Acoustical Noise Study of a Factory: Indoor and Outdoor Simulations Integration Procedure

Claudio Guarnaccia, Joseph Quartieri, Alessandro Ruggiero

Abstract**—**Industrial settlements are often source of disturbance for the surrounding area. In particular, from an acoustical point of view, the noise emitted by machineries operating in the production line and/or in the logistic activities, is a relevant pollutant to be considered in the environmental impact assessment. For this reason, the field measurement approach is usually preferred, to properly evaluate the noise levels in general conditions. The aid of predictive software may be particularly useful when it is difficult to perform a long term measurement campaign. In this paper, the combination of indoor and outdoor simulations will be presented on a case study in south Italy. The indoor modelling of the sources will help on one hand to understand the acoustic climate of the working environment, on the other hand to assess the overall outdoor noise emission of the factory. The values obtained with the indoor simulation, in fact, will be used to tune the "equivalent source" that simulate the factory emissions. An outdoor noise map will be drawn, in order to assess the impact on the surrounding buildings. Both the indoor and outdoor simulations are tuned with experimental field measurements and compared with results on fixed measurement points.

Keywords**—**Acoustical Noise, Environmental Impact, Indoor modelling and Simulation, Occupational Health, Outdoor modelling and Simulation, Predictive Software.

I. Introduction

THE protection from polluting agents of people in a certain environment, both indoor and outdoor, is evidently a very important issue. Major risks to be considered in any assessment are air pollution, acoustic noise, electromagnetic fields, climate conditions, natural radioactivity, etc.. In [1] the authors try to describe a complex index able to give, with the appropriate weights, an estimation of the environmental quality, considering several of the above listed polluting agents.

In an industrial context, many are the risks for the workers' safety, usually related to work conditions, time shifts, safety equipment, etc.. This paper is devoted to the analysis and the assessment of noise in workplaces, according to Italian national regulation D.Lgs.81/08, together with the evaluation of the noise impact outside the considered structure.

As it is widely reported in literature, exposure to noise can determine on humans several diseases. In [2], a detailed description of both auditory and non-auditory effects of acoustic noise on human health is reported. Beside the damage on auditory apparatus, in fact, a great variety of non-auditory effects can be evidenced, such as sleep disturbance, performance lowering, cardiovascular disease, etc..

The most important parameters to be considered in a noise occupational health analysis are, of course, the sound pressure level and the exposure time. In case of exposure to extremely high levels, the damage may also occur instantly, while, with constant sound levels, noise based injury increases with the increasing of the exposure time. Thus, the main parameters that are widely considered in noise control on working places (see for instance [3]) are:

- the level of the single *i*-esim working activity/source, $L_{Aeq,i}$
- the daily exposure level, obtained by the single $L_{Aeq,i}$ measurements, knowing the exposure time of the single working activity, indicated by $L_{Aeq,Te}$ and defined as:

$$L_{Aeq,Te} = 10 \log\left[\frac{1}{\sum t_i} \sum_{i=1}^{n} \left(10^{\frac{L_{Aeq,i}}{10}} t_i\right)\right] \qquad (1)$$

- the daily personal exposure evaluation, referred to T_0 = 8 hours, L_{EX} (*8h*), defined as:

$$L_{EX,8} = L_{Aeq,Te} + 10 \log\left[\frac{T_e}{T_0}\right] \qquad (2)$$

- the weekly personal exposure evaluation, referred to 5 working days per week, $L_{EX,w}$ (*week or 40 h*), defined as:

$$L_{EX,w} = 10 \log\left[\frac{1}{5} \sum_{k=1,\dots,m} 10^{0,1(L_{EX,8})_k}\right] \qquad (3)$$

Different limits may be fixed by national regulations. For instance, in Italy, regulation D.L. 81/2008, on the improvement of safety on working places, with the implementation of the European nose regulation 2003/10/CE, fixes the following exposure limits and action values:

- Exposure limit values are L_{EX} =87 dBA or p_{peak} = 200 Pa (140 dBC, referred to 20 μPa)
- Upper action values are L_{EX} = 85 dBA or p_{peak} = 140 Pa (137 dBC, referred to 20 μPa)
- Lower action values are L_{EX} = 80 dBA or p_{peak} = 112 Pa (135 dBC, referred to 20 μPa)

where L_{EX} is the daily personal exposure evaluated on 8 hours, $L_{EX,8}$, defined in (2).

