

Article

A Single Acoustic Quantity Index as Part of an Early-Stage Digitalized Procedure for the Restoration of Baroque Theatres to Be Used as Multipurpose Spaces

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Abstract: Historic theatres with a horseshoe shape, the so-called baroque theatres, constitute an architectural heritage and are of enormous importance. For these reasons, this paper aimed to identify a single acoustic quantity index as part of an early-stage digitalized procedure to improve the management of the complexity of their restoration process, both better preserving the original room acoustic field and making it variable for new different uses of the theatre space. The procedure introduces technical policies and design tools in a BIM execution plan (BEP) and is supported by a digitalization that inserts the restoration of theatres into industry 4.0. This choice was taken according to the new design goals and the new Procurement Code Directives, which underlie the use of digital technologies in this context. The described acoustic single number quantity, called a “multipurpose index”, summarizes the main room acoustic goals for when a baroque theatre is used as a multipurpose space after renovation, specifying and better controlling the requested room acoustic quality for people other than acoustics specialists, such as theater directors, and more generally for the management. As an example of this possible transition, the case study of “Teatro Ristori” is presented.

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1. Introduction

Without any doubt, historic theatres with a horseshoe shape, the so-called baroque theatres or “teatri all’italiana”, constitute an architectural heritage of enormous importance for the whole of Italy, and in a broad sense, they represent a cultural heritage as a symbol of civilization [1].

Baroque theatres are a mixture of architecture, music needs, and social behavior, housing the opera artistic form, built from the early days of the XVII century until the late XIX century, and able to represent the spirit of the society and its changes [1].

The shape of their room, with balconies around the perimeter walls, was thus consolidated from Venice throughout Italy and Europe. The horseshoe-theatre-building boom can be likened to that of variety and music hall entertainment in the second half of the nineteenth century. Their success was undoubtedly linked to the genre they represent, namely opera, but also to the fact that, with the introduction of balconies, they symbolized the social structure of Italy of the time: in the stall of public theatres, poor people gathered together; the balconies were rented annually to the aristocrats [2].

Over the course of about three centuries, more than a thousand baroque theatres were built in Italy [3–5]. Many of them have had numerous changes of use and others are in bad condition. Most of the famous ones have been restructured recently (e.g., la Scala, la Fenice, il San Carlo [6], il Petruzzelli [7]) and others are awaiting renovation.

Commonly, nowadays, theatres are publicly owned and require large sums of money to be restored and put into operation, and, in most recent cases of renovation, the tendency after the restoration is to use the theatre as a multipurpose space, because spaces dedicated to just a single use are often too expensive to maintain [8].

The renovation process of a baroque theatre usually has to respect the ancient quality of the main hall, preserving the original room acoustic field, and, at the same time, should make the building compatible with new the requirements of a modern performance space such as a polyfunctional room. Satisfactory acoustical properties should be achieved for concerts, as well as for theatrical performances and congresses. This can be partly obtained using movable absorbing and diffusing elements, and a stage craft system designed to transform the fly tower space according to the chosen configuration of the hall. Unfortunately, in most cases, variable acoustic elements and an acoustic shell are not included in the development of the design process, and the theatre operator often asks to install them temporarily, according to the theatre activities, after the renovation. This means the new theatre layout is not supported by an acoustic analysis to optimize the acoustic properties for different theatre uses.

The renovation process should be carried out with minimum disruption, so as not interfere with the existing evidence of the fabric of the building that must be preserved. This requires proper maintenance, color scheme, texture and material analysis, and should include new technical solutions.

To preserve the specific heritage of these Italian historical buildings, a standardized procedure for acoustic measurements in the main hall was defined by specialists for many years [9–11], while acoustic standards and regulations for buildings were identified [12–15] to support the process.

Usually the restoration, the economic planning of the theatre, and its new uses also require a renovation of the stage area and the machineries included, to create a flexible place that is easy to manage and keep in operation, with a particular emphasis on ease of intervention by stage operators. Alongside the more traditional fields such as structures, electrical systems, air ventilation systems, and the more recent energy analysis, some specialist fields such as acoustics and stagecraft systems have started to require initial in-depth study, even if they are still not recognized as being paramount.

Due to the increasing complexity of this restoration process, this paper suggests moving the theatre and multipurpose building sector toward Industry 4.0 [16], requiring the use of digital tools, both in the building process and in the maintenance phases.

The introduction of digitalization in the restoration of historic theatres is a key innovation for the architecture, engineering, and construction (AEC) sector. In industry 4.0, the theatre is no longer considered a (patrimonial) asset to be possessed, but rather as a function of the activities that it is able to provide during its life cycle, controlled by digital tools from the beginning of the restoration process.

For these reasons, this paper aims to preserve the room acoustic quality and increase the control of the restoration, identifying a single acoustic quantity index as part of an early stage digitalized procedure to improve the management of the complexity of their renovation process.

In this new context, to declare the main room acoustic goals clearly and systematically at the beginning of the process, an acoustic single number quantity able to summarize the capability of the theatre to be properly used as a multipurpose space (the potential to be a polyfunctional space), and to preserve the original acoustic field of the hall, is presented as a very useful tool both for the theatre management and for the acoustic specialists. This quantity represents a starting condition, a *sine qua non*, from which acoustic specialists can develop the acoustic project more in detail, including the standards of reference.

The originality of the paper also consists in indicating the multipurpose capability of a hall through a single acoustic quantity index, having organized the restoration process design phase in a digitalized workflow at an early stage, that systematizes a series of

digital instruments from the beginning of the renovation process. These instruments interact with each other, increase connections between all the specialist activities, including the preservation of the room acoustic quality, and suggest possible implementations of variable acoustic elements for multipurpose uses of the hall.

The scope of the new acoustic indicator includes providing an easy-to-understand single number quantity related to hall room acoustic quality for people other than acoustics specialists, such as theatre directors, and generally for the theatre management.

When a baroque theatre will be used as a multipurpose space after the renovation, the acoustic single number quantity clarifies and simplifies identification of the main goal of the restoration from the beginning of the process, specifying and better controlling the requested room acoustic quality.

Starting from aspects concerning the acoustics of historical theatres found in the literature (that are partially cited in the article, not being the focus of the research), this paper has two objectives that are linked to one another to optimize the room acoustic control during the renovation process. The first is proposed only at the early stage and aims to identify a procedure using a document, the so-called BIM execution plan (BEP), that outlines in steps how the project can be executed, managed, and delivered to optimize the control of the complexity of the restoration process (including all the specific fields, such as acoustics).

The second objective, the focus of this paper, aims to identify a new acoustic index, the so-called “multipurpose index”, as part of the BEP procedure, that summaries the capability of a hall to be set up in different configurations, without excluding a detailed acoustic analysis by specialists during the development process.

To achieve a successfully integrated design, a BIM execution plan (BEP), a procedure that includes technical policies and design innovation tools, is suggested as one of the most important support factors [17], in which the multipurpose index can be included. The BEP list can also help the management in the construction phase.

This paper refers to an elaboration for integrated buildable projects, and is intended to extend it to all interventions that require a specific and articulated commitment. Existing theatre heritage renovations, in fact, are still carried out in the absence of specific procedures, both in the traditional environmental, such as the structural field, and in more specific fields such as acoustics, multimedia systems, and stagecraft.

In Section 2, the methodology is presented in detail, starting from the BEP procedure and followed by the definition and the usability of the multipurpose index (MI) to control, from the preliminary restoration phase, the flexibility of the theatre for use as a multipurpose room. In Section 3, a possible application to the case study of Teatro Ristori (Verona, Italy) is explained. The conclusions follow.

