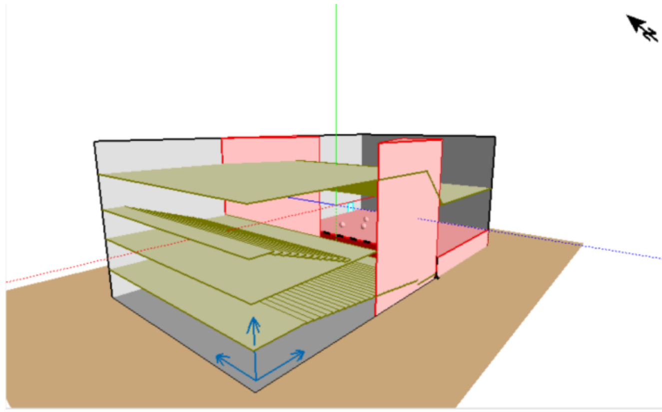


Figure 4. Simplified Model of Theater Established by SoundPLAN.

According to the information, the material of the main structure is reinforced concrete, and when the model is built in SoundPLAN, the main structure of the auditorium is selected as reinforced concrete (Figure 5). The ceiling part is set as a wood beam ceiling (Figure 5).

To ensure accuracy in the simulation and reduce workload, the stair steps selected for simulating the receiving surface are the first and last steps of the ground floor audience seating area, as well as the first and last steps of the mezzanine audience seating area. Adding 70 centimeters to the architectural elevation of the stairs, we can determine the sound pressure level experienced by the audience on those designated stair steps, thereby ensuring the accuracy of the experimental simulation.

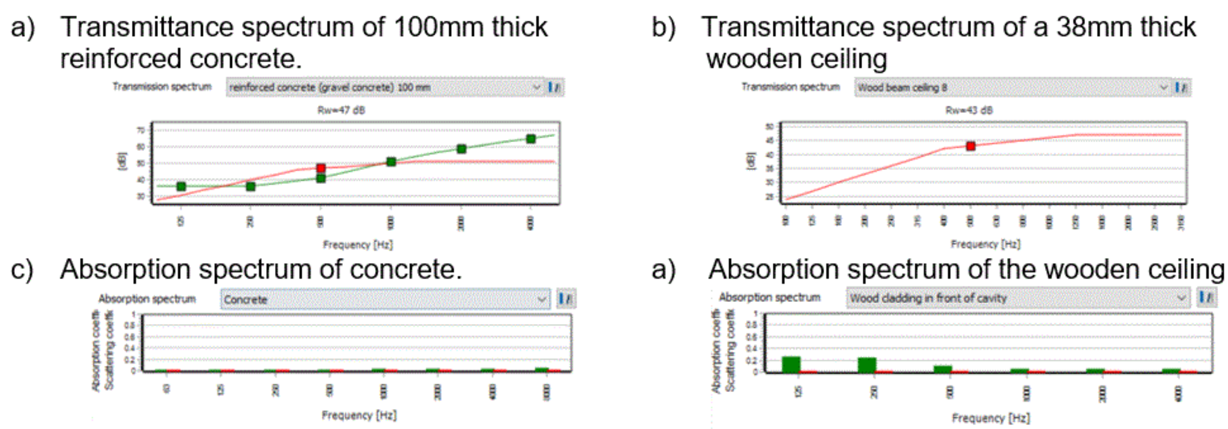
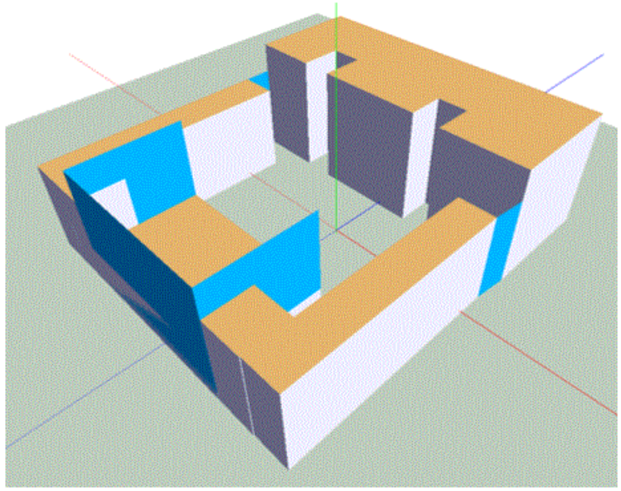