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In order to reduce risks associated with noise exposure, it is possible to intervene either by reducing the overall noise level, or by decreasing the exposure time of exposed subjects. Obviously, in order to study possible actions to reduce the noise levels, it is necessary to deeply analyse the considered environment. A proper modelling is often important in the analysis and it starts from the identification and the characterization of the main noise sources in the area under study. Then, the propagation within the environment and eventually outside is considered, in order to achieve a complete noise mapping of the area.

Therefore, if one wants to make a restructuring of the industrial environments or a design of the workplace, it should pay attention to the prediction of noise levels received by employees when production started. A high noise exposure predicted, in fact, may force the company to equip workers with personal safety equipment or to reduce certain time shifts.

Although in particularly simple cases the modelling is possible with easy and well-known mathematical relations (e.g. semi-reverberant field formula), a complete analysis needs numerical tools able to predict the propagation of sound waves from their source until extinction, underlying what happens in terms of reflection, absorption, diffraction, interference, etc.. Several forecasting approaches may be considered: image sources' techniques, ray-tracing, etc.. Indeed on the market, nowadays, there are several software of acoustics simulation for confined areas (such as an industrial environment). Usually they let the operator draw the model of the environment with all the noise sources present in it, simulate any modification (for instance the insertion of new sound sources or the usage of absorbing materials), predict the variation of the sound field produced by the performed action. In [4, 5, 6], for instance, the authors performed the study of two new built churches and suggested some improvements of acoustic climate by means of software simulations.

In this paper, the acoustic characterization of an industrial factory, referring to the Italian legislative decree 81/08, is presented. After a field measurements campaign, a noise map of the environment has been drawn in the RAP-ONE (Room Acoustics Prediction and Occupational Noise Exposure) software environment. This map has been used to find critical points and to estimate timing of daily exposure of individual workers, with the consequent identification of the most vulnerable workers.

Finally, the noise radiated by the factory in the surrounding environment has been investigated in the environmental acoustics forecast software CADNA-A.

II. Noise impact on health

Acoustical noise has different effects on human health. Besides the damage on auditory apparatus, with consequent hearing loss and/or frequencies detection reductions, a great variety of "non-auditory" effects can be highlighted. In the following, a brief review of these effects will be given.

A. *Auditory effects*

Several studies are present in literature that face the auditory effects problem and it has been evidenced that a continuous exposure to noise of 85–90 dBA, particularly over a lifetime in industrial settings, can lead to a progressive loss of hearing, with an increase in the threshold of hearing sensitivity (see for instance [7]).

The main auditory effects are: acoustic trauma, tinnitus, temporary hearing loss and permanent hearing loss.

The acoustic trauma is the sudden hearing damage that occurs in case of short extremely loud noise event, such as a gunshot, reaction engine burst, etc..

The tinnitus is the ringing or buzzing that is experienced in the ear because of a cochlear cells or auditory nerve damage.

The temporary hearing loss occurs immediately after exposure to a high level of noise. It is "temporary" in the sense that there is a gradual recovery after spending time in a quiet place. Complete recovery depends on many factors and may take several hours. It is also known as temporary threshold shift.

The permanent hearing loss growths in time, if noise exposure is not interrupted or protection equipment are adopted. It is hard to be cured by medical treatment. The main feature is that when noise exposure is suspended, the hearing ability is not recovered. This effect, that is also known as permanent threshold shift, can be combined with other effects, such as hearing loss related to ageing.

B. *Non-auditory effects*

Noise affects not only the hearing apparatus, but it is generally experienced that it disturbs human activities and communication, causing annoyance. In some cases, annoyance may be responsible of stress responses [8]. Moreover, besides annoyance, noise may directly have impact on health. Different features of sound, for instance intensity, frequency, complexity of sound, duration, etc., may influence response to noise. The main non auditory effects are briefly resumed in the following subsections.

Noise and sleep disturbance

Sleep is affected by noise from both objective and subjective point of view [9].

Exposure to noise disturbs sleep proportional to the amount of noise experienced in terms of an increased rate of changes in sleep stages and in number of awakenings. Habituation occurs with an increased number of sound exposures by night and across nights. There may also be after-effects during the day following disturbed sleep; perceived sleep quality, mood and performance in terms of reaction time all decreased following sleep disturbed by road traffic noise. Studies on noise abatement show that, by reducing indoor noise level, the amount of REM sleep and slow wave sleep can be increased [10]. It thus seems that, although there may be some adaptation to sleep disturbance by noise, complete habituation does not occur, particularly for heart rate.

Noise exposure and performance

Human performance is impaired by noise exposure [11]; in particular noise may reduce mental tasks such as text comprehension, it may slow rehearsal in memory and it may influence processes of selectivity in memory and choice of strategies for carrying out tasks.