2. The Methodology

In the context described above, the identification of the “multipurpose index” is explained, supported first by an elaboration of the BIM execution plan (BEP) list [18].

The BEP procedure allows building information modeling (BIM) to be used in the most effective way. Through BIM, in fact, a parametric virtual model of the building is elaborated with all the extractable technical information, as well as indications on the times and costs of construction and life cycle management.

The drafting of the BEP list can define the programmed objectives, the survey, and the directives of graphic restitution for each level of the design (up to the executive phase), monitoring each phase of the building process that has to be carried out, from the tender to the verification and control operations. The BEP creates the conditions for the building to be brought into compliance with the overall static and functional regulations (including acoustics, stagecraft, and lighting), while favoring, depending on the case, energy–environmental requalification (for these reasons, it is suggested to include the multipurpose index in the list, defining it from the beginning of the project).

The BIM execution plan also facilitates collaboration and communication between the numerous and diversified subjects involved, who can identify in the BEP their own roles, means, methods, and IT solutions, with indications of the definitions of level of definition/development (LODs) and level of information need (LOINs), as well as of the management of the information in the BIM as a whole [19].

The BEP list, a guideline in which the proposing subject has to communicate the tender requirements with reference to the main goals of the project and the BIM issue [20], is exposed in steps in the following paragraph.

To complete the procedure at the early stage, workflow organization in the digital field is also suggested, starting from the needs defined by the client and the organization of the building process.

2.1. The BIM Execution Plan (BEP) in the Early Stage

In the specific case of the restoration process of theatres, the main content of the BEP can be summarized at an early stage in a list, as follows:

- identification of goals and contents presented, including the potential of the theatre to become a multipurpose space. A single number quantity, the acoustic multipurpose index target (Section 2.2), is specified;
- previous skills and experience of the team, including an acoustic consultant with experience in the theatre field;
- survey/analysis of the current situation of the theatre, including room acoustic and building acoustic measurements, also considering specific tests to check the absorption coefficient of the surfaces that need to be replaced;
- BIM software to be used during the project and its versions;
- objectives and uses of information models, how data are shared, including exchange files for acoustic prediction analysis;
- information modelling and definition of LOINs;
- definition of the information documents;
- compliance with standards, including acoustics;
- operational details of the management with the identification of the BIM specialists, coordinators, and managers;
- storage methods and delivery strategies, including checking of the multipurpose index;
- contextual management of the collaborative design phase, the construction, and the maintenance.

The points on the BEP list are explained in their early stages.

First, the client has to properly define their own goals (including the desired multipurpose configurations, such as concert hall, opera house, congress hall, etc.), existing condition modeling, cost estimation, phase planning, programming, and site analysis of any pre-existing buildings.

Other data have to be given related to a series of aspects that are common with other building typologies, such as energy, environment, and indoor air quality. These are characterized by a number of steps: elaboration of the inventory, calculation of performance indicators, identification of measures to improve the energy performance and reduce the environmental load, identification of acoustic quantities to achieve high acoustic comfort, simulations of the behavior of the building–plant system (also in terms of indoor air quality), and of the stagecraft systems (also in terms of lighting and multimedia), followed by a cost–benefit analysis.

In addition, for existing buildings in Italy, regarding the choice of materials, the Environmental Minimal Criteria or Criteri Ambientali Minimi (CAM) have to be used together with the most recent fire prevention regulations and, for obvious reasons, with the acoustic regulations; the expected performance and the nominal life of the renewed building also have to be considered.

In terms of skills, it is necessary to combine the skills of those who deal with architecture, acoustics, stagecraft, lighting, structural aspects and articulated aspects of the plant engineering, and different possible control systems for “show activities”. All of these are closely related with automation systems, which unfortunately remain underestimated, which could ensure the full enjoyment of the buildings.

The need for precise knowledge of the current state of the building, which over time may have suffered numerous, significant, and uncontrollable changes to the point of lying in a state of degradation, is another important step. The acquisition of input data describing the current state of the building, due to the specificity of the theatre case, must lead to information modeling to ensure a precise capturing of reality through precise qualitative/quantitative information, including the potential to offer the targeted acoustic quality by changing the configuration of the hall.

Tools and procedures have to be used to guarantee interoperability between the different skills of operators and different digital tools, in real time, or through the immediate reporting of critical issues (interferences) avoided by the attention paid to the technical functioning of the models that characterize each discipline.

In this context, new technologies such as 3D laser scanners combined with BIM can become powerful tools to optimize the process and add value, especially in restoration projects including cultural heritage, where the shapes and geometry are quite diverse and complex, providing accurate data.

The use of 3D laser scanner technologies is recommended, to obtain a high level of detail for the graphic restitution; the simultaneous acquisition of color photos and clouds of 3D points; a significant reduction in time and cost considering the whole process; and finally integration with different systems such as CAD, 3D, and BIM. This allows the data collected by a 3D laser scanner to be imported to process different design views, starting from the cloud of 3D points.

After the initial survey conducted through the laser scanner and followed by acoustic measurements, it is possible to proceed to the creation of the 3D model, to the model calibration using dedicated room acoustic software including the chosen version (such as Ramsete, Odeon, etc.), and to the definition of a communication code based on normalized classification plans. In the case of replacing theatre walls to not change the acoustic response, analysis of their absorption coefficient must be considered and compared with that of the new technical solutions.

The skills of the survey/analysis team regarding the current situation of the theatre have to be combined with those in BIM, related to the interface between the BIM and room acoustic software, and those for facility management that can acquire the meaning of sustainable facility management.

The BIM used in theatres must have connotations similar to that of other historical buildings, for which many objects have to first be modeled on historical research, to become “loadable” objects in the project.

The operations are very complex and include detecting needs to be met; evaluating the decisions to be taken; selecting the technologies to be adopted; and controlling the costs, time, and outcomes in terms of management and also in terms of costs/benefits; a definition of the LOD preparation of the information follows. Like any programming phase, the definition of LOD is necessary according to the specific pre-determined objectives [21].

As previously mentioned, the LOIN must also be carefully defined; it is then necessary to work toward “families”, in order to make them homogeneous and comparable, creating synergies of a whole series of information, including acoustic properties, and operations that require, on the one hand, the appropriate definition of LOD and LOIN and, on the other hand, specific disciplinary skills. The BIM team should correlate architecture, structures, acoustics, energy, environmental engineering, and home automation in their activities to optimize costs and maintenance operations.

In this way, inconsistencies between the different design levels, times, and costs are reduced, and a database for the planned interventions can be set up.

By appropriately characterizing the model with the information derived from the database, a BIM model that faithfully reproduces the project can be created.

The BIM authoring software allows experts to first define structures, walls, slabs, ceilings, balconies, and furniture using parametric families which virtually represent the building components in the real world. The parametric families are updated based on field conditions and simulation results, allowing easy adaptation of the methodology for different theatre uses, layouts, and seat numbers, simplifying the data evaluation. The combination of all these objects determines the model. The development of a three-dimensional model and the design of the project database lays the foundation for the real operative phase, because the model does not contain only geometrical information but presents information of a specific nature.

To include acoustic, structure, and energy analyses in the process, the BIM interoperability is considered, and the Industry Foundation Classes (IFC) format is taken into consideration. The most frequently mentioned issue and the most researched topic is the “interoperability” between BIM and other building performance models (BPM) such as the building energy modelling (BEM) [22,23] and the building acoustic modelling (BAM).

Nevertheless, the interoperability is rarely perfect, and information is lost during translation from the BIM authoring tool to the simulation software [24]. The discrepancies in the data translation from the BIM authoring tool to the specific calculation virtual environments (CVE) for structures, energy, and acoustic evaluation must be considered. The architectural model is converted into an analytical model to perform different types of assessments in CVEs [25], defining the interoperability paths from BIM to CVE for structural, energy, and acoustic evaluations [26,27] (Figure 1).

