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# The Use of a Global Index of Acoustic Assessment for Predicting Noise in Industrial Rooms and Optimizing the Location of Machinery and Workstations

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*This paper describes the results of a study aimed at developing a tool for optimizing the location of machinery and workstations. A global index of acoustic assessment of machines was developed for this purpose. This index and a genetic algorithm were used in a computer tool for predicting noise emission of machines as well as optimizing the location of machines and workstations in industrial rooms. The results of laboratory and simulation tests demonstrate that the developed global index and the genetic algorithm support measures aimed at noise reduction at workstations.*

noise machinery optimization genetic algorithm

## 1. INTRODUCTION

Over a one third of employees in the European Union, i.e., ~60 million people, are exposed to high levels of noise during a quarter of their working day [1, 2, 3]. In agriculture, construction, manufacturing, including manufacture of wood, basic metals, food products and beverages, and in the entertainment sector, the limit values of exposure are frequently exceeded. Therefore, noise induced hearing loss is still the most common reported occupational disease.

Directive 2003/10/EC defines the general principles for eliminating risks and reducing exposure of workers to noise [4]. It covers

- eliminating risks arising from exposure to noise at their source;
- adapting work to employees by the design of workstations and places of work of reduced level of exposure, selecting machines and work equipment as well as procedures and methods characterized by reduced noise emission;
- locating machines, work equipment and workstations properly;
- adapting workstations to progress in technology related to technical measures of noise reduction (automation and remote operation of machines as well as soundproof cabins for personnel, sound-absorbent and isolating enclosures for machines, vibroisolation of machines, acoustic dampers, acoustic shields and acoustic adaptation of industrial rooms) as well as organizational measures (limited time of work and work breaks at workstations with high noise exposure, creating so-called oases of silence, medical prevention);
- selecting properly, using and inspecting the use of hearing protectors.

Technical measures for noise reduction are most effective if they are considered when an industrial

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plant is designed. Therefore, the global index of acoustic assessment of machines $Q_{GWA}$ [5, 6] has been proposed; it makes it possible to predict noise emitted by a machine in an industrial room and to optimize the location of machinery and workstations.

$Q_{GWA}$ is a function of five partial indices and can be defined with Equation 1 [6]:

$$Q_{GWA} = Q_N \cdot Q_R \cdot Q_\Theta \cdot Q_{imp} \cdot Q_F, \quad (1)$$

where $Q_N$ = sound power index, $Q_R$ = index of distance between workstation and machine, $Q_\Theta$ = radiation directivity index, $Q_{imp}$ = impulse and impact noise index, $Q_F$ = noise spectrum index.

Equations 2 and 3 describe $Q_N$:

$$Q_N = 1 + \frac{L_{NA} - L_0}{50}, \quad (2)$$

for $L_{NA} \geq L_0$ and

$$Q_N = \frac{1}{1 - \frac{L_{NA} - L_0}{50}}, \quad (3)$$

for $L_{NA} < L_0$, where $L_0$ = admissible value of $A$-weighted sound power level of a machine (if there is no admissible value of sound power level, $L_0$ = 90 dB is recommended) (in decibels); $L_{NA}$ = $A$-weighted sound power level (in decibels).

Equation 4 defines $Q_R$:

$$Q_R = \frac{3.7}{3.2 + \lg\left(\Omega r^2\right)}, \quad (4)$$

where $R$ = distance between workstation and machine (in metres), $\Omega$ = solid angle of radiation (in radians).

$Q_\Theta$ is described as

$$Q_\Theta = 1 + \frac{L_{pA} - L_{pAa}}{50}, \quad (5)$$

for $L_{pA} \geq L_{pAa}$ and as

$$Q_\Theta = \frac{1}{1 - \frac{L_{pA} - L_{pAa}}{50}}, \quad (6)$$

for $L_{pA} < L_{pAa}$, where $L_{pAa}$ = averaged $A$-weighted sound pressure level (SPL) around the machine at a distance equivalent to the distance between the workstation and the machine (in decibels), $L_{pA}$ = $A$-weighted SPL at the workstation (in decibels). Tables 1–2 list the values of $Q_{imp}$ and $Q_F$, respectively.