There is also evidence that noise may reduce helping behaviour, increase aggression and reduce the processing of social cues seen as irrelevant to task performance [12].

Noise and cardiovascular disease

There are scientific evidences of physiological responses to noise exposure, such as increase in heart rate and blood pressure, peripheral vasoconstriction and thus increased peripheral vascular resistance. Usually an almost rapid habituation to brief noise exposure occurs, while prolonged noise can lead to a very slow or null habituation [10].

The strongest evidence for the effect of noise on the cardiovascular system comes from studies of blood pressure in occupational settings [13]. Many occupational studies have suggested that individuals chronically exposed to continuous noise at levels of at least 85 dB have higher blood pressure than those not exposed to noise. In many of these studies, noise exposure has also been an indicator of exposure to other factors, both physical and psychosocial, which are also associated with high blood pressure.

Other non-auditory effects

Noise may cause several other effects, such as endocrine modified responses, psychiatric disorder, psychological symptoms, combined effects of noise exposure and other stressors, etc.. For a review, the reader may refer to [14].

III. Methodologies

A. Rap-one

RAP-ONE© software is an acoustic predictive software, developed by SOFTDB company, which allows the analysis and design of interventions in industrial, architectural and occupational hygiene. The software, although based on ray-tracing technique, was established with the specific intent to simplify user operation and to achieve a representation of the noise map of internal environment in few steps.

A room's noise map is a particularly useful graphic element for the analysis and the choice of acoustic treatments to be implemented, but also for presentations and project follows-up. With RAP-ONE, a noise map is rapidly obtained in three steps:

- designing the room;
- positioning the noise sources;
- calculating the noise map.

RAP-ONE allows to design the configuration of your room with the help of a set of tools to add walls, acoustic barriers, absorbing panels, and fitting areas. The program can be used for rooms of any shape, the only premise is that the ceiling and the floor must be flat and parallel. Other functions are used to determine the acoustic properties of the room's surfaces. A library of predetermined acoustic parameters is integrated in the program, for the most common types of material (cement, aluminum, wood, etc.).

With the source tool, it is easy to add and place the noise sources operating in the room. Last step for the source modeling is to determine the sources' acoustic power level. A source's power may be provided by the manufacturer or measured according to ISO regulations. If not, the program will assist the operator in estimating the power level with a series of specifically designed dialogue boxes.

At this point, the room's noise map can be obtained by letting the program run.

In addition to the noise map drawing, RAP-ONE has few important features more:

- it can predict the efficiency of possible noise mitigation actions to be planned by redrawing the noise map after having implemented the intervention;
- it can rapidly estimate the noise doses perceived by the workers by computing the exposition of each worker (in his work station) to the computed noise level for a certain time interval (work shift);
- it may help in the choice of optimal treatments by comparing different actions (noise reduction, absorbing improvement, shifts adjustment, etc.).

B. CadnaA

CadnaA (Computer Aided Noise Abatement) is an important software for calculation, presentation, assessment and prediction of environmental noise. This software is able to simulate all sound sources underlying the main parameters influencing the noise emission and propagation in the external environment. The analysis of any noise source, such as an industrial factory, a mart including a parking lot, a new road or railway scheme or even of entire towns and urbanized areas, may be handled by CadnaA.

CadnaA offers many tools to set up the calculation model, to present the results and to communicate with related applications like spreadsheet programs, CAD software or GIS systems via import and export interfaces. The calculation of noise's levels is always done according to the latest international standards and guidelines.

The software implements the inverse ray tracing technique, calculating the noise levels at given locations, using horizontal or vertical grids (or grids enveloping all facades of buildings), crossing and merging the contributes of each source operating in the environment. For some special sources like roads, railways and airports the acoustic emission levels are calculated from the technical parameter values. The geometry of all objects such as roads and railways is considered.

For further applications of the software in different conditions, the reader may refer to [15-19].

IV. Case Study: Indoor Simulation

The subject of analysis is an Italian company specialized in the construction of machines and tools for subsoil drilling. The company products are intended to be used in the construction phase of infrastructure projects, such as highways, bridges, dams, tunnels, buildings and ground consolidation. The products are: telescopic rods, bucket, propellers, core bits, maneuver tubes, etc. The company has a “make to order” organization, in the sense that the production is related to the market request. The layout of the factory is reported in the upper part of Figure 1.