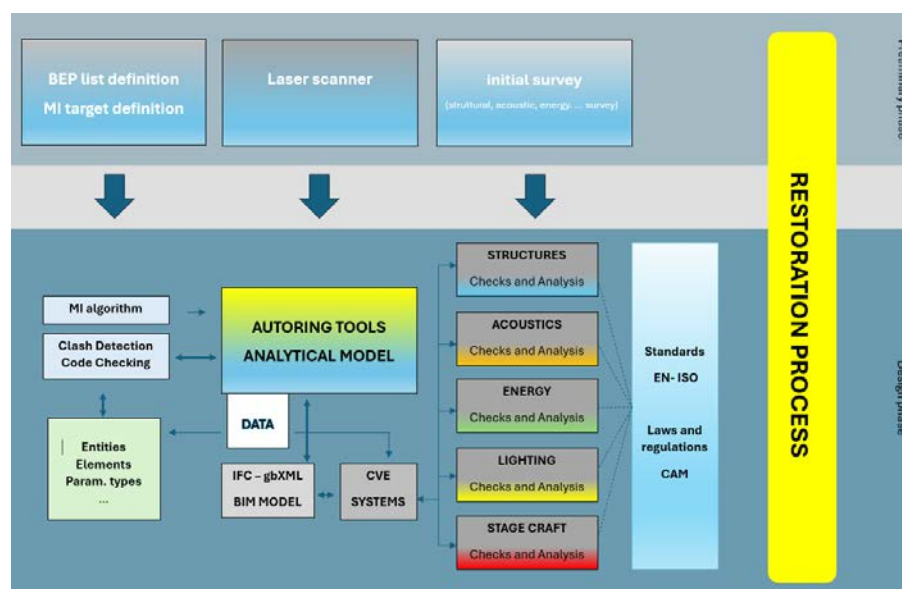


Figure 1. Restoration process workflow for the preliminary and design phases.

After planning, the various documents for the phases of tendering, construction, and operation have to be elaborated. In particular, the construction phase requires (in addition to 3D coordination) site utilization planning, construction system design, digital fabrication, and 3D control and planning; after that, the operational phase requirements include record modeling, maintenance scheduling, building system analysis, asset management, space management/tracking, and disaster planning [28].

2.2. The Multipurpose Index (MI)

If the renovation of the building requires the transformation of the theatre into a multifunctional hall, while respecting the original architecture, the acoustic design has to identify technical solutions, such as movable architectural elements and movable absorbing and diffusing materials [29,30], as well as considering flexible fly tower equipment. To achieve satisfactory acoustical properties, different sound energy distributions have to be studied, according to the possible layouts and configurations of the hall for concerts as well as for theatrical performances and congresses.

In multipurpose rooms, especially referring to Italian theatres, three main configurations have been identified [31]:

- “Italian Opera Theatre” configuration: in accordance with the original nature of the theatre, the stage is housed in the fly tower and the audience is placed in the stalls and galleries [32,33].
- “Concert Hall” configuration: an acoustic shell is set on the stage and its flat floor, made of platforms, is replaced by various levels to improve the orchestra sound distribution.
- “Congress Hall” configuration: the stage and stalls have the same layout as in the concert hall configuration. Many variable acoustic elements are placed in a position which maximizes their absorption coefficients, meaning the main acoustic parameter, the reverberation time, is reduced inside the hall.

The acoustics inside multipurpose halls have developed over the past few decades.

There have been studies on subjective evaluations of hall acoustics [34,35], on the effects of various indoor architectural features [36,37], focused on energy prediction models, and on the early-to-late energy balance [38], but an index to characterize the potential of a hall to be flexible for multipurpose use, maintaining the target acoustic quality for different layouts, is still missing.

The multipurpose index is a single-number quantity that represents the capability of a hall to be set up in different configurations, guaranteeing the basis for an optimal room acoustic quality to be developed by specialists, with consequences for the satisfaction of musicians and operators. Summarizing the polyfunctional tendency of a hall in the preliminary phase does not exclude a detailed acoustic analysis supported by prediction models and standard verifications during the development process.

Apart from the estimation of the reverberation time (RT), the main room acoustic parameter, the acoustic design of a performance hall is usually characterized by energy-based acoustic parameters, such as clarity (C_{80}) and strength (G) [39]. These are the same parameters that must be checked on site following ISO UNI 3382-1 [40], which also recommends how many source–receiver points must be included for each configuration and where they must be positioned.

As the multipurpose index summarizes the potential of a hall to be used as a multipurpose space for people other than acousticians, it is defined including acoustic parameters that are easy to explain to people using psychoacoustic correlations: the reverberation time (RT) and the clarity (C_{80}) for Concert and Opera House configurations, and the reverberation time (RT) and the sound transmission index (STI) for the Congress Configuration. The other parameters of ISO UNI 3382-1 are analyzed and optimized in the prediction analysis according to the workflow (Figure 2).

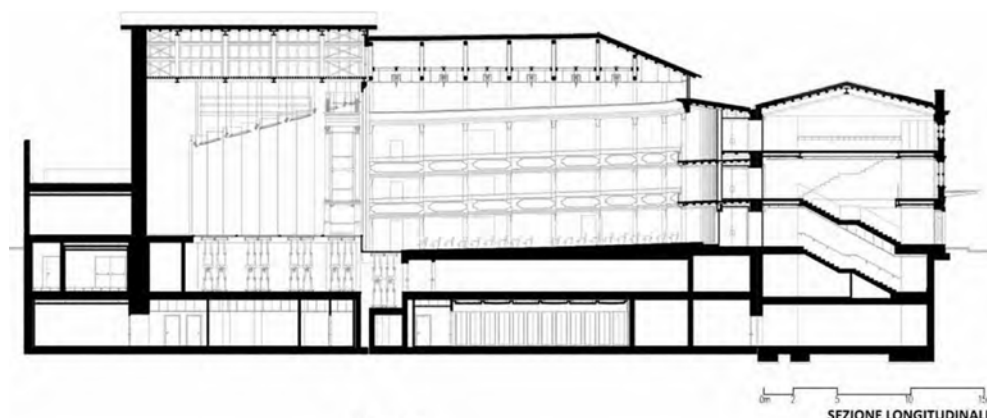


Figure 2. Theatre section.

The optimal range of quantities included in the MI is defined using the literature (Table 1) [39], according to the use of the hall or the range targeted by the acoustic designer in accordance with the values suggested in the literature itself, customizing the upper and lower quantity limits according to the specific project.

Table 1. The required acoustic target range for the main acoustic parameters [39].

Acoustic Parameters' Target RT [s], C_{80} [dB], and STI	
Concert Hall-Symphonic Music Configuration	$1.5 < RT < 1.9$; $-3 < C_{80} < 3$
Opera Configuration	$1.3 < RT < 1.6$; $-2 < C_{80} < 4$
Congress Configuration	$0.9 < RT < 1.3$; $STI > 0.65$

The index considers a hall as 100% suitable for a specific configuration if both the reference parameters fall within the optimal range specified in Table 2.

This means, in a single configuration, a value of 1 corresponds to MI when both the reference parameters are satisfied. Because the index includes three different configurations, adding them with equal importance, its maximum value is equal to 3. This property defines the multipurpose index (MI). The index formula, in fact, is not derived from another equation but has a new definition.

The reverberation time of a room was once regarded as the predominant indicator of its acoustical properties. While reverberation time continues to be regarded as a significant parameter, there is reasonable agreement that at least one other parameter is needed for a more complete preliminary evaluation of the acoustical quality of rooms.

