NOISE REDUCTION IN A FACTORY WORK PLACE USING RAY TRACING METHOD: A COMPLETE STUDY FROM PREDICTION TO EXPERIMENTAL VALIDATION

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SUMMARY

The aim of this study is to test the efficiency and the accuracy of the ray tracing method applied to factory noise prediction. The originality of the work lies in the complete validation of the method on a real factory workplace instead of a well controlled laboratory case. The main finding of this study is that the ray tracing method is able to accurately predict noise reduction provided by a set of acoustical treatments in a practical case. Finally, this study shows that the method is an useful tool for a industrial company to choose among several acoustical treatments and to optimize the gain/cost ratio.

SOMMAIRE

Cette étude a pour but de tester l'efficacité et la précision de la méthode des rayons appliquées à l'acoustique prévisionnelle dans les locaux industriels. L'originalité de ce travail consiste en une validation complète de la méthode sur un cas concret et non sur un cas de laboratoire. Le principal résultat est la bonne précision de la méthode des rayons pour prédire des réductions du bruit réalistes par un ensemble déterminé de traitements acoustiques dans un véritable bâtiment industriel, même si le modèle n'inclut pas les effets de diffraction des ondes acoustiques. Enfin, on a montré que la méthode est un outil fort utile pour un industriel afin de choisir une solution de traitement acoustique et d'optimiser le rapport réduction/coût.

1. INTRODUCTION

Several methods are available to predict noise levels in industrial buildings. The method most often used is certainly the diffuse-field theory (Sabine and Eyring theories), but it has restrictive applications [1]. In order to simulate the acoustic response of rooms with more details, geometrical methods have been developed, namely the method of images and the ray tracing method [2].

This paper presents the results of a noise control study using RAYSCAD+ software based on the ray tracing method which has been developed by INRS [2]. Hodgson [3] has clearly proven the usefulness and flexibility of the ray tracing method to model fitted rooms with a high accuracy. However, the prediction of noise abatement due to a room acoustical treatment has been rarely verified experimentally after setting up the acoustical treatment, see for instance reference [4].

This study has been made in a new factory hall following an exhaustive method: preliminary sound pressure level measurements before treatment, modeling of the room with the objective to reduce the noise levels, simulation of noise reduction provided by possible treatments (acoustic screens, absorbing walls, suspended absorption, ...), factory installation of the most promising solutions and validation measurements.

2. DESCRIPTION OF FACTORY HALL

The company studied is specialized in house appliances and mainly manufactures heat exchangers. With the aim to enlarge the work area, a new factory hall (see figure 1) has been built. This new factory hall (60 m length, 29 m width and 6 m height) is divided in two sections: the fabrication area (punching machines, cutting presses,...) and the assembly-lines area. The flooring is made of concrete, the walls of concrete blocks and corrugated steel and the roof of metal sheets. Since the relocation in the new factory, workers of the assembly lines are exposed to the noise emitted from the fabrication area machines.