Figure 5. Parameter setting of materials.

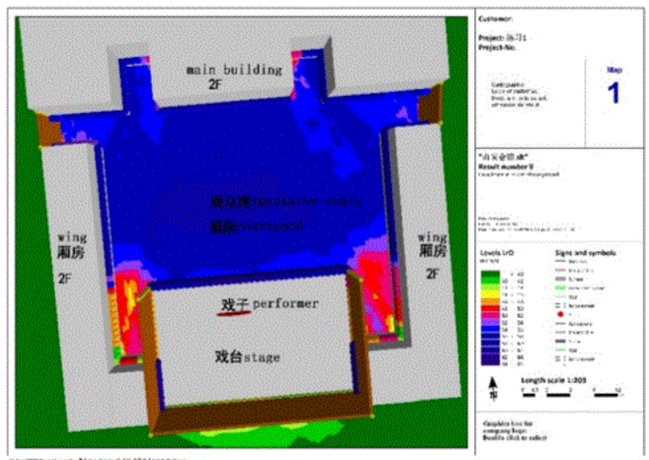
4. Analysis and Discussion

4.1 Simulation analysis and Results of the acoustic environment of the pre-20th century theatre

Based on the simulated sound pressure level distribution diagram (Figure 6b), the following conclusions can be drawn: the acoustic environment within the viewing space generally exceeds 56 dB. The main acoustic space of the courtyard within the viewing angle range of the stage is within a sound pressure level of 56 to 60 dB. Additionally, the sound pressure level in the courtyard shadow area on the front side of the stage is mainly above 56dB, making it clear to the audience in the courtyard. The sound pressure level distribution in this case does not exhibit radial contraction but rather spreads outwards from the center of the courtyard, primarily in the range of 56 to 58 dB. This is mainly because the performers' sound sources are positioned towards the front and center of the stage. Numerous historical records mention placing performers in the middle of the stage and musicians on the sides to accommodate the main viewing angle for the audience. This arrangement is more suitable for martial arts performances and spectator-centric operas. For operas primarily focused on listening, this positioning provides a better audiovisual environment for the audience, at least within this viewing space, catering to all present spectators. The sound received at the points on both sides of the side rooms and the outer corridors of the second-floor main hall reach up to 58dB, allowing guests on the second floor to fully hear the performers. The energy of sound received at various points is relatively uniform, indicating a relatively good-quality acoustic environment.



(a)



(b)

Figure 6. Simulation of Shan-Shan Guildhall. a) Simplified Model of performance space by SoundPLAN; b) The sound pressure level distribution chart at the sound receiver location.

