24th INTERNATIONAL CONGRESS ON SOUND AND VIBRATION
23–27 July 2017, London

ACOUSTIC CLASSIFICATION SCHEME AND DESIGN PROCEDURE FOR BUILDINGS PERTINENT TO INDUSTRIAL PREMISES FOR ENGINEERING OPTIMIZATION PURPOSES

Giuseppe Squadrone and Elisa Bacchi

TECNIMONT SpA, Via Gaetano De Castillia 6A, 20124 Milan, Italy
e-mail: g.squadrone@tecnimont.it

Generally, the acoustics design of civil structures and indoor spaces at early design stage is neither cared nor organized so much for buildings not devoted to fulfil specific acoustic performances such as noise protection or sound quality. This does not mean that the final acoustical quality of the building is arguable, indeed it is often excellent, but simply that the acoustic design has not been carried out based on either customary or standardized methods. Whereas such approach for building and room acoustic design is common and accepted for architects and civil engineers practices, even the largest ones, giving to each project its own uniqueness, for those buildings which can be defined as "ordinary", or for companies like design firms and global contractors, process standardization would offer advantages. Aiming to building acoustic design standardization and making simpler the construction elements selection, it has been drafted the internal procedure here described, inspired by the standards and the procedures for the design and the construction of sound insulation for piping systems. Main feature of the procedure is a proposed classification scheme for the two building categories generally located in industrial complexes: the ones used to confine noisy machineries and the ones where protection from outdoor noise is required. Once selected the acoustic class of building, this labelling will be used in the BIM 3D Model from which extract project documents referred to the architectural drawings that shall be given to the construction company. The classification scheme includes also the acoustic parameters necessary for the assessment of the indoor sound quality, to avoid excessive reverberant field or let speech communication be suitable. Directions on how to proceed with building and architectural acoustic design and acceptability criteria complete the methodology.
Keywords: classification, design, BIM, industrial, standardization

1. Introduction

Labelling or indexing product elements, either by values or by classes of range values, is a common rating system that allows recognizing at a glance main features or performances related to an object. Classification schemes are often standardized, according to worldwide-recognized systems, as for example the IP coding for electrical enclosures [1]. Classification also simplifies assessment or design process, leading to savings and a better information organization. Examples of such a usage in the field of acoustics are the national standards issued in Europe for sound classification of dwellings, recently involved in a EU harmonization framework project [2, 3], which give evaluation procedures for building categorization, or the international standard ISO 15665 [4], which defines the performance of piping sound insulation assemblies to be used for design purposes, organized by classes.

Looking then specifically at acoustic design of buildings or rooms, generally it is carried out for units or spaces where sound insulation or quality is essential for their final use only, apart from the extreme cases of auditoria and opera houses or rehearsal rooms and recording studios. An example of design standardization is the well-known building bulletin 93 issued in the UK [5], a comprehensive guideline for acoustic design of schools. For other types of building or indoor spaces, further standards or bibliographic references exist, in which acoustic requirement classification [6, 7], building component construction details with relevant sound ratings [8, 9, 10, 11] or specific design procedures [10. 11] are given.

Although mentioned reference bibliography is for sure valuable for supporting an accurate acoustic design or refurbishment of civil buildings or single rooms, it seems not much suitable for setting up a standardized design procedure based on element series.

The need of design standardization recently appeared following to some disruptions occurred during the acoustic design of buildings integrated in industrial premises, either continuously manned or enclosing large machineries. While facing such a methodology problem, the hint for a building and building elements acoustic classification scheme for design optimization scopes looked to be the solution to the issue. In the following sections it is described the whole speculative approach to the standardization/classification project.

2. Background: industrial plant design experiences and terminology

The most important legacy coming from the industrial plant design lead by engineering companies is the strict organization of documents and procedures used for the project execution [12]. In the specific, the methodology used for piping systems acoustic insulation design [13] is the main reference for the development of an analogue procedure to be applied on buildings.