For these reasons, a hall will be 65% suitable for a configuration only if the reverberation time falls within the specified range and 35% only if the other parameter satisfies the required conditions. The MI considers the adequacy of a hall in the three configurations listed above, which is therefore defined as follows:

$$MI = \sum_{i=1}^3 (0.65X_{RT,i} + 0.35X_{y,i}) \quad y = C_{80} \text{ or } STI \quad (1)$$

Where an i equal to 1 indicates a Concert Hall, equal to 2 an Opera House, and equal to 3 a Congress Hall. To calculate the MI, the RT values at middle frequencies (500 Hz and 1000 Hz) and the clarity must be evaluated for the configurations of Concert Hall (1) and Opera House (2), and the RT and STI values have to be determined for a Congress Hall (3).

In the design phase, the acoustic parameters referred to the predicted values, in the commissioning phase, they are the ones measured on site.

X_i is defined as the target satisfaction quantity (TSQ): this is determined by comparing the evaluated acoustic parameter with its relative defined target range. X_i has to be set to 1 if the parameter value (RT, C_{80} or STI) is inside the target range, which means the parameter satisfies the acoustic demands; it is equal to 0 if it is outside the suggested optimal interval.

In Formula (1), the two target satisfaction quantities are weighted with different coefficients for the following reasons:

- as reported in literature, in many theatres, the reverberation time target is achieved but the clarity target is not [41], as in several traditional Italian opera houses.
- thus, RT target compliance is mandatory, while the other parameters (C_{80} or STI) are considered second-order parameters; that is, without RT compliance, a good C_{80} or STI may result in an environment that is not acceptable acoustically.

The multipurpose index is a numeric representation measuring the multipurpose potential of a hall, whose value varies from 0, equal to “bad”, to 3, equal to “excellent”. A reference scale was proposed (Table 2) as the result of a questionnaire submitted to 26 theatre operators and 52 musicians. Their answers also confirmed the choice of RT as a mandatory parameter.

Table 2. Multipurpose index. Reference scale.

Multipurpose Index	Quality
0–0.65	bad
0.7–1	poor
1.05–1.7	fair
1.95–2.35	good
2.65–3	excellent

The reference scale was established by considering the operators answers to a questionnaire on all 64 theoretical MI results, using the combinations of the possible target satisfaction quantity values (equal to 1 or 0) applied to the three proposed configurations. The 64 possible theoretical MI combinations were presented to the people interviewed, using psychoacoustic correlations for which the subjective dimensions of the acoustical quality of a closed space, based on the opinions of the people, were linked with physical attributes that could be measured and predicted. In particular, musicians referred to a reverberant space as being “live”; on the contrary, the hall was referred to as being “dead”. Clarity refers to the degree to which a listener can distinguish sounds, and STI to the speech comprehension.

Every possible condition of the three different configurations included in the MI was described in the questionnaire using the subjective dimension. For each of these conditions, the respondent was asked to rate the potential of the hall to be used as a multipurpose space, choosing among five adjectives “bad, poor, fair, good, excellent”.

Firstly, the data of all the collected answers were analyzed in detail, organizing them from the lowest to the highest quality assigned, then the values of the weighting coefficients were determined, and the reference scale for the MI was defined, as follows.

The quality that was considered by the operators and musicians as “bad” referred to an MI equal to 0, 0.35, or 0.65, coming from seven TSQ combinations. This means only one acoustic parameter, in only one configuration, achieves the target range.

The quality “poor” refers to an MI equal to 0.7 or 1, considering 12 possible combinations. This means the secondary acoustic parameter achieves the target range in two different configurations or the main acoustic parameter together with the secondary parameter achieves the target range in the same configuration or in two different ones.

The quality “fair” refers to an MI equal to 1.05, 1.3, 1.35, 1.65, or 1.7 considering 26 possible combinations. This means many results are included, among them

- the secondary acoustic parameter achieves the target range in all the three different configurations;
- the main acoustic parameter achieves the target range in two different configurations;
- the main acoustic parameter and the secondary parameter achieve the target range in the same configuration, and the secondary parameter achieves the target range in another configuration;
- the main acoustic parameter achieves the target range in two different configurations, and the secondary parameter achieves the target range in the same or in another configuration.

The quality “good” refers to an MI equal to 1.95, 2, 2.3, or 2.35 considering 18 combinations. These results include

- the main acoustic parameter achieves the target range in all the three configurations;
- both the main and secondary parameters achieve the target range in two different configurations;
- both the main and secondary parameters achieve the target range in one configuration, and in another configuration the main acoustic parameter achieves the target range, while the secondary parameter satisfies the target range in the residual configuration;
- the main acoustic parameter achieves the target range in all three configurations, together with the secondary parameter achieving the target range in one or two configurations.

The quality “excellent” refers to an MI equal to 2.65 or 3, considering a case in which the main acoustic parameter achieves the target range in all three configurations together with the secondary parameter, or only the target of a secondary parameter is not achieved in a single configuration.

The weighting coefficients of 0.65 and 0.35 were found through an iterative process to correspond to an MI value increase, with the increase in the quality resulting from the questionnaire answer analysis. Starting from the calculation of all 64 theoretical MI results considering both weighting coefficients equal to 0.5, the same calculation was repeated increasing the weighting coefficient that multiplied the main target satisfaction quantity $X_{RT,i}$ and reducing the other one $X_{y,i}$, both with steps equal to 0.05, till identifying the threshold for which the secondary parameters were not dominant over RT.

As an example, with weighting coefficients equal to 0.55 for $X_{RT,i}$ and 0.45 for the secondary STQ, when the main acoustic parameter achieved the target range in all three configurations ($X_{RT,1}$ $X_{RT,2}$ $X_{RT,3}$ equal to 1 and the other STQ equal to 0), the evaluated MI was lower than the one obtained when the optimal range for the main parameter was achieved in a single configuration and the secondary parameter was satisfied in all the three possible configurations (the increase in the MI value does not correspond to an increase in the quality assigned in the questionnaire).

With weighting factors equal to 0.6 for RT and 0.4 for the secondary parameter, the MI value’s sensitivity is reduced; that is, the differences due to different possible combinations become negligible.

The multipurpose index is part of a larger research effort focused on developing a proof-of-concept implementation of a digital framework that relies on connecting existing technologies to support the digital use of building data, including in acoustics and other specific fields such as stage equipment systems in theatres, to define quantities that can be implemented in BIM and visualized in a “theatre digital twin” [31].

The multipurpose index is defined to be helpful in the design and construction phase, and to be easily accessible to operators, management, and customers of the theatre during the life cycle of the building. For existing or new buildings, this index provides a single number quantity to control the main acoustic goals that can be easily implemented in the workflow, simplifying the approach to the complexity of the building design process

maintenance, and information exchange in the multipurpose building sector moving toward Industry 4.0 and digitalization.

It is recommended to consider the MI four times during each building process: first, in the pre-renovation state of the theatre (using either in situ measurements or simulation, depending on the condition, to calculate the acoustic metrics), to determine its potential to be used as a multipurpose hall before setting the new design goals.

Then, a target or desired MI must be fixed according to the requirements set for the renovation (applying the reference scale presented in Table 2).

In the design phase, the targeted MI must be calculated and verified through a prediction analysis, and finally, it must be confirmed based on experimental measurements taken after the renovation or commissioning phase.

This index is also in accordance with the new technologies and suggestions in the new Italian Procurement Code [42], which underlines the use of algorithms and artificial intelligence systems in building design and construction processes, for which, a BIM model is developed.

Equation (1) is, in fact, a new definition of a synthetic method to calculate the compliance of a given hall with several quality acoustic parameters (as defined and widely tested in the literature), looking at their optimal range and weighting them according to their relative importance.