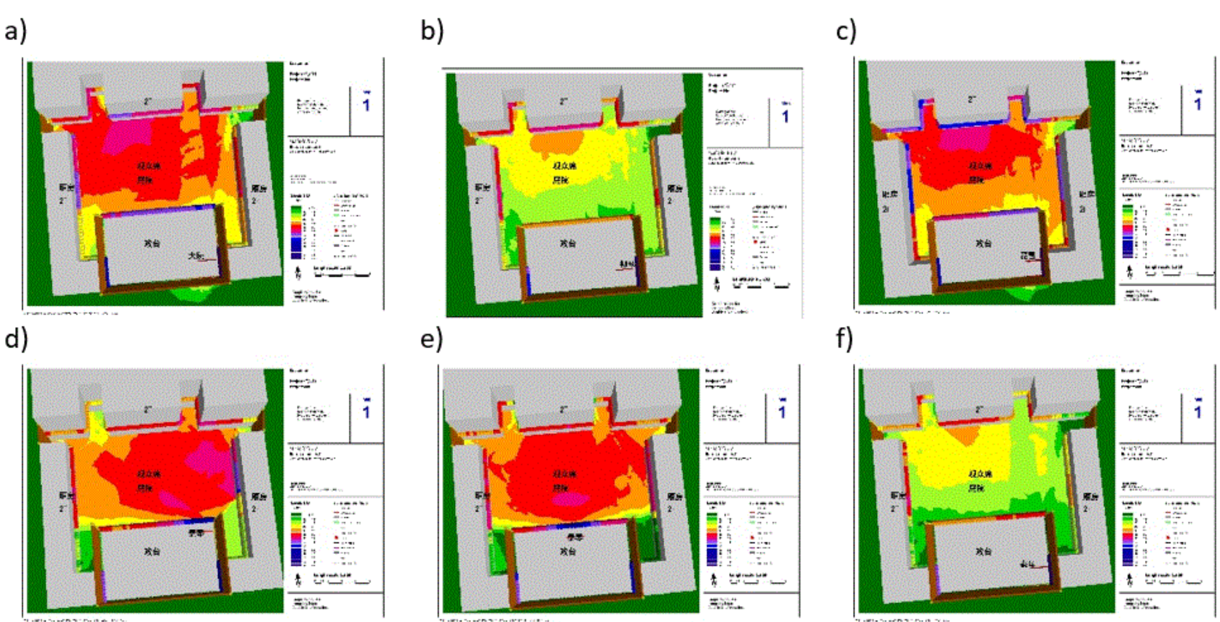
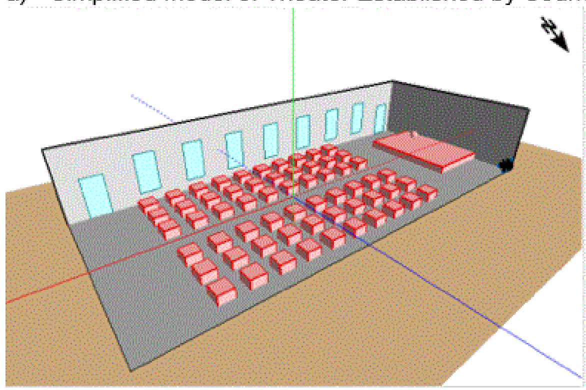


Figure 7. Sound Pressure Level Distribution of Different Sources at Different Locations.

At the same time, we put the sound sources of different instruments in the same position (Figure 7a-7c), as well as put the sound sources of the same instrument in different positions (Figure 7d-7f). The sound pressure level in the viewing space changes greatly, which is causally related to the positional arrangement of the ancient musicians, and we speculate that the positional arrangement of the ancient musicians is the result of many experiments to make the acoustic environment of the viewing space reach the optimal state.

4.2 Simulation analysis and Results of the acoustic environment of modern theatres in Wuhan

a) Simplified Model of Theater Established by Sound PLAN



b) The sound pressure level distribution chart at the sound receiver location

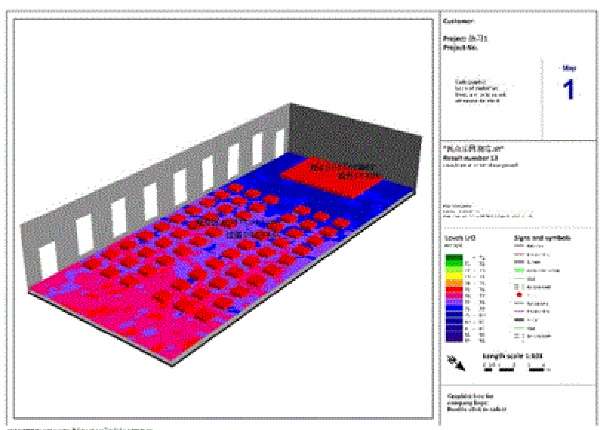


Figure 8. Simulation of Hankou People's Paradise.