Piping acoustic insulation design is carried out in four stages:

- Definition of the acoustic requirements, in terms of sound pressure or sound power level, based on project noise limits;
- Individuation of pipe stretches emitting excessive noise on Piping and Instrumentation Diagrams (in the following referred to as **PIDs**);
- Selection of the sound insulation class to be applied, according to a **Specification** defining the construction of sound insulation system (e.g. ISO 15665 [4]), to fulfil the noise requirements;
- Issue of detailed project documentation for material procurement and work requisition, to be conveyed to suppliers and erection companies.

This procedure is roughly followed by the majority of **EPC** (Engineering, Procurement and Construction) companies and it is well established to build industrial plants [14]. The strong point of the method is represented by the use of the **Classes** of piping sound insulation. On the subject, the applicable definition of Class is that of set encompassing materials, elements, components, features, arrangements, rules and other constituents [15]. This means that a Class is a consistent collection of items, whose combination determines a defined performance, not just a performance level itself.

By referring again to the piping acoustic insulation design, Classes are generally labelled with one or two letters and or digits, like for other types of piping coatings, which are part of a comprehensive **Line Number**, used as identification code for the lines representing pipes in **PIDs.**

After the desktop design, the detailed engineering of piping acoustic insulation is carried out by preparing a document set for the procurement and the installation of insulation materials on the pipes. Among these, of particular interest are [13]:

- the **Line List**, generally in form of a long table. summarizing all piping information graphically shown in the PIDs and even more;
- the Bill of Materials (**BOM**), extracted from plant 3D model by means of the Material Take Off (**MTO**) execution;
- the Quantity and Price List (**QPL**), defining the unit costs for supply and installation of the insulation coatings;
- the **Isometric** drawings, necessary to the construction company for piping erection and insulation works;

- the Work Requisition (**WR**), being the technical scope of work, which enclose the above listed documents among others as annexes.

As already said before, it is customary for EPC contractors to apply such a method and to prepare such a document suite, for the piping acoustic insulation design and installation. Besides the application of procedure appears reliable and robust, while the final results are generally satisfactory. For these reasons, to avoid blunders during building design carried out by non-acousticians and pointing towards design efficiency improvement, the use of methods for classification, standardization and simplification as depicted in next sections has been proposed.

3. Classification scheme

The Buildings of Industrial Facilities, considered as structural construction products, are classified according to the materials used for bearing elements, wall cladding and internal partitions in following simplified categories:

- **Masonry/Concrete Block wall based** – are buildings in reinforced concrete structures for bearing elements (columns, beams and floor slab) and masonry external walls in concrete block (CMU, Concrete Masonry Unit) or brick walls.
- **Steel Structure based** – are buildings in steel structures for bearing elements and external wall cladding in steel sandwich insulated panels or steel single skin panels. Multi-level mezzanine framing system (steel deck panel and reinforced concrete slab) could be required for equipment installations.
- **Reinforced Concrete based** – are buildings in reinforced concrete structures for bearing elements (columns, beams and floor slab) and external walls, used in particular for blast design requirements.
- **Modular Packaged based** - are pre-engineered and module wise buildings in steel structures for bearing elements and external wall cladding in steel sandwich insulated panels.

The internal wall partitions are in concrete block wall (CMU), brick wall or gypsum wall system.

For industrial plants, basically, all above construction types are employed, that are the concrete and the steel based ones. The timber-based type is not usual. In the specific, steel based structures are mainly utilized for process buildings, machinery rooms, workshop and storage buildings, whereas concrete structures are used for electrical substations, administrative and control buildings, offices, canteens and, for projects including support and logistic areas, also accommodations, canteens, general services and worship buildings.

From acoustical point of view, it is more practical to group the edifices erected within industrial district according to two categories: those that shall enclose noise sources and those where people are more or less attending. This has suggested an initial distinction between the classifications schemes for these two categories of buildings, to be precise the Active and the Passive buildings.