The scope of this indicator includes providing an easy-to-understand single number quantity related to hall acoustic quality for people other than acoustic specialists, such as theater directors, etc., and generally for the management. This justifies the choice of considering the parameter values only in the middle frequencies and of including only two quantities specified by the ISO UNI 3382-1 [39]. As explained above, the indicator is only based on the compliance with a set of well-known quality indicators ($RT...$), with their quality range, and a weighting procedure that accounts for their different levels of importance in the auditory experience.

To improve the use of the index in the deeper room acoustic analysis of a space by acoustic experts, further research could determine adaptation terms to describe the standard deviation of the evaluated acoustic parameters, as well as different weighted coefficients in case other parameters, such as G , are added to the same index, supported by listening tests and analysis of a reasonable amount of data.

To assign the MI to a theatre, acoustic parameter values are needed in the three above-described configurations.

If a MI value is defined at the beginning of the renovation process, this means acoustic goals are preliminary suggested for all three main configurations (Opera, Concerts, and Congresses), and the index must be verified upon commissioning, supported by acoustic measurements.

Considering the traditional Italian theatres in use, for which a MI was not requested and, in most cases, the measurements in the literature refer to opera configurations [43–46], MI estimation remains possible by analyzing their most common layout conditions, as suggested by the theatre operators.

A first evaluation of their potential to be used as a multipurpose hall can follow.

$X_{RT,i}$ and $X_{C80,i}$ are assumed to be equal to 1 in the opera configuration, being the main potential of the space.

To achieve the reverberation time range for concerts (without acoustic design support), an acoustic shell is usually installed on stage. $X_{RT,i}$ is equal to 1, but, in a conservative position, it can be estimated that the C_{80} optimal range for concerts will not be achieved ($X_{C80,i}$ equal to 0), especially in the oldest baroque theatres with boxes.

In most cases, congresses also take place, closing the house curtains to reduce the reverberation time, and this means the $X_{RT,i}$ is equal to 1, but a good value of STI is achieved using electroacoustic equipment support ($X_{STI,i}$ equal to 0). With these hypotheses, the M index is equal to 2.3, classified as a “good” multipurpose potential for the space.

Baroque theatres, in fact, are used as multipurpose spaces, but without an acoustic study to support the acoustic response of the temporary setup for concerts and congresses, an excellent result for MI is difficult to achieve.

As validation examples, an MI equal to 2.3 was found in the Opera di Roma (Italy) [47] and in the Teatro Petrarca (Arezzo, Italy) [41], for which an acoustic shell was not designed by an acoustic consultant.

An MI equal to excellent was found for the Teatro La Fenice (Venice, Italy) [48] and for the Opera House in Astana [8], for which a multipurpose use was declared at the beginning of the building process.

The MI was proposed, for the first time, during the restoration process of the Ristori Theatre (the case study explained in the following section), when both the client and the other experts required help in identifying the main goals of the restoration process for obtaining the maximal space and acoustic flexibility, avoiding free temporary installations to control the acoustic field after the renovation. This meant an “excellent” multipurpose status of the space had to be achieved.

Since the completion of the works, the Ristori has also been considered a pilot case for a general procedure to be developed through a BEP, because of the initial bad condition of the theatre, for which the specialists of different specific fields were very involved, and where a very detailed procedure was necessary to control the restoration process.

3. The Case Study of the Ristori Theatre in Verona, Italy

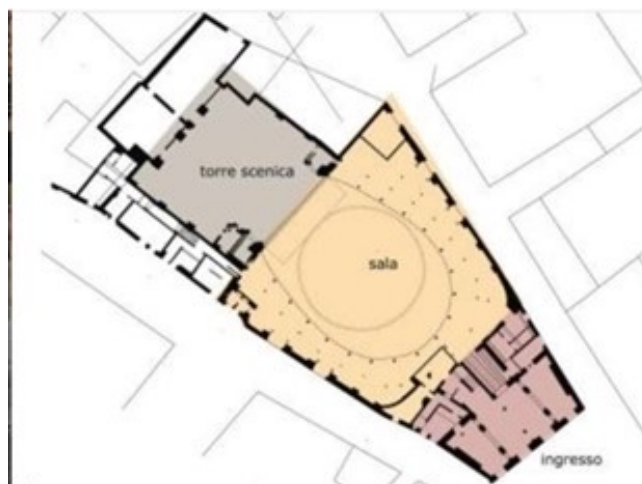
The Ristori theatre, a baroque theatre built in the nineteenth century with a capacity of around 600 seats and a volume of ca. 7400 m³, underwent various changes in use until its last renovation, which returned it to its former glory (Figure 2).

The restoration preserved the historic heritage of the theatre hall, achieving an efficient and versatile space as a poly-functional auditorium. The renovation design identified the original architectural and acoustic quality. It also made it compatible with the various configurations and sound field requirements of a multi-purpose room, characterized by a changeable audience distribution, variable acoustic field conditions, and different stage equipment layouts. In 2001, Cariverona purchased the half-ruined building, thus beginning the restoration and complete renovation of the building, which was completed in 2012. The intervention aimed to keep the external appearance of the building and the hall as similar as possible to how it was in the past, while for the other spaces, such as the foyer, a new and complete refurbishment was carried out, with a more modern style. The condition of the theatre at the time of the purchase by Cariverona was very bad (Figure 3a).

Nonetheless, the main architectural elements were still clearly visible. The building was composed of three blocks, the fly tower, the main hall space, and the foyer space (Figure 3b).



(a)



(b)

Figure 3. Façade (a) and theatre plan (b) before the last restoration.

Entering the hall from the foyer, the horseshoe shape was visible from the distribution of the boxes and the presence of the scenic arch, while in the stalls there were no seats and the trace of a circular path for the circus horses was evident (Figure 4a,b). The proscenium was discreetly preserved, delimited by two pairs of pilasters and ceiling decorations.



(a)



(b)

Figure 4. Galleries (a) and proscenium (b) before the last restoration.

A small orchestra pit opened towards the hall, for approx. 30 musicians, which could be closed if necessary. The scenic tower, the stage, and the curtain were in a degraded condition (Figure 4a,b).

In the stalls, the floor finish was missing, replaced by crumbly soil in order to better exhibit the animals. The ceiling was absent, and it was possible to see the beams supporting the roof, while the tiers of balconies, without subdivisions, were in position.

The spaces around the hall were not in as a good condition as the facade. The condition of the hall was not considered to be representative of the original acoustic field, and specific research to identify the sound distribution, including the reverberation time values, was requested.

3.1. The Polyfunctional Auditorium Project, a “Flexible Container”

The hall was set up with a partially removable stage and the stalls could be emptied of the chairs and thus transformed into a place for theatre in the style of the Shakespearean Globe Theatre and in memory of its circus vocation. Four main hall configurations (Figure 5) were designed.

- Italian opera theatre configuration: according to the original nature of the theatre, with the stage housed in the fly tower and the audience placed in the stalls and in the galleries.
- Congress Hall configuration: made similar to the opera configuration by closing the house curtains, by uploading the proscenium platform, and by opening the curtains near the recording box on the rear wall of the theatre.
- Concert Hall configuration: an acoustic shell can be set on the stage, and the floor, made of four platforms, can be replaced at various levels helpful for the orchestra distribution.
- Central space configuration: this allows having the stage in the center of the stalls (with temporary structures) and seats surrounding the new stage, which are also arranged to occupy the area of the traditional old stage.

Another configuration was included:

- Black Box configuration: the theatre space becomes an empty box and the stage can be made coplanar to the stalls to host temporary installations or events.