Based on the simulated sound pressure level distribution diagram (Figure 8b), the following conclusions can be drawn: the sound pressure level within the room is not lower than 75 dB. The sound pressure level is higher near the front side of the stage, reaching around 80dB, while at the end of the room, it's around 77 dB. The difference in sound pressure level throughout the entire performance space is within 4dB. The height of the indoor stage is generally only several tens of centimetres, making it convenient for audience members in the back rows to see clearly, without the need for a high outdoor stage. This eliminates the shadow area in front of the stage, allowing the reception points in front of the stage to receive normal sound levels without obstruction. Audience sightlines are also unobstructed, allowing for the use of the space in front of the stage. Comparing the outdoor viewing space of the Shan-Shan Guildhall with the indoor performance space of the People's Park, it is found that the overall acoustic environment quality of the indoor viewing space in the People's Park is superior to that of the outdoor performance space at the Shan-Shan Guildhall. In enclosed spaces, there is less loss of sound during propagation. On one hand, unlike the upper part of the outdoor courtyard space, which is a completely absorbent surface, the indoor roof also reflects sound energy to the audience. On the other hand, the construction and decoration of this comprehensive entertainment venue are more refined, with interior walls being painted and smoother, resulting in less absorption of sound energy.

4.3 Simulation analysis and Results of the acoustic environment of theatres in Wuhan after the founding of the People's Republic of China

Table 1. Range of sound pressure levels for the experimental steps.

Step series T/t	step height h(m)	Receiving height of sound source T(m)	Sound pressure level range (dB)
T1	1.4	2.1	67~71
T9	3.8	4.5	67~69
t1	7.6	8.3	65~67
t12	10.9	11.6	66~67

T1 - first row of seats on the first level, T9 - last row of seats on the first level, t1 - first row of seats on the mezzanine level, t12 - last row of seats on the mezzanine level.

Based on the analysis of the simulation results (Table 1), the following conclusions can be drawn: The sound pressure level at the first row of seats on the ground floor ranges from 67 to 71 dB. The sound pressure levels for the entire row are mainly between 67 and 69 dB, interspersed with levels between 69 and 71 dB, which is due to the superposition effect of secondary reflected sound from surrounding objects. The sound pressure level at the last row of seats on the ground floor is between 65 and 67 dB. These seats are located towards the back, experiencing mainly direct sound with minimal reflected sound reaching them, resulting in a difference of about 3 dB compared to the front rows. In comparison to modern auditoriums with large depths and low opening viewing spaces, the difference in sound pressure levels in this simulation is relatively small, and the sound pressure levels across the entire row of seats are relatively uniform, thus improving the quality of the audiovisual environment.

The sound pressure level in the first row of the mezzanine at Wuhan Theatre is between 65-67 dB. The distribution pattern for this row shows higher levels on the sides and lower in the center, which is due to the reflections from the side walls adding to the sound pressure at the side seats. The last row of the mezzanine has sound pressure levels between 66-67 dB. The slightly higher levels in the back compared to the front rows result from secondary reflections from the ceiling over the orchestra pit, which increase the sound pressure in the rear mezzanine seats. After simulating and comparing these results with those of the People's Paradise's viewing space, it was found that Wuhan Theatre not only experiences minimal sound energy loss across all audience sections but also has a higher capacity. With these new acoustic measures and design principles, the acoustic environment quality in both levels of Wuhan Theatre's audience area is excellent.