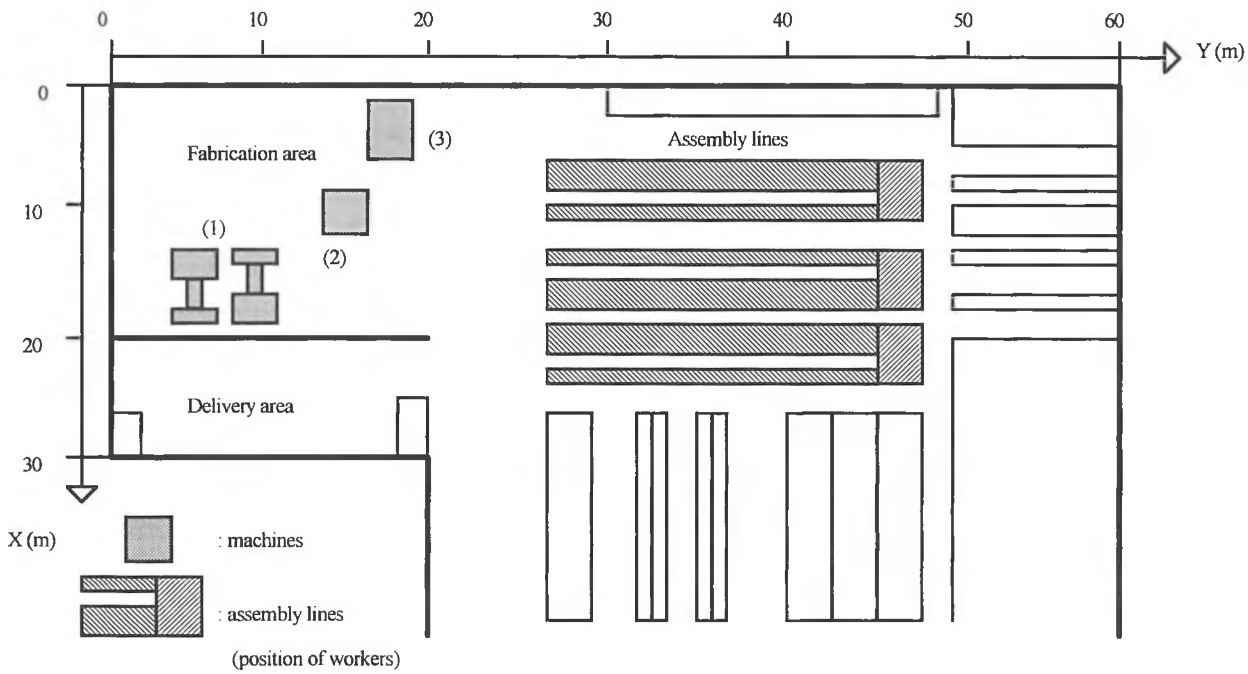


Figure 1. General overview of the factory hall

Table 1: Maximum sound pressure levels measured at one meter of the machines during one impact (dB(A))

	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Punching machine (1)	81	93	95	94	90
Punching machine 60 tons (2)	75	84	87	89	87
Cutting press (3)	77	86	90	90	92

Noise sources are power presses which produce a broadband noise each time an impact cycle occurs. The predominant source is a pair of punching machines (numbered (1) in figure 1) located on the other side of the wall which separate the fabrication area and the delivery area. The secondary sources are a cutting press and two punching machines (numbered (2) and (3) respectively in figure 1). Sound pressure levels measured individually at one meter from those noise sources are reported in table 1.

The sound pressure levels measured at the assembly-line worker stations can vary strongly depending on whether the machines are operating simultaneously or not. Measurements conducted in the assembly-line area vary from 75 dB(A) up to 85 dB(A). Those noise levels are not excessive, but the workers of the assembly lines are disturbed by the presence of the fabrication area noise since this noise problem did not exist in the old factory hall.

As the workers are far away from the noise sources (from 10 to 40 meters), it was assumed that the directivity of the machines did not have much importance at those distances. Moreover, the use of a well controlled sound source was preferred rather than the actual noise sources because of the strong variability of the impact noise emitted by punching machines. No control could be exercised on the gage of the punched steel sheets, the diameter of punching tools and the machine activity since these factors depended upon production schedules.

The main goal of this study was to protect the workers on the assembly lines from the fabrication area noise, as well as the operators in the delivery area to obtain a less "noisy and resonant" working environment.

3. PRELIMINARY MEASUREMENTS

A first set of measurements has been made in the room using the controlled noise source. This source is a sphere composed of twelve loudspeakers. Those loudspeakers are driven by a 500 W Yamaha amplifier with white noise generated by a Brüel & Kjaer analyzer type 2133. The sound pressure level has been measured with a Brüel & Kjaer sound level meter type 2218 and recorded for further investigations on a Sony PCM-2000 digital audio tape recorder.

Table 2: Absorption coefficient at 1 kHz

	Present study	Hodgson study [1]
Air absorption coefficient	0.001 Np/m	0.001 Np/m
Empty room surface absorption coefficient	0.10	0.08
Fitted room surface absorption coefficient	0.142	0.140

The sound power level of the machines has been evaluated using the inverse square law applied to the average sound pressure levels measured at one meter from its center. It has been verified through RAYSCAD+ that the reflections contribution was negligible (< 1 dB) in the factory hall at one meter. As to the sound source, it had been calibrated in a semi anechoïc chamber.

Sound pressure level measurements have been made in the fabrication area corridors, along the assembly lines and in the delivery area. These measurements were used to characterize the noise distribution in the factory hall.

A second set of measurements has been made on a straight line starting from the noise source. Each measurement point was separated by 5 meters. These experimental measurements were used to evaluate the sound propagation decay (Lp(at x meters from the source) - Lw(source)) in the factory hall from the source to the receiver position.