- **Active buildings**, mainly referring to machinery houses, are those in which indoor sound absorption is controlled for occupational exposure reasons and external walls soundproofing is managed to reduce outdoor sound emissions.
- **Passive buildings** are those for which the indoor sound absorption, the airborne sound transmission of internal and external walls and the impact sound transmission for floors are ruled to ensure speech intelligibility, work concentration, or relax, the latter in case of employees accommodations.

Since Active buildings actually are outdoor sound sources, their emitted sound power level is included and controlled in the environmental noise study, reason for which in the internal procedure it has been also included a reference abacus.

The building element acoustic properties considered for classification are the wall, roof and floor airborne and impact sound insulation, the air opening insertion loss and the room internal finishing sound absorption. The acoustic descriptors used to define the above-mentioned properties are:

- Weighted and weighted apparent sound reduction indexes (**R_w** and **R'_w**) [16, 17] for the Active and Passive buildings characterization of external walls, roofs, doors, windows sound insulation and the Passive buildings characterization of internal walls, doors and floors sound insulation;
- Weighted element normalized level difference (**$D_{n,e,w}$**) [16, 17] for the Active buildings characterization of ventilation openings insertion loss;
- Sound absorbing coefficient (**α**) [18, 19] for the Active buildings characterization of room sound absorption;
- Weighted normalized impact sound level (**$L'_{n,w}$**) [20, 21] for the Passive characterization of buildings internal floors impact sound insulation;
- Reverberation time (**RT**) [22, 23] for the Passive buildings characterization of room sound absorption.

The combination of building categories with applicable acoustic descriptors to building elements is summarized in following **Table 1**.

Table 1: building categories, building elements and applicable acoustic descriptors

Building category	External elements			Internal elements				Room absorption		
	Walls Roof	Doors windows	Openings	Walls	Doors	Floors (Air)	Floors (Impact)	Walls ceiling	Small volume	Large volume
Active	R'_w	R_w	$D_{n,e,w}$	--	--	--	--	α	--	--
Passive	R'_w	R_w	--	R'_w	R_w	R'_w	$L'_{n,w}$	--	RT	RT

For the acoustic descriptors shown in **Table 1**, three classes have been defined, based on the expected performance level:

- A – Basic (minimum, poor)
- B – Standard (medium)
- C – Enhanced (high grade)

The numerical values characterizing the classes defined for building element acoustic properties are shown in following tables, relevant to Active and Passive buildings.

Table 2: Active building components acoustic properties classification

Active Building Soundproofing Class	Walls and Roof R'_w [dB]	Doors, Windows R_w [dB]	Openings $D_{n,e,w}$ [dB]
A	22 – 34	17 – 24	7 – 14
B	35 - 45	25 – 37	15 - 25
C	> 45	> 37	> 25

It shall be noted that, for sliding doors or roll gates, the R_w values for Active buildings can be reduced by at least 3 dB. The soundproofing performance for Active buildings has to be intended not affected by structure-borne noise transmission from piping supports and equipment foundations, for which dedicated noise control design specification are issued.

Table 3: Passive building components acoustic properties classification

Passive Building Soundproofing Class	External		Internal		Floors	
	Walls and Roof R'_w [dB]	Doors, Windows R_w [dB]	Walls R'_w [dB]	Doors R_w [dB]	Airborne R'_w [dB]	Impact $L'_{n,w}$ [dB]
A	30 – 39	22 – 29	27 - 35	15 - 24	37 - 45	73 - 85
B	40 – 50	30 – 37	36 – 48	25 – 32	46 – 55	58 – 72
C	> 50	> 37	> 48	> 32	> 55	< 58

The acoustic insulation performance of Passive building components does not consider the structure-borne transmission via the foundations and, in case, specific studies have to be carried out.

Table 4: Active and Passive building sound absorption classification (in the range 500-2000 Hz)

Room Sound Absorption Class	Active Building Walls and Ceiling α [-]	Passive Building Max Reverberation Time RT [s]	
		Small Volume Room	Large Volume Room
A	< 0.3	1.6	2.5
B	0.3 – 0.7	1.0	1.6
C	> 0.7	0.4	1.0

For Active buildings, the room acoustic absorption is intended to control the reverberant sound field mainly for occupational hygiene reasons; the floor is not considered as it is generally sound reflecting and difficult to be acoustically treated.