4.4 Discussions

Through theoretical analysis of the viewing and performance spaces and independent theater buildings throughout Chinese history, combined with acoustic environment simulation of theater buildings from three historical periods in China, this study explores the relationship between the quality of the acoustic environment in viewing spaces and factors such as social development, architectural structure, and the position of sound sources. The results of the simulation indicate that the sound pressure levels in the viewing spaces of theater buildings from the three periods show an increasing trend, suggesting that the auditory effects of the viewing spaces have been improved with the enhancement of various factors. After comprehensive analysis, it was found that the development of ancient theater buildings was slow, mostly attached to other buildings, the viewing spaces were not standardized, and acoustic measures were based on experience. The ancients used instruments with resonant chambers, courtyard sound reflection, and the rich singing of performers to enhance the quality of the acoustic environment; modern theater buildings were influenced by Western theater building models, and theater buildings gradually took shape independently, the viewing spaces became standardized, structures affecting indoor sound propagation were removed, and sound insulation measures were taken, which greatly improved the quality of the acoustic environment; after the founding of the People's Republic of China, the importance of theater buildings increased, and through continuous reference and learning, new design theories, acoustic measures, and new materials were introduced, the interior space, plane, and decoration were carefully considered according to the characteristics of sound propagation, which continuously improved the capacity, order, and quality of the acoustic environment. In addition, it was found that different performance sound sources produce different sound pressure level distributions, and after multiple experiments, an optimal sound source placement position was found, which is interpretable for the arrangement of performers in dramatic performances, and the variety of Chinese drama types and different sound sources have an impact on the quality of the acoustic environment. Compared with previous research limited to architectural physics and acoustics or only a single element, this study comprehensively considers a series of factors affecting the viewing and listening effects, such as the construction materials, structure, and instrument types of theater buildings, and the results obtained are more comprehensive.

However, this study uses a limited number of sound sources and a limited number of theater buildings studied, which still has shortcomings in the research on the factors affecting the acoustic environment quality of theater buildings. In addition, due to the complexity of Chinese wooden structure buildings, this study did not consider the impact of indoor structural changes on the acoustic environment.

5. Conclusions

By comparing and analyzing the results of the acoustic environment simulation experiments of representative theater buildings from the Qing Dynasty, modern times, and after the founding of the nation, it can be seen that as the viewing spaces of theater buildings evolve from outdoor to indoor and then to the continuous deepening of the interior, the sound pressure level in the audience area gradually increases, proving that the audience hears clearer sounds, and new structural materials increase the number of audience seats, the design of the viewing space is more reasonable, and the viewing line of sight is getting better and better. Whether it is the selection of indoor decoration materials and the placement of performance sound sources from an acoustic perspective, the planar design, and the new type of building materials to meet the cantilever structure design of the mezzanine audience seats, etc., these factors are all affecting the development of the acoustic environment of theater buildings, and ultimately create a high-quality audio-visual environment. In addition, it was found that different performance sound sources have a great impact on the acoustic environment. In summary, the acoustic environment of Chinese theater buildings is related to the social background of the period, musical instruments, drama, architectural structure, building materials, and other factors.

This study considered factors such as the main structure of the building, the characteristics of materials, and performance sound sources in the process of acoustic environment simulation analysis. It is well known that the construction of ancient Chinese wooden structures is complex, which makes the internal space of theater buildings not smooth and closed, especially the exposed dugong and beams in the roof area, these factors will affect the propagation characteristics of sound. The number of building structures simulated this time is limited, and the impact of Chinese wooden structures on the acoustic environment has not been deeply explored. This will be the direction of our next research, we will continue to explore the impact of different structures on the indoor acoustic environment and how to effectively integrate the unique Chinese wooden structure space with the acoustic environment, thereby creating a good audio-visual environment. At the same time, it will provide a scientific basis for the restoration of theater buildings. In addition, we will also simulate according to the sound source configuration used in various Chinese dramas, and study the arrangement of performers and the layout of the viewing space.

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Conflicts of interest

The Authors declare that there is no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors/s.

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