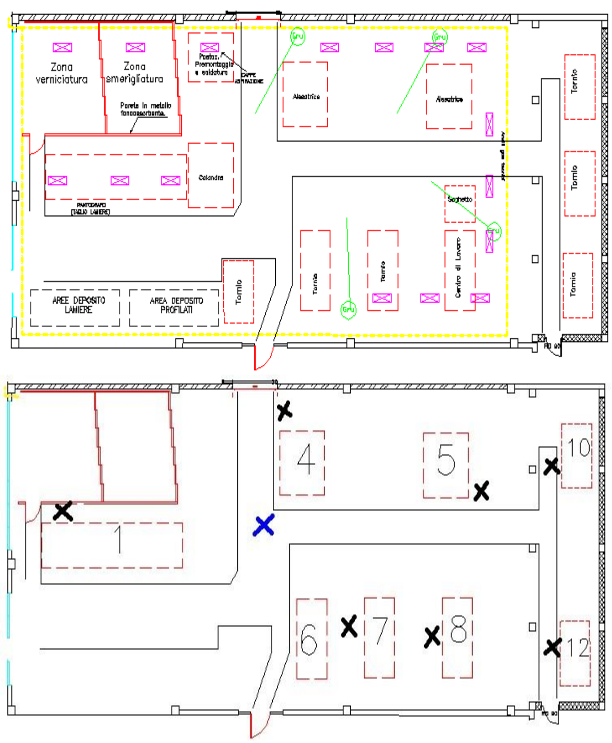

Fig. 1: lay-out of the factory (up) and measuring points placement in the factory (down)

A. Design and execution of the measurement survey

The measurement survey has been designed in accordance with the procedure developed in the framework of the quality management system of the authors institution. In particular, the choice of measurement locations (sources characterization and fixed measurement points) have been chosen according to the layout of the factory.

A sound emission characterization of each production machine of the industrial factory has been performed. The considered machines are four lathes, two reamers, one pantograph and one machining center. In the bottom part of Figure 1, the measurements points (represented by black crosses), each of them representing the characterization of the machine operating, are reported. The blue cross in the center of the factory represents the position of a sound level meter that has been kept fixed during all the measurement campaign. In order to correlate the sound level measured at 1 m of distance to the source emission, a solid angle normalization should be performed. The high reflective surfaces present in the hangar let the authors reasonably neglect this normalization and choose the measured value as source emission. This will probably cause a slight underestimation of the overall noise levels.

The measurements were performed according to the international regulation, in particular taking into account the criteria and methods of the Directive ISO 9612-2009 “Determination of occupational noise exposure” and UNI 9432-2011 “Acoustics-Determination of the Level of Personal Exposure to Noise in Working Environment”. The standard specifies the noise variables and methods of measurement to be used for the definition of the noise situation of a particular work environment and the levels of noise exposure of individual workers. The duration of each measurement has been chosen taking into account the noise characteristics and the machines of the environment under examination.

For the measurement’s campaign two first class sound level meters have been used: a SOLO sound level meter and a two-channels apparatus HARMONY with two microphones. Measurements outside the door of the factory have been taken, with different conditions (closed or opened door), in order to estimate noise radiated by the factory in the surrounding environment. In [20], a discussion on the determination of the uncertainty in environmental noise measurements is reported.

In Figure 2, four samples of emission spectra are reported respectively (from top to bottom plot) for the pantograph, the lathe 2, the machining center and the reamer 1.

B. Indoor Acoustic Characterization

The measurement campaign was carried out in order to analyse the noise climate of the working environment and to characterize the main sources of noise. With these results, the exposure levels of workers may be evaluated with the aid of RAP-ONE software.

The first step to be performed, to produce a predictive model of the factory under study, consists in designing the structure of the building, in terms of size and shape. Then, the materials must be selected, in order to define the absorption coefficients of the environment. At this point the noise sources must be located and defined providing the input frequency spectrum, properly weighted in octave bands. The estimated power level values for each source are reported in Table 1 and two simulations of single machine operating are plotted in Figures 4 and 5. It is evident that, in the case of lathe 2, the high source emission level and the presence of obstacles let the levels be very high in the proximity of the machine.

Finally, the workers/receivers have to be placed. In these places the software evaluates the exposure levels, assuming that in each of them an operator works for a given time interval. In this case study, 6 workers are considered (i.e. the number of workers employed by the company during the day and the night shifts), each of them working for a certain percentage of time on a single machine.