For Passive buildings, the sound absorption is described with the reverberation time, which is increasing with the room volume, reason for which the values shown in Table 4 are referred to volumes from 50 to 2000 m^3.

It has to be remarked that, at present stage of the whole project, rather than the magnitude and the range of the class acoustic descriptors, which will be analysed and discussed later, the attention is focused on the design methodology optimization, whose procedure is described the in following section.

4. Design and detailed engineering methodologies

The proposed acoustic design procedure for buildings pertinent to industrial plant premises consists of following steps:

- Recognize the acoustics requirements to be applied for building components or rooms;
- Assign the acoustic descriptor values directly to each building element or enclosed space on the architectural drawings;
- Select the building element sound insulation or room absorption class to apply, related to a **database** collecting walls, roofs and floors packaging and finishing, fulfilling the acoustic requirement;
- Prepare the detailed project documentation for material procurement and work requisition, to be conveyed to suppliers and erection companies.

Details of each single step of the procedure are below given.

The acoustic requirement source is either deriving from an environmental noise study, occupational noise limits, speech comprehension, work concentration, quietness needs, or straightforward from contractual annexes.

Implementing BIM Methodology in Corporate work procedure the architectural drawings are strictly connected to a database of building standard components by means of a BIM 3D model [24, 25], compliant with the Industry Foundation Classes (IFC) [26], which links relevant items among them.

The acoustic requirements, related as parameters to building standard components of BIM Content, can be interoperated with Acoustic Analysis software in which the calculations could be performed or, more easily, they can be abstracted in report schedules and exported/imported to/in other acoustic calculation software.

The acoustic requirement fulfilment of building components is checked by comparing their acoustic descriptor values with the required ones. The check of room absorption requirement is at present carried out with separate calculations. In case a sound insulation requirement is not satisfied, a further structural packaging with improved properties is designed, added to the database, and then included in the BIM 3D model where necessary. Analogously, for the room absorption condition, finishing surface of structural packaging is modified and a new database element to be used in the BIM 3D model is created as well.

The detailed project documentation for building construction purposes, to be annexed to the contract with construction company, includes:

- the **Building Elements Architectural Specification**, extracted from database, containing a collection of technical sheets showing the layers of compound walls, floors, ceilings, etc.;
- the Bill of Materials (**BOM**) and the Bill of Quantities (**BOQ**), for the consumable materials, both extracted from the BIM 3D model, by operating with Material and Quantity Take Offs (**MTO**, **QTO**);
- the Quantity and Price List (**QPL**), defining the unit costs for supply and construction of each building component;
- the **Construction Detail** drawings, necessary to the construction company for building erection and finishing;
- the Work Requisition (**WR**), enclosing the above documents along with a set of annexes.

The design phase of the engineering cycle of buildings is followed by the construction, during which field assistance and supervision are carried out by the EPC Company, then by the acceptance test of acoustic performances, with possible corrective actions design in case of failures; procedures for these further stages are not discussed in present paper.

5. Discussion

To ease the development and test of a methodology for building acoustic design optimization, as previously said, the piping sound insulation engineering cycle has been taken for reference. The analogies between project documents, activities and relevant items used for both piping and building design are summarized in Table 5, where correspondences are shown.

Table 5: Correspondences between the piping sound insulation and the building acoustic design items