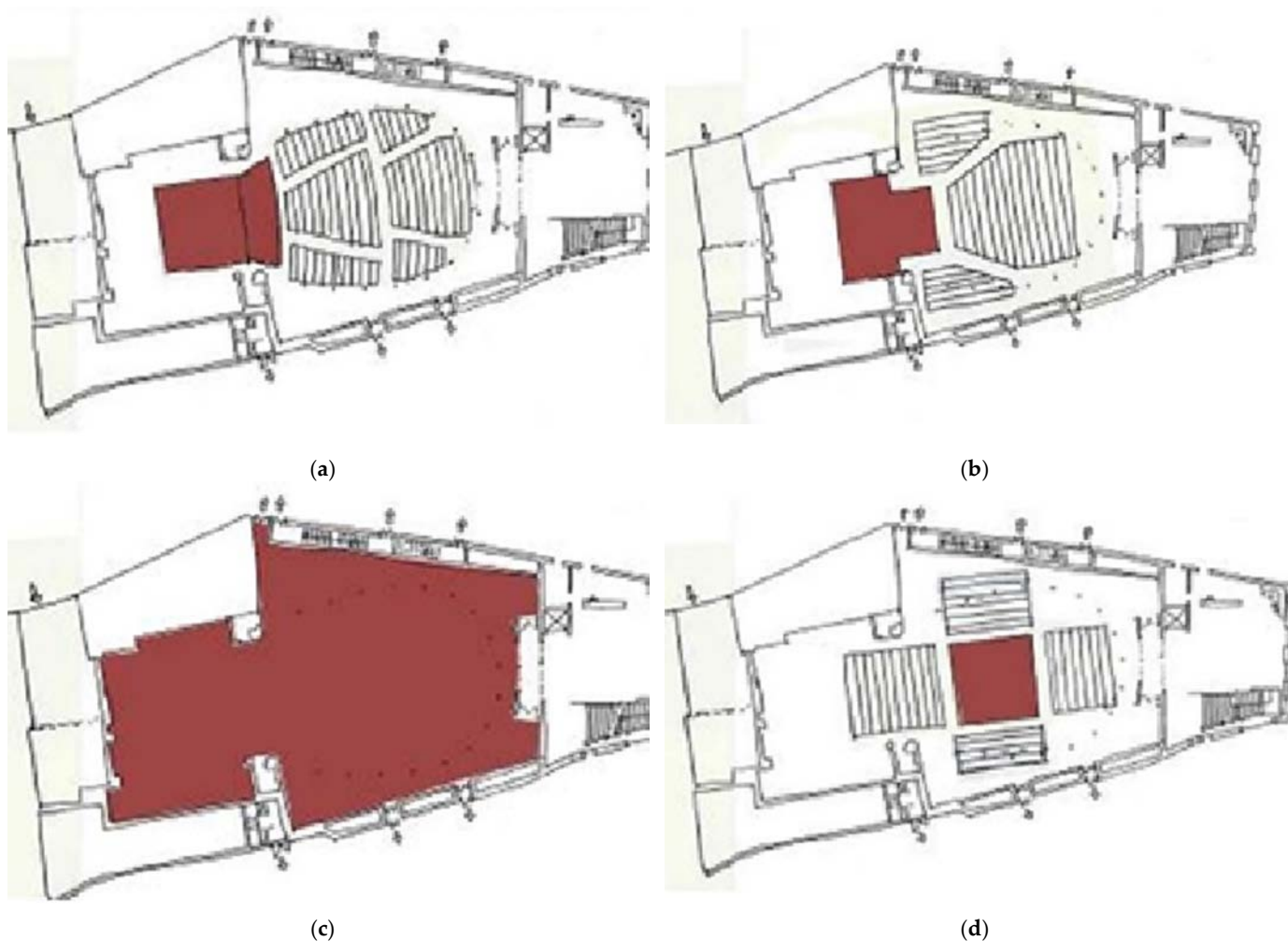


Figure 5. Four main configurations: Concert hall (a), Opera (b), Black box (c), Central hall (d).

Rehearsal rooms, dressing rooms, and a recording studio were placed on level 2. Over them and under the stalls, a large storage area was designed in the main hall block. Level 0 was considered the entrance level to the stalls through the foyer that is on two levels, and also on the first floor, linked to the first gallery in the main hall. On the upper floor, in the foyer block, there is a multimedia room; in the main hall block, there is the second gallery (Figure 6).

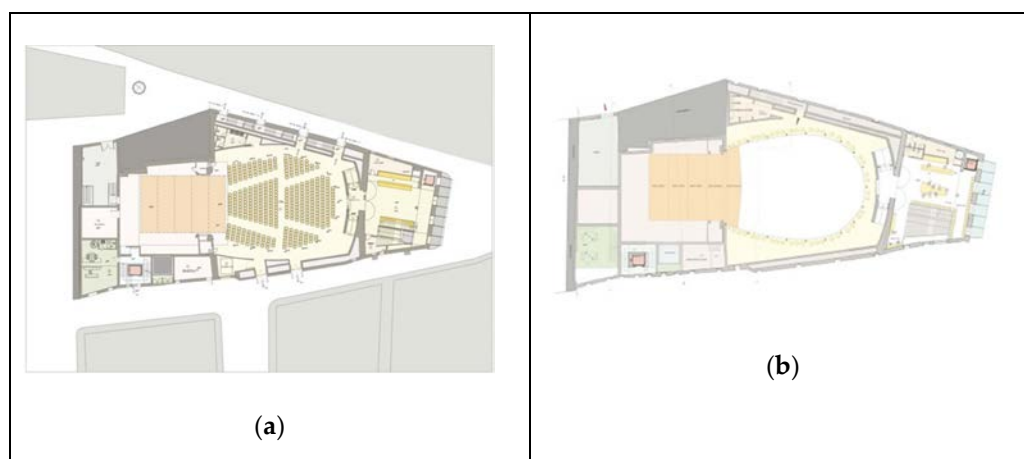


Figure 6. Theatre plans, ground floor (a) and first level (b).

The building required a careful restoration project, respecting the original appearance both externally (skyline) and internally (Italian-style hall characterized by two overlapping galleries supported by wooden columns).

The restoration retained the original materials inside the main hall, with the exception of the galleries and the hall ceiling, for fire protection and acoustic requirements.

The work on the volumes involved excavations to build two floors for storage rooms, housing of technological equipment, and rooms with various uses, which were useful to provide the theatre with the space needed for its various functions.

Traditional fields such as the structure, electrical systems, air ventilation system, and the energy analysis were developed together with the specialist fields for theatres such as the acoustics and stagecraft design.

The restoration process was developed considering other Italian-style theatres of a similar size and number of seats [37–41].

The main goal of optimizing the acoustic quality for the hall inside the theatre building aimed at a variable acoustic field according to the demands of the main configurations. This meant that a multipurpose index equal to “excellent”, considering the three main configurations of the seating capacity, was selected. A black box configuration and central hall configuration were also added, for which the acoustic field varies according to the specific seating capacity (seats are removable) and the show setup.

Other requests, linked to the building acoustic properties (not part of the focus of this paper) followed, including

- a particularly high acoustic insulation between the interior and the exterior of the hall, with a sound reduction index that can also achieve a $R'w$ of ca. 60 dB.
- a low sound level of internal noise when the systems are operating, not exceeding 25 dB(A)."

3.2. The Multipurpose Index Evaluation

The reference scale was established through the questionnaire described above, before the beginning of the Ristori restoration, so it was possible to fix the MI value to be achieved in the case study. The MI was checked during the design process through an

acoustic simulation model (using Catt Acoustic software, v.7) and verified in the commissioning phase. The main target acoustic parameters were defined during the design phase (Table 3) together with a multipurpose index that was requested to be excellent.