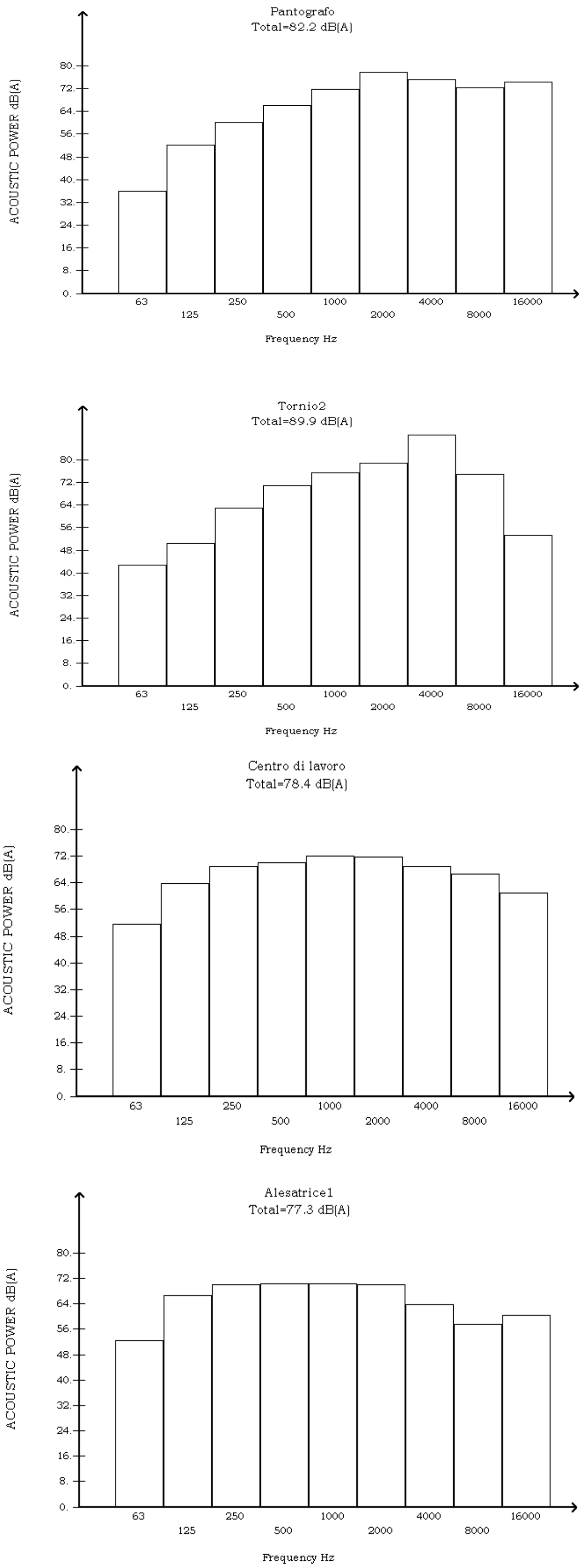

Fig. 2: Emission spectra of (from top to bottom): the pantograph, the lathe 2, the machining center and the reamer 1.

Table 1: Estimated power levels for each source operating in the factory.

Source	L_W [dBA]
Pantograph	82.2
Lathe 1	75.1
Lathe 2	89.9
Lathe 3	81.6
Lathe 4	81.6
Machining center	78.4
Reamer 1	77.3
Reamer 2	79.5

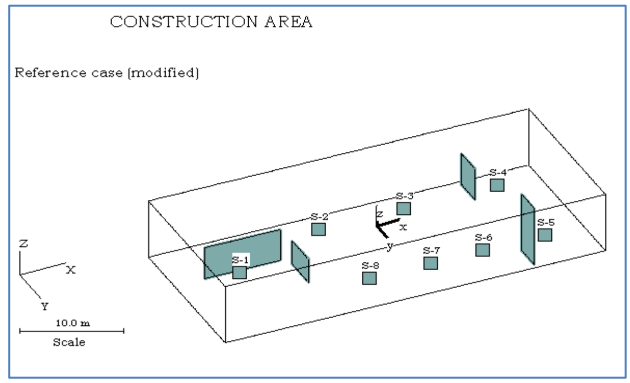

Fig. 3: Rap-one design of the factory under study.