ITEM TYPE	(Mechanical) PIPING SYSTEMS SOUND INSULATION	(Civil) BUILDING AND ROOM ACOUSTICS
Document	Piping & Instrument Diagram (PID)	Architectural Drawing (AWDA)
Document	Piping Sound Insulation Specification (Spec)	Building Elements Architectural Specification (Spec) and BIM Content
Identifier	Sound Insulation Class	Acoustic Performance Class
Identifier	Line Number	Building Element Code
Document	Line List	***Not Available at time being***
Model	Plant 3D model	Building 3D model (BIM)
Construction drawing	Isometric Drawing (ISO) from 3D model	Architectural Drawing (AWDA) from BIM 3D model
Activity	Material Take Off (MTO) as extraction from 3D model	Material Take Off (MTO), Quantity Take Off (QTO) as extraction from 3D model
Document	Bill Of Materials (BOM)	Bill Of Materials (BOM), Bill Of Quantities (BOQ)
Document	Quantity and Price List (QPL) for BOM accounting	Quantity and Price List (QPL) for BOM and BOQ accounting
Document Set	Work Requisition (WR), containing Spec, ISO, QPL and other documents	Work Requisition (WR), containing Spec, AWDA, QPL and other documents

For the building acoustics design and detail engineering optimization, it is presently in progress the application of the described methodology according to the Plan-Do-Check-Act management cycle, widely used for the control and continual improvement of processes and products. At the moment, progresses are expected for both minimum requirement absolute values and ranges, which look reasonably relaxed, as tentatively set on the basis of previous experiences in industrial plant design, often located in areas which the land use was planned for exclusive production settlements and for which contractual requirements, especially for indoor acoustics were not present.

Further, it is under evaluation the need for a summary table, analogous to the Line List, for building elements (walls, roofs, floors and ceilings) and rooms, requiring improved sound-proofing or sound-absorbing design, in which doors, windows and openings are considered as complementary components associated to the main item (mostly external or internal wall), limiting the Sound insulation efficiency and modifying the sound absorbing properties.

Typical building/rooms in industrial premises for which the passive requirement design of building components has to be carried out to fulfil acoustics requirements from company regulations, local laws, etc., are generic machinery houses, single or open-plan offices, meeting rooms, control and radio-communication rooms, laboratories, canteens, workers' accommodation and rest areas.

The acoustic design of building elements is generally limited to calculation checks of building and room acoustic properties, taking into account materials and structures selected during civil, structural and architectural design, as reported in the technical sheets collected in the BIM database. Should be necessary better acoustic efficiency classes, following design options apply:

- Selection from a list or database [5, 8, 9, 10, 11] construction elements matching with the required acoustic properties and combine them accordingly while designing;
- Insertion of additional layers, or modification of some of them, to get required acoustic properties for the specific building structure;
- Application of acoustic treatments, by coating walls and/or ceiling or by adding suspended baffles, on indoor environment to obtain the necessary sound absorption;
- Carefully design the layout and the construction details to avoid structure-borne sound transmission, which can dramatically reduce the planned acoustic performance;
- Inclusion of proper selection or specification of all accessories in the acoustic design to have best performance of building once erected;

Calculation methods and formulas for building acoustic design are given in EN 12354 [27]/ ISO 15712 [28] standard series, apart from specific literature. Where possible, calculation shall be carried out in octave band spectra.

Once applied any of above technical solutions, the BIM database and the BIM 3D model shall be updated, to provide for detail engineering documentation accordingly.

The development of BIM Methodology considering the acoustic design will be performed as per following main steps:

1. BIM Content setting of Building Standard Components (walls, roof, slab, false ceiling and flooring, doors windows....)
2. Acoustic requirements and parameter setting related to Building Standard Components
3. Acoustic analysis software selection
4. Interoperability and acoustic calculation tests

6. Conclusion and further developments

A classification scheme for building components and a method for acoustic design of buildings and rooms related to industrial complexes, inspired to previous experiences on industrial plant engineering, pointing towards a standardization and optimization of the procedure, has been described then discussed.

At present stage, rather than to the classification scheme, the attention is focused on the design methodology optimization applied to BIM; subsequently actions to improve the classification range pattern are planned.

Lastly, a supplementary expectation of present work is that the illustrated methodology based on a classification scheme would be extended also to civil building design in other engineering fields, not only limited to the industry one, and that it would advance in the acoustic BIM design too.

7. Acknowledgements

Gratitude is expressed to all colleagues who are supporting to make possible the procedure application within the optimization process and the ones who supplied with information necessary to draft this paper.

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