**TABLE 1. Impulse and Impact Noise Index $Q_{imp}$**

| $L_{Cpeak}$ (dB) | $n$ | $Q_{imp}$ |
|---|---|---|
| $135 < L_{Cpeak}$ | 0 | 1.10 |
| $125 < L_{Cpeak} \leq 135$ | ≤100 | 1.08 |
| $115 \leq L_{Cpeak} \leq 125$ | ≤1000 | 1.06 |
| $105 \leq L_{Cpeak} \leq 115$ | ≤10 000 | 1.04 |
| $100 \leq L_{Cpeak} \leq 110$ | ≤100 000 | 1.02 |
| $L_{Cpeak} \leq 100$ | no limit | 1.00 |

*Notes.* $L_{Cpeak}$ = $C$-weighted sound pressure level; $n$ = number of impulses in 8 h of work.

**TABLE 2. Noise Spectrum Index $Q_F$**

| $\Delta_{C\_A}$ | $Q_F$ |
|---|---|
| ≤ 0 | 1.00 |
| 0.1–2.0 | 1.05 |
| 2.1–4.0 | 1.10 |
| 4.1–9.0 | 1.15 |
| 9.1–15.0 | 1.20 |
| >15.0 | 1.25 |

*Notes.* $\Delta_{C\_A} = L_{pC} - L_{pA}$ (dB); $L_{pC}$ = $C$-weighted sound pressure level (dB), $L_{pA}$ = $A$-weighted sound pressure level (dB).

Each partial index is always positive, it is dimensionless and one is a neutral value. If the value of each index is over one, a parameter has an adverse effect on the acoustic climate in the working environment, whereas a value under one means that a parameter can improve acoustic conditions. For example, if the value of $Q_{GWA}$ is under one, a machine can be considered acoustically safe, whereas if the value of $Q_{GWA}$ is over one, the noise emitted by the machine will exceed the admissible value of SPL at the workstation.

## 2. GENETIC ALGORITHMS

It is increasingly common to use new technologies and innovative technical solutions for noise reduction, such as smart materials, neural networks, active methods and genetic algorithms, to reduce and eliminate exposure to noise.

In general, the genetic algorithm [7, 8] is an algorithm that searches through the space of alternative solutions of a defined problem to find the best alternatives. The operation of genetic algorithms resembles biological evolution: they use the mechanisms of natural selection and inheritance; therefore, optimization is based on adaptation mechanisms found in biological systems. Optimization should be described as a procedure of finding a solution for a defined task that provides the best results, taking into account defined objectives. The search for a solution is carried out on the basis of its parameters, whereas its assessment is carried out on the basis of the so-called objective function, which illustrates, with defined criteria, how good a solution is. A basic genetic algorithm is relatively simple and consists of three operations that follow a cyclical pattern:

- reproduction,
- crossover,
- mutation.

As a result of these operations, a "child" solution is produced from "parent" solutions. A child solution is then submitted to the same processes and constitutes a basis for the next generation. Thanks to appropriate selection methods, each new generation comprises specimens that are better adapted to their tasks. The process of creating new generations is terminated when a specimen able to perform a given task with the adopted accuracy is obtained.

In recent years, genetic algorithms have been more frequently used in preventing vibroacoustic risks in the working environment, e.g., to optimize the coefficients of filters used in systems of active noise reduction [9], to identify noise sources [10], to optimize the location of noise sources and workstations [11, 12] and to develop a strategy for noise reduction [13, 14].

## 2. THE USE OF GENETIC ALGORITHM IN A COMPUTER TOOL

The definitions of partial indices and $Q_{GWA}$ make it possible to state that $Q_N$ does not depend on the parameters of the acoustic environment (an industrial room) where a machine is located, whereas $Q_{imp}$ and $Q_F$ depend on the acoustic environment to a limited extent only. These three indices are mostly related to the machine itself (its acoustic parameters and operation technology). Therefore, when developing software for predicting noise emission of a machine (based on $Q_{GWA}$), it was assumed that $Q_N$, $Q_{imp}$ and $Q_F$ during the simulation, together with calculations with the use of genetic algorithm, do not change, whereas the process of predicting and optimizing is based on a proper selection (minimization) of the index of distance between the workstation and the machine $Q_R$ and the radiation directivity index $Q_\theta$. This approach has strong practical grounds as it makes it possible to support a correct distribution of machines through a change in the geometrical parameters of the working environment (location and interaction between machines and workstations in the industrial room) without interfering in the design of the machine.