Table 3. Reverberation time optimal range for the main configurations and the virtual model.

Configuration	Target Range RT [s]	Other Acoustic Quantities [dB]
Concert Hall	$1.6 < RT < 1.9$	$-3 < C_{80} < 3$
Opera Theatre	$1.3 < RT < 1.6$	$-2 < C_{80} < 2$
Congress Hall	$0.9 < RT < 1.1$	$STI > 0.65$

Unfortunately, due to the bad condition of the theatre, it was not possible to carry out the measurements before the restoration process.

To control the room acoustics in the main hall, sound field simulations for the four identified configurations were carried out using the above described dedicated software. The surfaces inside the space were developed through technical solutions, achieving the acoustic properties (sound absorption and sound diffusion) checked in the virtual model.

Acoustic parameters such as the reverberation time RT, clarity C_{80} , lateral fraction LF, strength G, etc., were predicted. The simulated average quantities necessary to evaluate the MI are plotted in the following table (Table 4), referring to the source and receiver positions used in the commissioning. The satisfaction quantity X_i was determined as equal to 1 (acoustic parameters inside the optimal range), for which the MI was equal to 3, and the potential of the theatre to be used as a multipurpose space was classified as “excellent”, complying with the design goals.

Table 4. The simulated average quantities of the acoustic parameters necessary to evaluate the MI.

Configuration	RT[s]	C_{80} [dB]	STI	Optimal Range
Concert Hall	1.7	0.1	-	verified
Opera Theatre	1.4	1.5	-	verified
Congress Hall	0.9		0.72	verified

The original balustrades were maintained for the two levels of open galleries. The variation in reverberation time was achieved mainly by varying both the position of the orchestra pit platform and the stage craft elements from configuration to configuration.

In the commissioning phase, when works on site were completed, acoustic measurements were carried out following ISO UNI 3382-1 [40], using an omnidirectional source and a sine sweep signal in the proscenium zone for the three main configurations. From the microphone and the analyzer, the signal was imported for real-time analysis in post-processing noise and vibration software.

The source was ca. 0.80 m from the longitudinal axis; microphones were distributed in the hall as follows (Figure 7):

- n. 6 microphones in the stalls
- n. 4 microphones in the first gallery
- n. 4 microphones in the second gallery



Figure 7. Source (red dot) and microphone positions (blue dots).

The measured average values for the RT in the middle frequencies, the C_{80} quantity, and the STI were also verified inside the target range. The satisfaction quantity X_i was determined (Table 5), for which the multipurpose index equaled 3, classified as “excellent”, complying with the design goals.

Table 5. Average measured acoustic parameters and referred satisfaction quantity x_i .

Configuration	Measured RT [s]	$X_{RT,i}$	Other Measured Acoustic Quantities	$X_{C80/STI,i}$
Concert Hall	1.83	1	$C_{80} -0.5$ [dB]	1
Opera Theatre	1.52	1	$C_{80} 1.6$ [dB]	1
Congress Hall	0.98	1	STI 0.65	1

3.3. The Stage Craft for Variable Acoustics

Regarding the theatre hall, the introduction of a stage subdivided into five vertically moving platforms utilized a highly modular scene, easily set up for different functions, artistic genres, and configurations, reconnecting with the ancient tradition of the opera house. The technical grid is important and extends from the stage over the entire auditorium by means of “light bridges” of large bearing capacity, intended to support the lighting and sound system, with the ceiling above endowed with a sound-absorbing capacity according to the specific configuration.

The orchestra pit is formed by lowering one or two stage platforms, making performances with an orchestra possible. It is equipped with mountable canopy panels, allowing around 40 musicians to be accommodated, benefitting from an accurate acoustic environment for unamplified performances.

The fly tower remains unchanged; nevertheless, the stage system becomes suitable for different performances and configurations, due to the size of the new stage access portals, the scene loading system on the stage, and stage pulleys for hoist trusses (six sets placed on six different grid alignments).

As generally suggested for baroque theatres [49,50], for the concert configuration, setting up an “acoustic shell” on the stage consisting of heavyweight wooden panels becomes easy. The acoustic shell vertical panels are mounted on slides more than 6 m high to define the side walls and horizontal panels, which are moved with stage pulls defining the “roof” of the acoustic shell (Figure 8). The real installation is shown in Figure 9, together with the other main configuration layouts.

In the congress hall configuration, the orchestra pit platforms come up to stage level to create the proscenium for the conference speakers and the house curtain is closed.

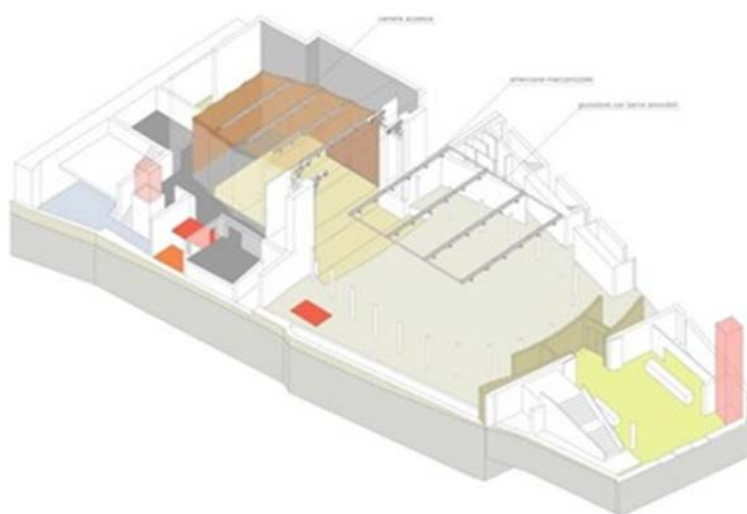


Figure 8. Stage craft equipment: fly bars, acoustic shell and horizontal platforms in the fly tower, light bridges on the stalls.

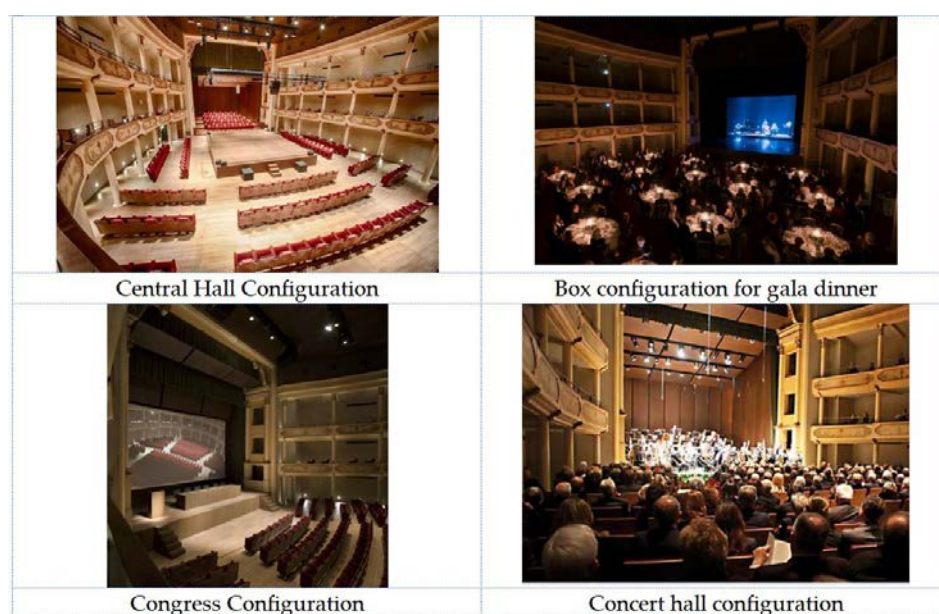


Figure 9. Configuration layout realization.