The entire study was concentrated in the octave band frequencies between 250 Hz and 4 kHz. Representative results presented in the remainder of this paper will be limited to the 1 kHz octave band for brevity and because the 1 kHz octave band was the dominant octave band in measured spectra in the factory hall.

4. MODELLING THE FACTORY HALL

The factory hall is modelled as close as possible to reality. Dimensions of the factory have been measured; walls, ceiling and floor materials have been identified. The data computed in the 1 kHz octave-band are given in table 2.

The absorption coefficient values computed are typical for an industrial hall, they are very close to those determined by Hodgson [3] for another room in another building. Indeed Hodgson [3] has calculated absorption coefficient values using reverberant time determination whereas in this paper, an average absorption coefficient has been calculated from the individual absorption coefficients and surfaces of each room surface (walls, ceiling, ...). These results confirm the fact that empty room surface absorption coefficient can be estimated with the values given by Hodgson [3]. The "fitted room" surface absorption parameters are quite similar to those obtained by Hodgson [3]. Because these parameters are the most difficult to evaluate, it is more convenient to use the ones given by Hodgson as starting values for modelling purposes.

The geometry of the hall has been modelled with 11 planes with corresponding absorption coefficients representing each surface of the room. Three encumbered zones have been defined, the first two correspond to the 0 to 2 meters height and the 2 meters to the roof zones in the studied area of interest (fabrication area + delivery area + assembly lines) and the third zone corresponds to the rest of the factory. The fitting parameters (absorption and density) have been estimated with typical data given in the RAYSCAD+ software data bank. The values chosen have been confirmed according to A.M. Ondet [6] who has extensively validated the data bank values.

The sound pressure levels are calculated using a 29 $\times$ 59 grid of 1711 reception cells equally distributed in the factory hall model. Each cell has a volume of one cubic meter (1 $\times$ 1 $\times$ 1 meter), the center height of these cells is 1.5 meters and the distance between two cells is 1 meter as shown in figure 6.

5. BEFORE TREATMENT: COMPARISON OF EXPERIMENTAL AND PREDICTION RESULTS

5.1 Sound propagation decay

The sound propagation decay has been calculated for both experimental and calculated results. The sound propagation curves are presented in figure 2.

The comparison between the two curves demonstrates a very good agreement between calculated and experimental results. The difference is less than 2 dB at any measurement point. This difference can be attributed to the measurement deviation as well as the estimated calculation parameters. As the sound propagation decay curves do not present significant differences for any octave-band, the parameters computed in the model have been taken as satisfactory.

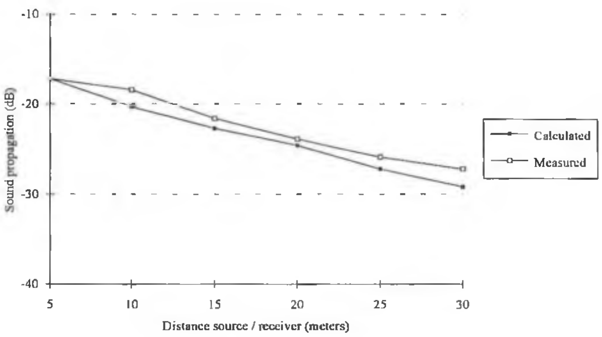


Figure 2. Sound propagation decay at 1 kHz before treatment

5.2 Sound Pressure Levels

As the sound pressure levels could not be measured at 1711 points, the comparisons between experimental and calculated results are limited due to actual accessibility to 29 measurement points. Table 3 presents the differences that can be observed in the factory hall before acoustical treatment installation. The discrepancies range between 0 to 3 dB, and mostly around 1 dB.

It can be observed that maximum error points are located in a specific area on a line from 24 to 44 meters on the X axis and 21 meters on the Y axis. This line is located between two storage racks which produce a local sound absorption increase. The encumbrance is not equally distributed in the room as it is assumed in the RAYSCAD+ software calculation hypothesis. Moreover, measurements were made on point locations when calculations are averaged on one cubic meter volumes. Local differences may be observed for all these reasons.

Overall, a good agreement is observed with an average error over the whole room of 1.1 dB.