To determine the value of $Q_\theta$, SPL at the workstation should be defined on the basis of the acoustic parameters of the machine, acoustic parameters of the industrial room and geometrical co-ordinates of the location of the machine and the workstation in the industrial room. Since calculations are time-consuming and must be repeated as many times as the number of population during one cycle of genetic algorithm iteration, it was assumed that the distribution of sound pressure would be determined with a statistical method. According to this approach, the relation between sound power level of the machine and sound pressure in the distance $d$ from the machine can be described as

$$L_{pA} = L_{NA} + 10\log\left(\frac{\Omega_\theta}{4\pi d^2} + \frac{4}{R_c}\right), \tag{7}$$

where $d$ = distance from the machine (in metres), $R_c$ = room constant (in square metres), $\Omega_\theta$ = directivity coefficient.

Equation 8 defines the room constant $R_c$ (in square metres):

$$R_c = \frac{S\alpha_m}{1-\alpha_m}, \tag{8}$$

where $\alpha_m$ = mean absorption coefficient of the industrial room, $S$ = total room surface (in square metres).

While developing the software it was assumed that it would be used for

- determining the distribution of $Q_{GWA}$ in chosen limited sections of cubicoid shape, i.e., a typical shape of an industrial room, with the statistical prediction method for SPL in rooms,
- making visualizations for independent evaluations of partial indices influencing the value of $Q_{GWA}$,
- optimizing the location of machines and workstations in terms of minimizing adverse effects of noise with the genetic algorithm that uses the notion of $Q_{GWA}$ to calculate the adaptation.

Parameters of the working environment that are optimized include geometrical co-ordinates of the location of machines and workstations in the industrial room. Optimization can involve the location of workstations, the location of machines, and the location of workstations and machines. In all three cases, the objective function $F_c$ is defined with Equation 9 as the product of global indices of the acoustic assessment of machines at a workstation:

$$F_c = \min\left(\prod_{i=1}^{M}\prod_{k=1}^{N} Q_{GWAik}\right), \tag{9}$$

where $Q_{GWAik}$ = global index of quality of $i$th machine determined at $k$th workstation, $M$ = number of machines in an industrial room, $N$ = number of workstations in an industrial room.

According to the previous determination of $Q_N$, $Q_{imp}$ and $Q_F$ do not depend on the geometrical parameters of the model of the working environment. $Q_R$ and $Q_\theta$ influence the value of the objective function. Considering Equation 7, this dependency can be described as

$$F_c = \min\left(\prod_{i=1}^{M}\prod_{k=1}^{N} Q_{Rik}\cdot Q_{\theta ik}\right), \tag{10}$$

where $Q_{Rik}$ = index of distance of $i$th machine determined at $k$th workstation, $Q_{\theta ik}$ = radiation directivity index of $i$th machine determined at $k$th workstation.

The genetic algorithm described here was used in a computer tool for predicting noise emission of a machine and the optimum location of machines and workstations in industrial rooms.

Section 4 discusses sample activities that accompanied the development of the calculation model and simulation calculations of the developed computer tool.

The structure of the calculation model of the software consists of the following elements: algorithm, industrial room, sound source and workstation. When predicting and optimizing, the user introduces the model of an acoustic workstation into the graphics software, arranges the sources of sound (machines) and workstations. Afterwards, the user defines relevant acoustic parameters of machines and the industrial room, and the parameters of the genetic algorithm.

## 4. RESULTS AND DISCUSSION

During the tests, the following parameters of the genetic algorithm were adopted: the number of population = 500 chromosomes, crossing probability = 0.6, mutation probability = 0.001, number of iterations = 20.