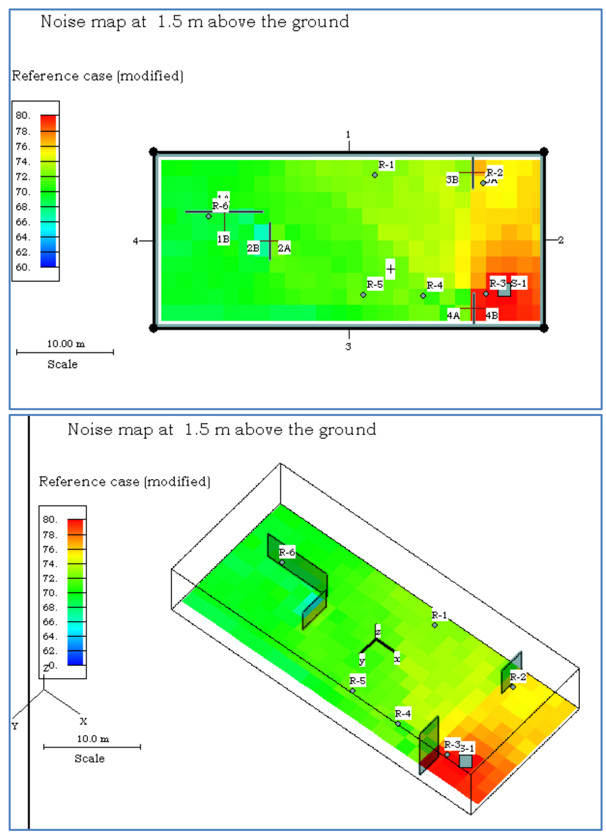

Fig. 4: Noise map of the factory when lathe 2 is operating.

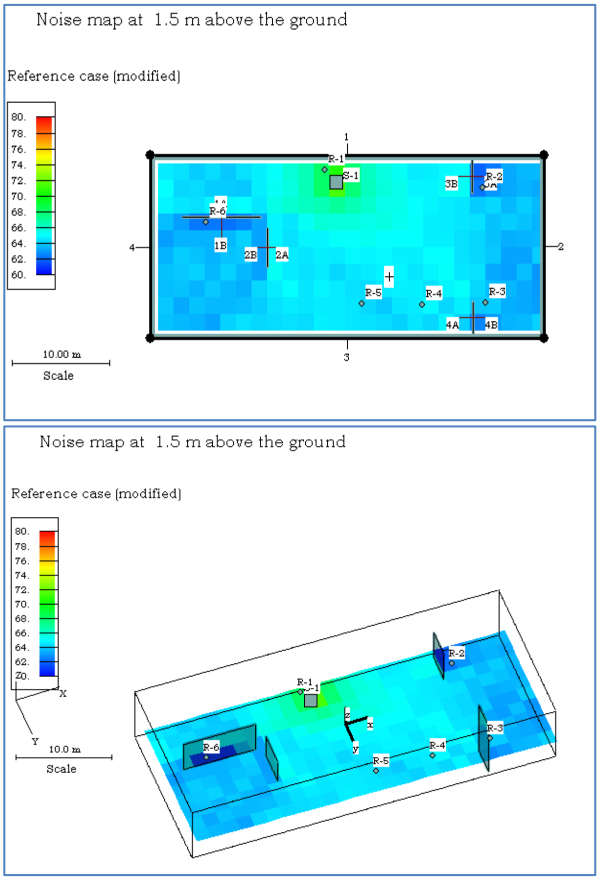

Fig. 5: Noise map of the factory when reamer 2 is operating.

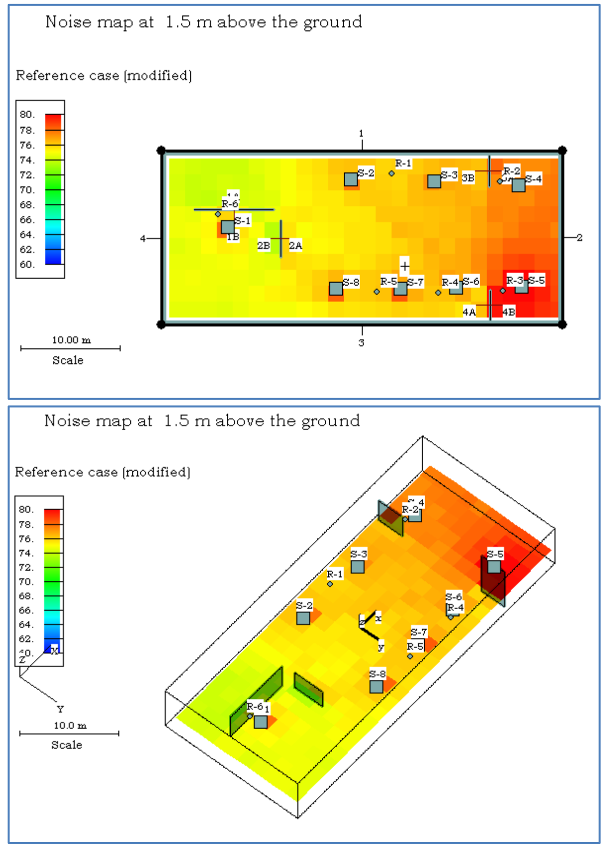

Fig. 6: simulated noise maps in the first configuration, i.e. all the machines operating.