6. DESCRIPTION OF THE STUDIED TREATMENTS

6.1 Acoustical treatment for noise reduction in the delivery area

The noise in the delivery area was high enough to render impossible any conversation including phone calls. The delivery area is located beside a 3.6 meter high partial wall (see fig. 3) separating this zone from the fabrication area (see fig. 1).

The obvious solution in this case is to raise the wall. Simulations have shown that it is preferable to raise the wall up to the roof in order to decrease the noise level down to the level of background noise. Since RAYSCAD+ does not

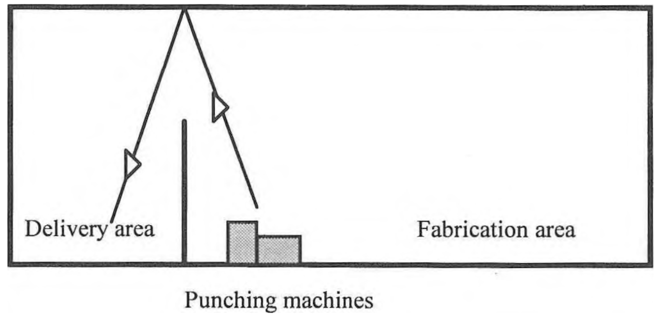


Figure 3. Separation wall between fabrication and delivery areas

include transmission loss effects, verifications have been made to insure that the transmission loss of the wall was at least 30 dB within the octave bands between 500 Hz and 2 kHz. The actual wall is made of double wall corrugated steel sheets separated by an air gap partially fulfilled with thermo-acoustic material.

6.2 Acoustical treatment for punching machines noise reduction

As mentioned earlier, the punching presses are the most important noise sources in the fabrication area. Since no economical and practical noise control solutions at the source were available, it has been decided to protect workers by adding acoustical screens around the pair of punching presses. The company did not want to install a full enclosure for various production reasons. Figure 4 describes the partial enclosure made with 3 m high screens with an inner surface covered of absorbing material ($a = 0.9$ at 1 kHz) and protected by a perforated metal sheet. The screen frame is made of 0.012 m plywood. Some important remarks must be made at this stage. Firstly, even though it was not possible to install a full enclosure equipped with a roof, the installation of absorbing baffles above this area will help to improve the efficiency of the partial enclosure. This has been confirmed by simulations and by the actual reduction measured (see section 7). Secondly, transmission loss of the wall is well above 15 dB, therefore insuring the transmitted field to be negligible. Thirdly, as RAYSCAD+ did not predict the diffraction effects, uncertainties will undoubtedly affect the predictions.

6.3 Acoustical treatment for noise reduction in the assembly-line area

Since the noise sources (production area) are far away from the assembly line (see figure 1), the most suitable way of decreasing noise is to act on the sound propagation. For this specific goal, RAYSCAD+ has proven to be quite powerful in the sense that it has permitted to evaluate the acoustic efficiency of various scenarios. These efficiencies can then be compared versus cost and the relative advantages and

Table 3. Relative error between calculation and experiment at 1 kHz before treatment

X (m) \ Y (m)	5	10	15	20	24	29	34	39	44	49
3					0.8	0.9	2.4	2	2.5	0.1
4	0.9	0.4	1.2	-0.1						
12					2.3	-0.1	0.7	-0.5	0.2	0
14	-0.8	-0.9	0.3	1.1						
21					1.1	2.3	1.7	2.2	3	
23	0.8	0.4	0.3	2						

(positive value: calculated SPL lower than measured SPL)