At the first stage, laboratory tests were carried out to determine the distribution of SPL around power generator CMI C-G800 (Eurmate, Germany) in an evenly distributed network of measurement points in an industrial room (Figure 1). The dimensions of the room were 6.46 × 3.15 × 3.36 m, it had a concrete floor, one of the longer walls was made of polycarbonate sheets, the other longer wall (made of concrete) was plastered, one of the shorter walls was made of bricks and covered with plaster, whereas the opposite wall consisted of polyvinyl chloride (PVC) doors that were open during all measurement sessions. The ceiling was covered with plaster on concrete. Table 3 presents measured values of SPL for this case.

In the second stage of the experiment, the model of the working environment for this case was created with the developed computer software. The distribution of $Q_R$ and $Q_{GWA}$ were determined.

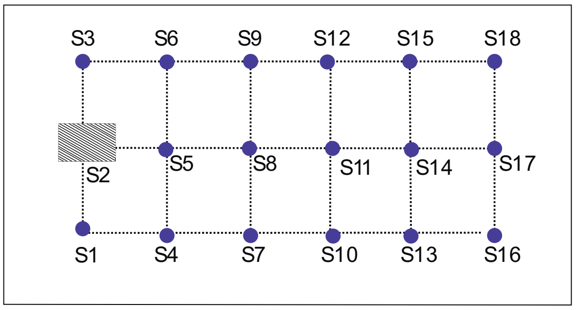


**Figure 1. Location of power generator CMI C-G800 (Eurmate, Germany) and measurement points in an industrial room.** *Notes.* S1–S18 = measurement points; ▧ = power generator.

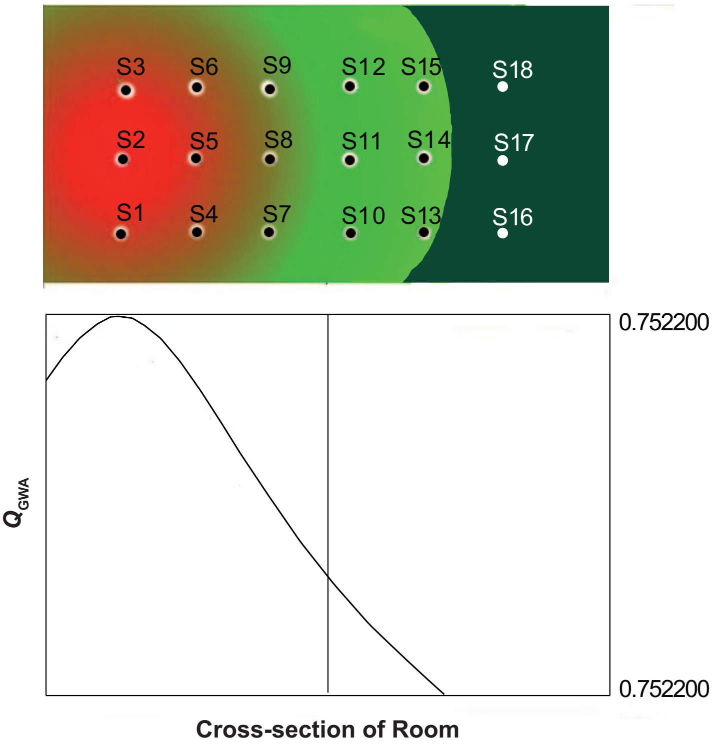


**Figure 2. Distribution of the global index of acoustic assessment of machines $Q_{GWA}$ in a cross-section of an industrial room at the height of 1 m.** *Notes.* S1–S18 = measurement points.