3.4. A Possible Restoration Process Actualisation Through Integrated Digital Tools

According to the main content of the BEP list for the restoration process of theatres summarized in the methodology section, an actualization of a restoration process starts with the identification of goals and content presentation, including the multipurpose index and a competent and experienced team. A team with years of experience in the theatre restoration process is required, which includes a theatre planning consultant, acoustic consultant, lighting designer, energy consultant, and CAM consultant, side by side with historians, structural engineers, and plant engineers.

The restoration process has to start with an understanding of the state of the building, for which it was difficult to find updated technical documentation as it was collected in a disorganized way. Nowadays, data are first used for the BIM model, helping to compile accurate knowledge of the building and its components to be integrated with the geometric information obtained using a 3D laser scanner [51,52].

The required data for a building and its parts, including geometrical and descriptive information are collected through topographical survey/analysis and inspection reports; during the actualization of the process, geometric information obtained using a 3D laser scanner is implemented with acoustic measurements, structural checks, electrical system checks, etc. A 3D model can be studied in a holistic manner, such that its scope can be comprehensive, yet not detailing materials or specific system configurations.

After the survey, digital tools can be used during the process of constructing and populating a documentary model of a building, such as RVT + images and DWG + XLS for the restitution and a computerized maintenance management system (CMMS) to populate data.

In the renovation process of a theatre, the structural conditions have to first be considered to evaluate the possibility of putting the building into operation and implementing all the stagecraft machinery and heavy show equipment.

In a BEP, the integration level of structural engineers, who have a strong influence on a multitude of disciplines and a strong impact on the structural system itself, is defined at the beginning of the process, and an integrated structural process model (ISPM) can be added [53,54].

By using the BEP including the M index, management of the collaborative design process is enabled, identifying responsible operators, their tasks, role, and responsibilities (including the stakeholders).

In this way, inconsistencies between the different design levels, times, and costs are reduced, and a database for the planned interventions can be set up.

The development of the 3D model and the design of the project database are fundamental steps to better control the process of presenting information of a specific nature (for example the sound reduction index, the absorption coefficient, etc.) [55].

Technical elements correspond to different BIM families, while another level is usually associated with BIM materials. Specifically, the model has to be prepared to ensure the achievement of different LODs and LOINs, according to the building conditions. Subsequently, the BIM object models can be used to prepare a database that will facilitate the facility management and schedule maintenance operations.

For the renovation project of the Ristori theatre, some properties could be implemented with shared parameters: customizable fields that can be created within the software, transferred to text files, and recalled whenever they are needed. Within the BIM model, shared parameters are transformed into editable fields in the properties interface, increasing the interoperability and integration of BIM/BPM.

For example, despite the fact the acoustic behavior has a significant impact on the results of the process, acoustic simulations have to be carried out with specific software not yet interoperable in BIM. In acoustic terms, the use of BIM to generate the building acoustic modeling (BAM) is currently the subject of study by researchers and software manufacturers, but it is already useful to reduce the time for exchanging information [27]. The value of the multipurpose index can be included to better focalize the goals, among the information on the BIM architecture.

By appropriately characterizing the model with the information derived from the database and in compliance with standards/national technical regulations, a BIM model that faithfully reproduces the project can be elaborated.

Finally, the next necessary step is the preparation of the project documentation to make it possible for the client to choose a construction company, offering a complete tool for a specific cost analysis.

The BEP list for the Ristori theatre can be summarized as follows (Table 6).

Table 6. Ristori Theatre BEP summary.

BEP Points	Ristori Summary
Identification of goals and contents present	Transform the Theatre in a Multipurpose Room
Multipurpose index target	3
Previous skills and experience of the team	Team with multi-year experience in theatre restoration process including: theatre planning consultant acoustic consultant lighting designer energy consultant CAM consultant
Survey/analysis of the current situation of the theatre	Geometric information obtained using a 3D laser scanner acoustic measurements structural check electrical system check ...
BIM software to be used during the project and its versions	Revit
Objectives and uses of information models, how data are shared	Loadable objects for theatres (columns, parapets, armchairs, etc.) data are shared through IFC
Information modelling and definition of the Levels Of Information Need LOIN	Suggested 5
Compliance with standards	Collection of all standards required in the included specific fields

4. Conclusions

Nowadays, the restoration process for historic theatres with a horseshoe shape entails a complexity that can be optimized through digitalization support.

The introduction of digitalization into the restoration process design phase for historic theatres is a key innovation for the architecture, engineering, and construction (AEC) sector, which implies a new approach with the use of digital tools and a holistic vision, where all the fields involved, including acoustics, are controlled by a procedure specified in a single document, the BIM execution plan.

The development of a building process for theatres, supported by a BIM execution plan list, represents a procedure that produces positive effects for the project and for the management of the building over time, confirming the advantages of using digital tools, as requested by the Procurement Code. By introducing the multipurpose index (MI) quality as part of the document, this also simplifies the identification of the main goals of the restoration from the beginning of the process, helping to guarantee their achievement, and preserving the acoustic heritage when the theatre is used as a multipurpose hall after commissioning.

During the life cycle, aspects of building automation are also used to optimize costs and maintenance operations, involving, if necessary, the technical office of the client in surveying, analysis, modeling, and data flow.

Through the case study of the “teatro Ristori”, in which the MI was applied for the first time, this paper shows how the same project could have been better controlled by applying a BEP list with BIM and MI support. The BEP summary, presented for the Ristori theatre, can be easily applied to other restoration processes for historic theatres, considering new technological instruments.

Furthermore, the proposed workflow can easily include specific theatrical fields, such as acoustics and stagecraft, and can be characterized by environmental sustainability.

With the BEP being proposed at an early stage, further research could analyze each step of the list, specifying in detail links to the BIM support and reference standards.

The presented case study also confirmed that, to standardize the process for application to the entire building category, objects have to be modeled on historical research first, to become “loadable” objects that are usable in most cases of Teatri all’italiana and in which acoustic properties are included. Data from 3D laser scanners and from acoustic measurements collected in the preliminary phase must be considered as a starting point, together with the identification of the main goals, which, in most cases, means transforming a traditional space into a multipurpose hall.

As a further development, a BIM model supported by the presented BEP could be the basis for creating a new detailed workflow to better control the restoration process from the preliminary to the construction phases, including architectural acoustics, material thermoacoustic property checks, documented restoration activities, etc. Using a digital twin to optimize the room acoustic quality of a building in all possible configurations, implementing all software and app data exchanged during the entire theatre life cycle, is another research direction.

The BEP list could have an impact on the entire Italian cultural heritage of baroque theatres, including the conservation of indoor acoustic quality considering the MI, and could be adopted for the same building category abroad. The MI could also be used to evaluate the multipurpose potential of Italian theatres in use and to better control possible layout implementations with the support of an acoustic analysis. The multipurpose index, in fact, can easily represent the potential of a hall to be flexible as a multifunctional space, using a simple single number quantity, and it clarifies and simplifies the main goals identified when a baroque theatre will be used as a multipurpose space after renovation. To improve the use of the index by experts for a deeper room acoustic analysis of a space, further research could determine adaptation terms to describe the standard deviation of the evaluated acoustic parameters, supported by listening tests and analysis of a reasonable amount of data, with different weighted coefficients in case other parameters are added to the same index.

Even if referring to early-stage research, these conclusions underline the advantages of developing a digitalized workflow supported by a BIM execution plan list, in which the MI quality is defined as a methodology to optimize the restoration process of “teatri all’italiana” in general.

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