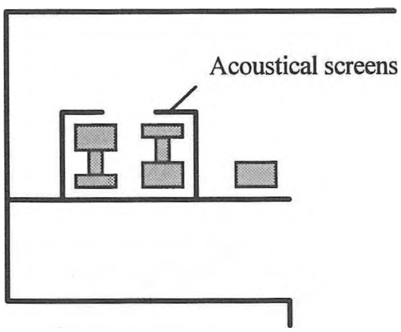


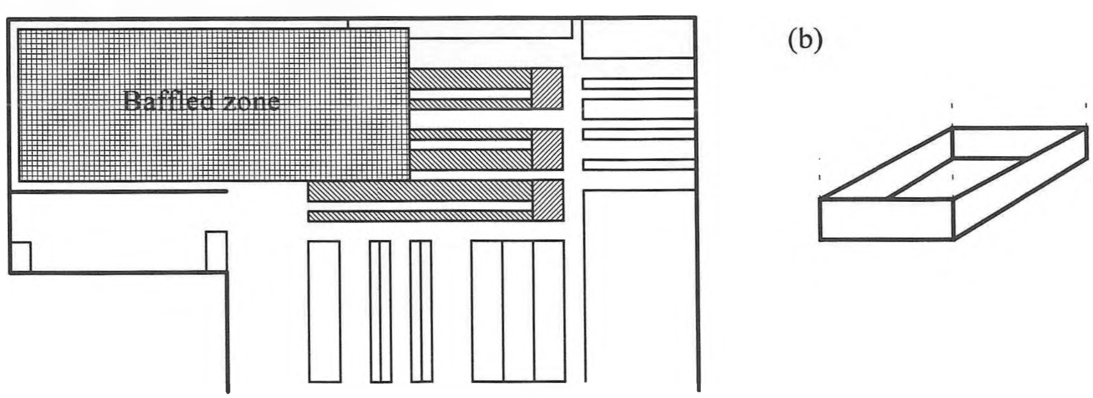
Figure 4. Acoustical screens around the pair of punching machines

constraints from the company's production point of view. Therefore, informed decisions can be exercised by company executives and engineers. It would be too long to describe the numerous scenarios but some of them deserve to be mentioned.

Partial screens from the roof towards ground or vice versa installed in the corridor between the production and the assembly line had proven to be efficient. The installation of baffles above the production line was predicted to be insufficient. The same can be said about installing baffles just above the assembly line. On the contrary, the installation of baffles all over the roof surface was predicted to be too efficient, so that an intermediate solution was chosen to limit costs. Baffles would be installed over the production area and above half the assembly area (see figure 5). Various baffle configurations have been simulated in accordance with the selected solution. For a good parametric study of baffle's effects, we refer the reader to recent work done by Hodgson et al. [5].

The chosen installation was such that each baffle is 2.4 meter long and 0.6 meter high and demonstrated an absorption of 0.9 at 1 kHz. The entire acoustical treatment of the roof consists of 280 baffles in a square arrangement (see figure 7). Those baffles are modelled with only 27 planes crossing every 2.4 meters. However, in practice, all these baffles could not be installed because of the presence of a suspended electric pulley tracks. The actual baffles were made of a sandwich consisting of two 2.5 mm acoustic tiles separated by 0.05 m air gap. This sandwich was supported by a steel frame.

(a)



(b)

Figure 5. Acoustical baffles over the fabrication area. (a): location of the treatment, (b): four baffles disposed in square