**TABLE 3. Sound Pressure Level (SPL) at 18 Measurement Points Located in an Industrial Room Around Power Generator CMI C-G800 (Eurmate, Germany)**

| Point | SPL at Point (dB) | | Point | SPL at Point (dB) | |
|---|---|---|---|---|---|
| | $L_{pA}$ | $L_{Cpeak}$ | | $L_{pA}$ | $L_{Cpeak}$ |
| S1 | 77.0 | 94.9 | S10 | 76.3 | 93.7 |
| S2 | 77.4 | 95.2 | S11 | 75.7 | 93.7 |
| S3 | 77.6 | 97.5 | S12 | 76.2 | 94.2 |
| S4 | 77.5 | 94.2 | S13 | 75.1 | 92.4 |
| S5 | 78.1 | 95.8 | S14 | 75.0 | 91.4 |
| S6 | 77.5 | 95.0 | S15 | 75.5 | 92.7 |
| S7 | 76.8 | 94.2 | S16 | 74.7 | 91.6 |
| S8 | 77.1 | 93.6 | S17 | 75.1 | 91.4 |
| S9 | 77.0 | 95.1 | S18 | 74.7 | 92.5 |

*Notes.* $L_{pA}$ = *A*-weighted SPL (dB), $L_{Cpeak}$ = *C*-weighted SPL. For the location of the power generator, see Figure 1.

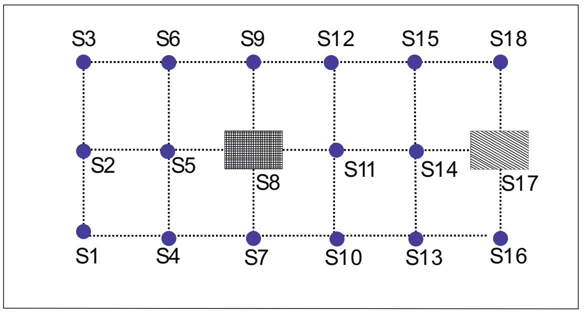


**Figure 3. Arrangement of workstations S1–S18 and machines in an industrial room before optimization.** *Notes.* = power generator CMI C-G2000 (Eurmate, Germany); = power generator NT250Up (Nutool, UK).

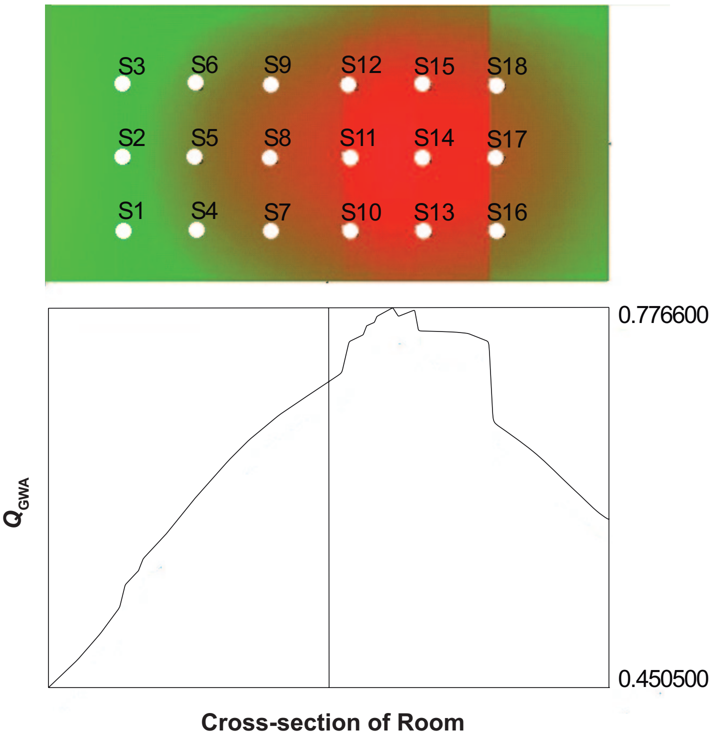


**Figure 4. Distribution of the global index of acoustic assessment of machines $Q_{GWA}$ in a cross-section of an industrial room at the height of 1m for the configuration of noise sources and workstations in Figure 3.** *Notes.* S1–S18 = measurement points.

The values of these indices decrease when the distance from the generator increases. The highest value of $Q_R$ ($Q_R$ = 0.8575) was recorded in close proximity to the generator, whereas the lowest value of 0.7112 was recorded where measurement points S13–S18 were located. The distribution of $Q_{GWA}$ was similar: from 0.7522 (in close proximity of the generator) to 0.6239 where measurement points S13–S18 were located. Figure 2 presents the distribution of $Q_{GWA}$ in the cross-section of the industrial room obtained within simulation tests.