Since the company has a "make to order" organization, i.e. it produces only after a request, without store supply, it is not easy to consider a standard production process. In addition, the machines usage depends on the type of product to be produced. Anyway, considering that an optimum process usually let all the machines work in parallel, in order to have the highest productivity, two simulations are performed: the first one with all the machines operating, the second one with the most frequent operating condition. The latter has been designed according to company suggestion and includes only 6 sources. Taking into account that the pantograph does need an operator to stay continually at the machine, this configuration considers one operator per machine, except for operator 6 that works 25% of the time (2 hours) at the pantograph, while during the rest of the shift (75% of the time) it helps in another work station.

The simulated noise maps are reported in figures 6 and 7.

Knowing the noise levels in each position, one can evaluate the daily or weekly noise exposure level (L_{EX}) of any worker, according to formula (2) and (3). Results of our case study are reported in Table 2.

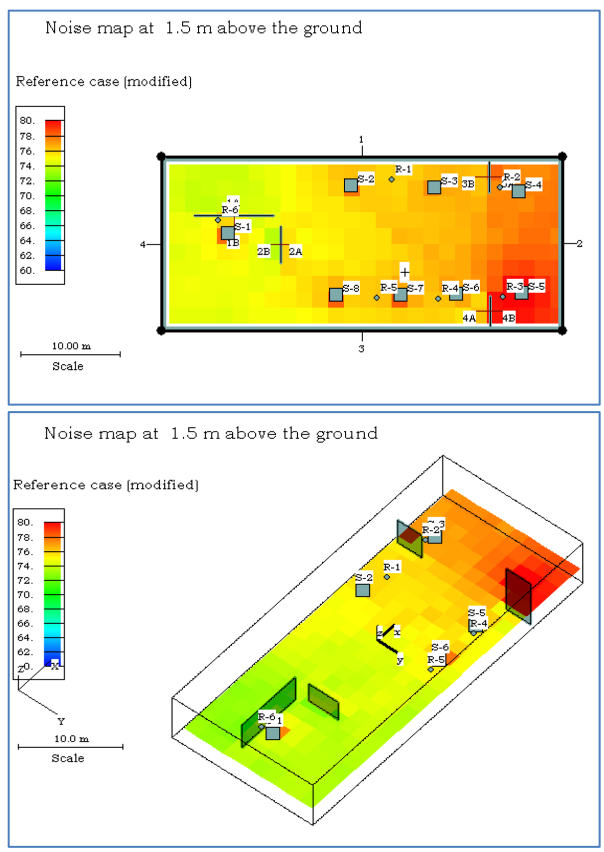

Fig. 7: simulated noise maps in the second, i.e. most frequent operating condition.

Table 2: $L_{EX,8h}$ [dBA] evaluated for each worker, in the two simulated configurations. Worker 6 values are given as an interval between minimum and maximum values, according to the time spent on the pantograph.

	Configuration 1 $L_{EX,8h}$ **[dB(A)]**	**Configuration 2** $L_{EX,8h}$ **[dB(A)]**
Worker 1	75.5	75.7
Worker 2	77.5	77.0
Worker 3	79.7	79.4
Worker 4	76.3	75.4
Worker 5	76.2	75.3
Worker 6	75.8	75.1 (min)
		78.6 (max)

The simulated exposure levels are within the limits of the Italian regulation.

The model was validated through a comparison between measured data and simulated data in configuration 1 (all the machines operating), in the two different positions reported in Figure 8. *H* and *S* are respectively the positions of Harmony and Solo sound level meters.

Results of the comparison (Table 3) confirm a good agreement, as evidenced by a maximum difference of 1.5 dBA.

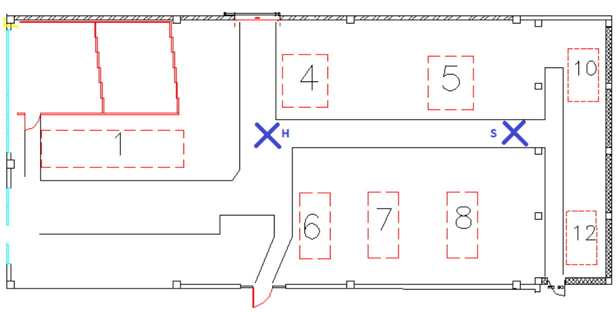

Fig. 8: positions of the Harmony (H) and Solo (S) sound level meters used for comparison between measured and simulated noise levels.