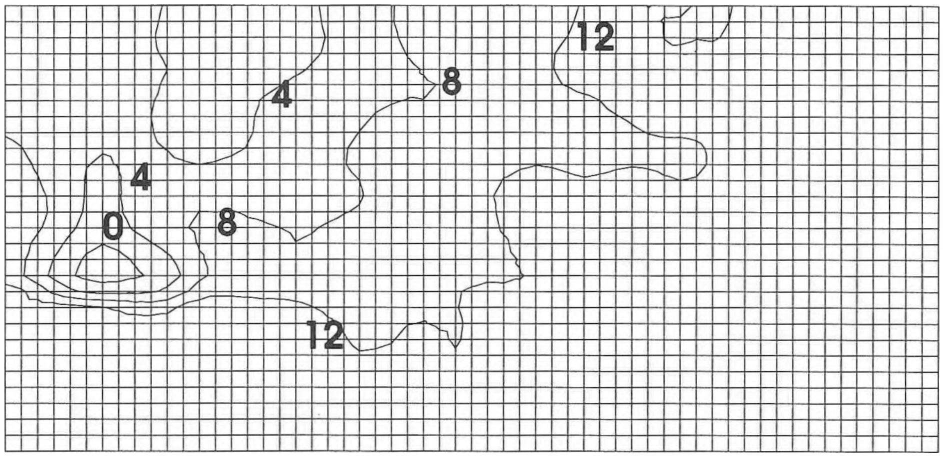


Figure 6: Predicted noise reduction at 1 kHz

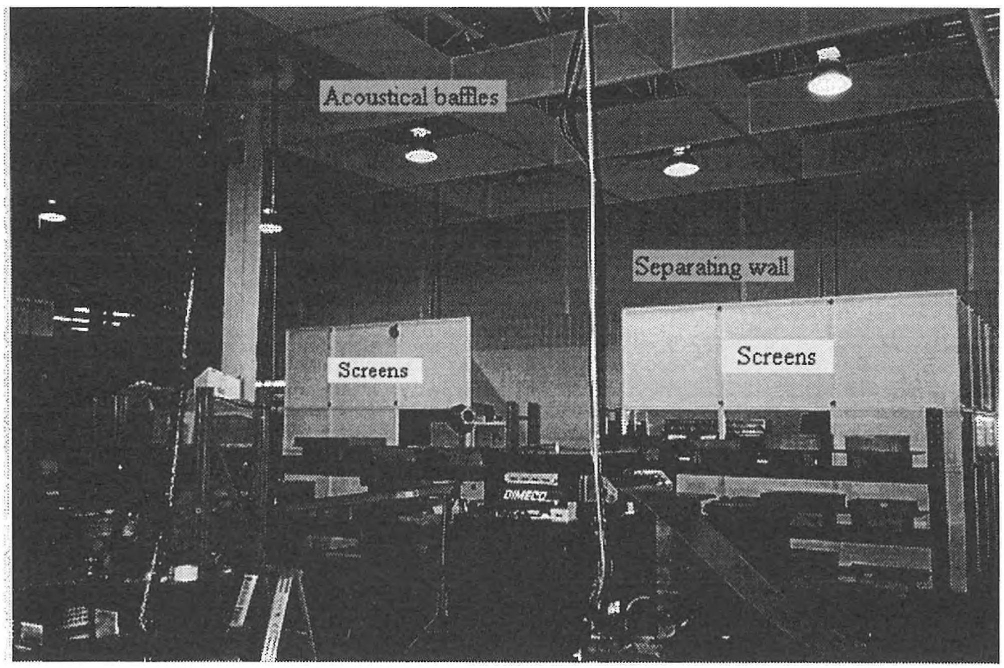


Figure 7: Photograph of the Venmar factory hall after treatment

7. AFTER TREATMENT: COMPARISON BETWEEN PREDICTED AND MEASURED RESULTS

Following the acoustical treatment installation, noise levels were measured in the fabrication area corridors, along the assembly lines and in the delivery area in the same manner used in the preliminary measurements.

7.1 Sound propagation decay

The new sound propagation decay has been measured on a straight line starting from the sound source, in the middle of the fabrication area, towards the assembly area. The measured and the predicted results are presented in figure 8. The agreement is quite good. Further away from the source, at 20 to 30 m, one may notice a small overestimation. This

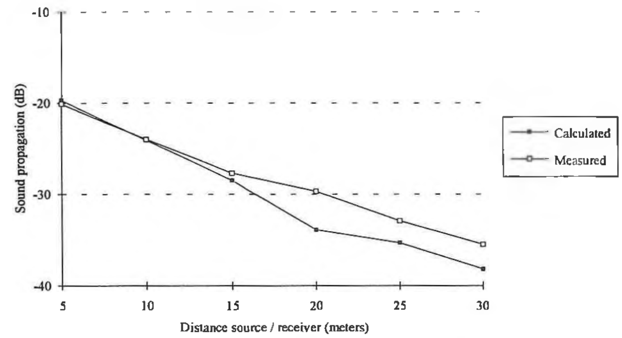


Figure 8. Sound propagation decay at 1 kHz after treatment

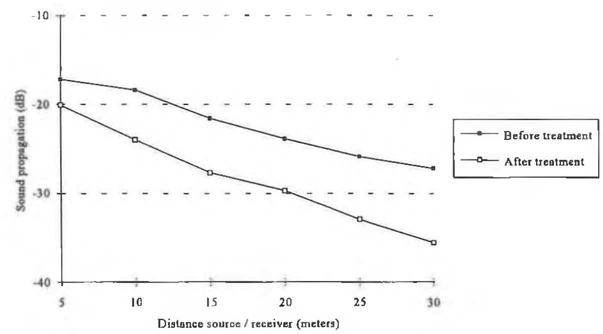


Figure 9. Sound propagation decay before and after treatment, experimental results

Table 4. Reverberation time before and after ceiling treatment

Frequencies	500	1 kHz	2 kHz	4 kHz
T.R. before(s)	1.6	2.2	1.8	1.6
T.R. after (s)	0.8	1.2	1	0.9

may be due to several reasons: (i) the fact that diffracted waves are not taken into account in RAYSCAD+; (ii) because the installation of baffles in the area of pulley tracks was not possible resulting in the use of less than 280 baffles; (iii) a small overestimation of the baffle absorption coefficient. Nevertheless the agreement is quite satisfactory and the gains obtained (figure 9) readily observable. To complete this aspect, reverberation time before and after treatment, under the treated zone have been measured. The results are given in Table 4. This explains also which the acoustic confort have been persued as greatly improved by the workers.