Table 4 presents the results of a series of simulation tests, together with the values of *A*-weighted SPLs determined at measurement points S1–S18 and values of $Q_R$, $Q_\Theta$ and $Q_{GWA}$. The values of *A*-weighted SPLs, measured within the experimental tests (Table 4) as $SPL_P$ confirmed that the measurements carried out with the use of the software were correct.

The differences between the values of *A*-weighted $SPL_s$ measured $SPL_p$ at measurement points in Figure 1 and the values calculated at these points with the developed software ($SPL_s$) were within the limits from 0.1 to 1.6 dB. For most measurement points, this difference did not exceed 0.5 dB, whereas it exceeded 1 dB in 4 measurement points only.

**TABLE 4. Values of $SPL_p$, $SPL_s$, $Q_R$, $Q_\theta$ and $Q_{GWA}$ at Measurement Points S1–S18**

| Point | Index | Value | Unit | Point | Index | Value | Unit | Point | Index | Value | Unit |
|---|---|---|---|---|---|---|---|---|---|---|---|
| S1 | $SPL_p$ | 77.0 | dB | S7 | $SPL_p$ | 76.8 | dB | S13 | $SPL_p$ | 75.1 | dB |
| | $SPL_s$ | 77.2 | dB | | $SPL_s$ | 76.7 | dB | | $SPL_s$ | 76.4 | dB |
| | $Q_R$ | 0.83 | | | $Q_R$ | 0.78 | | | $Q_R$ | 0.72 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.73 | | | $Q_{GWA}$ | 0.68 | | | $Q_{GWA}$ | 0.63 | |
| S2 | $SPL_p$ | 77.4 | dB | S8 | $SPL_p$ | 77.1 | dB | S14 | $SPL_p$ | 75.0 | dB |
| | $SPL_s$ | 77.5 | dB | | $SPL_s$ | 76.8 | dB | | $SPL_s$ | 76.4 | dB |
| | $Q_R$ | 0.86 | | | $Q_R$ | 0.79 | | | $Q_R$ | 0.72 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.75 | | | $Q_{GWA}$ | 0.69 | | | $Q_{GWA}$ | 0.63 | |
| S3 | $SPL_p$ | 77.6 | dB | S9 | $SPL_p$ | 77.0 | dB | S15 | $SPL_p$ | 75.5 | dB |
| | $SPL_s$ | 77.2 | dB | | $SPL_s$ | 76.7 | dB | | $SPL_s$ | 76.4 | dB |
| | $Q_R$ | 0.83 | | | $Q_R$ | 0.78 | | | $Q_R$ | 0.72 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.73 | | | $Q_{GWA}$ | 0.68 | | | $Q_{GWA}$ | 0.63 | |
| S4 | $SPL_p$ | 77.5 | dB | S10 | $SPL_p$ | 76.3 | dB | S16 | $SPL_p$ | 74.7 | dB |
| | $SPL_s$ | 77.0 | dB | | $SPL_s$ | 76.5 | dB | | $SPL_s$ | 76.3 | dB |
| | $Q_R$ | 0.81 | | | $Q_R$ | 0.74 | | | $Q_R$ | 0.71 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.71 | | | $Q_{GWA}$ | 0.65 | | | $Q_{GWA}$ | 0.62 | |
| S5 | $SPL_p$ | 78.1 | dB | S11 | $SPL_p$ | 75.7 | dB | S17 | $SPL_p$ | 75.1 | dB |
| | $SPL_s$ | 77.2 | dB | | $SPL_s$ | 76.6 | dB | | $SPL_s$ | 76.3 | dB |
| | $Q_R$ | 0.83 | | | $Q_R$ | 0.75 | | | $Q_R$ | 0.71 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.73 | | | $Q_{GWA}$ | 0.66 | | | $Q_{GWA}$ | 0.62 | |
| S6 | $SPL_p$ | 77.5 | dB | S12 | $SPL_p$ | 76.2 | dB | S18 | $SPL_p$ | 74.7 | dB |
| | $SPL_s$ | 77.0 | dB | | $SPL_s$ | 76.5 | dB | | $SPL_s$ | 76.3 | dB |
| | $Q_R$ | 0.81 | | | $Q_R$ | 0.74 | | | $Q_R$ | 0.71 | |
| | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | | | $Q_\theta$ | 1.00 | |
| | $Q_{GWA}$ | 0.71 | | | $Q_{GWA}$ | 0.65 | | | $Q_{GWA}$ | 0.62 | |