Table 3: measured and simulated noise levels in H and S position.

Config 1	**H position** L_{eq} **[dB(A)]**	**S position** L_{eq} **[dB(A)]**
Measurement	79.8	82.9
Simulation	78.5	81.4

V. Case Study: Outdoor Simulation

After having analyzed the acoustic environment inside the factory, an acoustic characterization "outdoor" has been performed, in order to study the impact that noise generated from factory operating has outside. The aim is to show how inner and outer studies may be combined in order to achieve noise predictions both on internal and external environments. The analysis was performed with the aid of the predictive software Cadna-A.

The area of interest has been properly extracted from a common map found with the help of Google maps©. Once the file has been imported, the drawing of the buildings has been performed. The second step was the roads, car parks and green areas placement. Roads, in particular, need to be taken into account since they are one of the most important noise source in urban environment. Several models, in fact, have been developed to consider the impact of traffic noise (see for instance [13-23]). Once the modeling and the elements characterization (especially in terms of dimensions and acoustic power level) have been completed, the simulation has been performed.

The first simulation was performed by placing a point source inside the building we were studying. Since the software does not allow to easily compute the absorption of the building, the value of sound power emitted by the source has been chosen tuning the parameter in order to obtain, at the position of the external microphone during the campaign of measures, the same equivalent level measured experimentally. With this tuning, the source power has been fixed and the simulation has been performed, resulting in the map shown in Figure 9. The noise arising from the operation of the factory does not significantly impact on the surrounding environment.

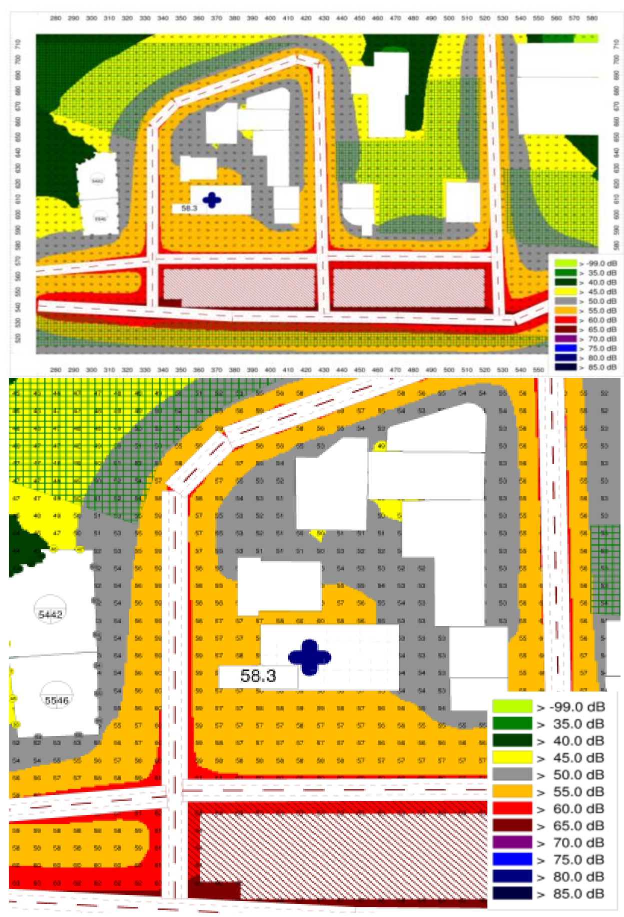

Fig. 9: outdoor noise map simulation in CadnaA: map of the area (up) and zoom on the factory under study (down).

VI. Conclusions

In this paper, an industrial factory acoustic climate and emission outdoor have been analyzed. According to the international standards and to the Italian national regulation, a field measurement campaign has been performed, in order to characterize each source emission and to have reference values for the comparison between model simulations and observed data.

The indoor simulation has been implemented in the framework of RAP-ONE predictive software. The calibration of the model has been done using the single machine operating measurement and the results of the simulations have been compared with the fixed sound level meter results, showing a good agreement.

The outdoor simulation has been performed in an environmental predictive software framework, CadnaA, using the results of the indoor simulation has calibration for the "equivalent source" in charge of simulating the building emission.

The aim of connecting results from field measurements, indoor and outdoor simulations, was fully achieved, pointing out a pragmatic procedure to estimate both internal and external noise impact produced by an industrial activity. In fact, knowing how many machines operates and which is their sound level power emission, RAP-ONE may give an assessment of the internal acoustic climate and, with this prediction, CadnaA may be tuned to predict the noise impact outside.

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