7.2 Sound pressure levels

The sound source is now located into the partial enclosure. Before presenting any results, it must be noted that the background noise inside the factory is about 54 dB. In order to compare actual levels with the predicted ones at each point, the predicted levels have been calculated by adding the background noise which was far from being negligible especially in the assembly and delivery areas.

In the first comparison (before treatment), no background noise correction had to be done. The main reason is that with no treatment, noise levels measured far from the sound source were still higher than the background noise.

Table 5 gives the comparison for several points distributed all over the three areas of interest. In general, and considering the complexity of the problem, the results are quite satisfactory. The precision is around or less than 2 dB for most of the points. However, in a central area, discrepancies up to 6 dB may be found. It is interesting to keep in mind that these discrepancies are given in the most severe case, that is to say for precise position. If we compare average levels on a given area (delivery, fabrication, assembly), discrepancies go down to about 2 dB. One may note that levels are well predicted in front of the opening of the partial enclosure. On the sides, however, reductions are overestimated and this is mainly due to the fact that diffracted waves (directly diffracted or diffracted and reflected) are not taken in account by RAYSCAD+.

8. EFFICIENCY OF THE PROPOSED NOISE TREATMENTS

The predicted and measured reductions have been calculated with sound sources located at the punch presses and cutting press positions. No attempt has been made to, after the fact, change some parameters to obtain a better fit. Data shown here are raw data (see figure 6).

- **Noise reduction in the delivery area:**

The predicted noise reduction was 12 dB (including the background noise) and the measured reduction, in this area shows an average of 13.5 dB. Not only is the prediction good but the objective of being able to sustain a conversation in this area is now achieved.

- **Noise reduction in the production area:**

Inside the partial enclosure the level is almost the same, as expected. The worker is essentially exposed to the direct field. By adding absorption on the inside walls of the partial screens we have made negligible the contribution of the supplementary reflected waves created by these new proximity walls. In this area, the predicted and measured noise reductions are 6 dB and 5.5 dB respectively. One may note here that this gain is partly due to the screens, partly due to the baffles.

Table 5. Relative error between calculation and experiment at 1 kHz after treatment, considering background noise

X (m) \ Y (m)	2	5	10	15	20	23	28	33	38	43
4						5	4	4	4	3
5	0	-1	1	5	4					
10	0	0	2	6	4	5	4	1	1	1
13	2	-1	6	4	5					
18						2	2	0	1	
23	3	2	2	2	4					

(positive value: calculated SPL lower than measured SPL)

- <u>Noise reduction in the assembly line area</u>:

The predicted noise reductions in this area varies from 8 to 12 dB, and the measured ones vary from 7 to 10 dB. The reasons for this overestimation have been explained previously. In the factory, during a normal workshift, this difference is clearly audible and results in the achievement of the main objective of the study.

9. CONCLUSION

In this study, the ray tracing method has been confronted not only to academical laboratory well controlled conditions but also to a real industrial one in all its complexity. The case chosen here included several degrees of complexity and the solutions tested involved all major situations such as: adding walls, adding partial enclosures, adding baffles.

Thanks to systematic measurements before and after treatment, it has been shown that RAYSCAD+ is undoubtedly a good and efficient tool. The predictions are generally reliable with a clear restriction stemming from its weakness of not including the diffracted waves. This effect of including the diffraction for a barrier was studied by L'Espérance [7], who in recent simulations [8], confirms that ignoring this effect may cause a 1 to 3 dB underestimation of the insertion loss of a barrier. The main advantage lies in the possibility for a given industry to choose rationally between various scenarios and to optimize the ratio gain/cost. Although the software is not complicate to use, knowledge in room acoustics is necessary to adequately adjust the model and to optimize the various solutions.

10 ACKNOWLEDGMENTS

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