*Notes.* $SPL_p$ = measured *A*-weighted sound pressure level, $SPL_s$ = calculated *A*-weighted sound pressure level, $Q_R$ = index of distance of workstation from machine, $Q_\theta$ = radiation directivity index, $Q_{GWA}$ = global index.

As already mentioned, $Q_{GWA}$ and the genetic algorithm can be used for optimizing

- the location of machines and workstations in an industrial room,
- the location of workstations in an industrial room,
- at the same time the location of machines and workstations in an industrial room.

Those optimizations reduce noise at workstations: the lower the value of $Q_{GWA}$, the greater the efficiency of the optimization. Examples of simulation tests for all three optimizations follow.

In addition to minimizing the value of $Q_{GWA}$, the following assumptions were adopted for the tests:

- the distance between the machines and workstations, and the walls of the industrial room could not be shorter than 0.45 m,
- the distance between workstations could not be shorter than 0.5 m.

Figure 3 presents the arrangement of workstations S1–S18 and the location of two power generators in an industrial room before optimization. Figure 4 presents the distribution of $Q_{GWA}$

that corresponds to this configuration. The values of $Q_{GWA}$ are highest at workstations S13, S14 and S15 (i.e., between noise sources); $Q_{GWA} = 0.77$.

Figure 5 presents the results of simulation tests after an optimization of the location of machines, without changes in workstations location, and the distribution of the global index of acoustic assessment of machines $Q_{GWA1}$ after optimization.

Figure 6 presents the location of workstations in an industrial room after an optimization of workstations location, without changes in machines location, and the distribution of the global index of acoustic assessment of machines $Q_{GWA2}$ after optimization.

Figure 7 shows the location of workstations and machines after an optimization of the location of both workstations and machines, and the distribution of the global index of acoustic assessment of machines $Q_{GWA3}$ after optimization (Figure 7).

Table 5 presents values of global indices of acoustic assessment and the results of optimizations.

As a result of the first optimization, i.e., the optimization of the location of noise sources, $Q_{GWA}$ decreased for 12 workstations (the noise level for these workstations decreased in the process), whereas its value did not change for 3 workstations and increased for 3 workstations, too. The optimization of the location of workstations only resulted in lower $Q_{GWA}$ for 15 workstations, the same for 2 workstations and increased for 1 workstation.

**TABLE 5. Values of $Q_{GWA}$, $Q_{GWA1}$, $Q_{GWA2}$ and $Q_{GWA3}$ at Workstations S1–S18**

| Workstation | Index | Value | Workstation | Index | Value | Workstation | Index | Value |
|---|---|---|---|---|---|---|---|---|
| S1 | $Q_{GWA}$ | 0.53 | S7 | $Q_{GWA}$ | 0.63 | S13 | $Q_{GWA}$ | 0.71 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.54 | | $Q_{GWA1}$ | 0.59 |
| | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.56 | | $Q_{GWA2}$ | 0.58 |
| | $Q_{GWA3}$ | 0.55 | | $Q_{GWA3}$ | 0.54 | | $Q_{GWA3}$ | 0.55 |
| S2 | $Q_{GWA}$ | 0.53 | S8 | $Q_{GWA}$ | 0.66 | S14 | $Q_{GWA}$ | 0.73 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.58 |
| | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.53 |
| | $Q_{GWA3}$ | 0.55 | | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.52 |
| S3 | $Q_{GWA}$ | 0.53 | S9 | $Q_{GWA}$ | 0.63 | S15 | $Q_{GWA}$ | 0.71 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.54 | | $Q_{GWA1}$ | 0.56 |
| | $Q_{GWA2}$ | 0.54 | | $Q_{GWA2}$ | 0.54 | | $Q_{GWA2}$ | 0.55 |
| | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.55 |
| S4 | $Q_{GWA}$ | 0.58 | S10 | $Q_{GWA}$ | 0.68 | S16 | $Q_{GWA}$ | 0.64 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.51 | | $Q_{GWA1}$ | 0.67 |
| | $Q_{GWA2}$ | 0.50 | | $Q_{GWA2}$ | 0.55 | | $Q_{GWA2}$ | 0.53 |
| | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.52 | | $Q_{GWA3}$ | 0.52 |
| S5 | $Q_{GWA}$ | 0.60 | S11 | $Q_{GWA}$ | 0.71 | S17 | $Q_{GWA}$ | 0.66 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.51 | | $Q_{GWA1}$ | 0.67 |
| | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.54 |
| | $Q_{GWA3}$ | 0.52 | | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.53 |
| S6 | $Q_{GWA}$ | 0.58 | S12 | $Q_{GWA}$ | 0.69 | S18 | $Q_{GWA}$ | 0.64 |
| | $Q_{GWA1}$ | 0.53 | | $Q_{GWA1}$ | 0.49 | | $Q_{GWA1}$ | 0.65 |
| | $Q_{GWA2}$ | 0.53 | | $Q_{GWA2}$ | 0.54 | | $Q_{GWA2}$ | 0.54 |
| | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.53 | | $Q_{GWA3}$ | 0.54 |

*Notes.* $Q_{GWA}$ = global index of acoustic assessment of machines before optimization, $Q_{GWA1}$ = global index of acoustic assessment of machines after optimization of machine location, $Q_{GWA2}$ global index of acoustic assessment of machines after optimization of workstation location, $Q_{GWA3}$ = global index of acoustic assessment of machines after optimization of machine and workstation location.

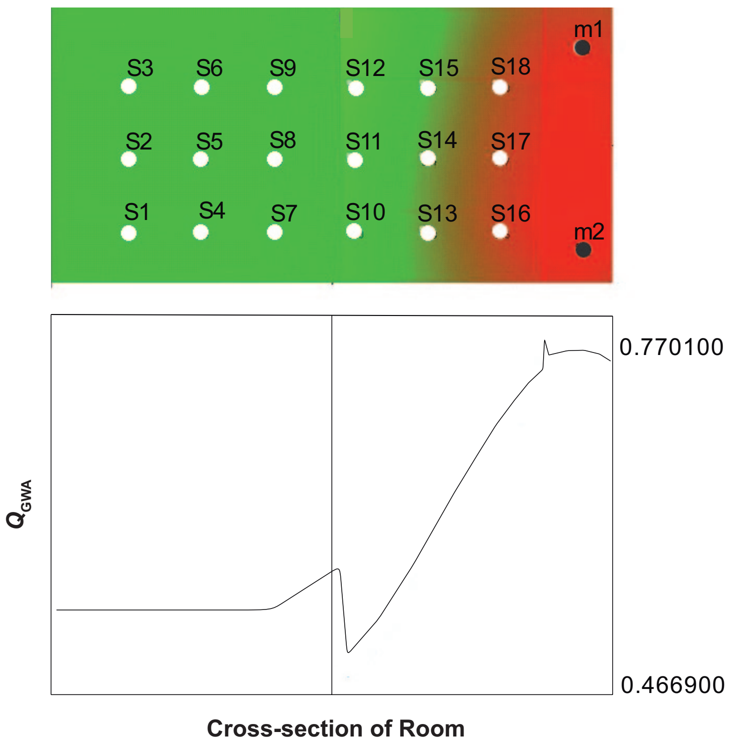


**Figure 5. Location of power generators CMI C-G2000 (Eurmate, Germany) and NT250Up (Nutool, UK) after the optimization of their location, without changes in the location of workstations, and the distribution of global index of acoustic assessment of machines $Q_{GWA1}$ in a cross-section of an industrial room at the height of 1 m.** *Notes.* m1 = power generator CMI C-G2000 (Eurmate, Germany); m2 = power generator NT250Up (Nutool, UK); S1–S18 = measurement points.

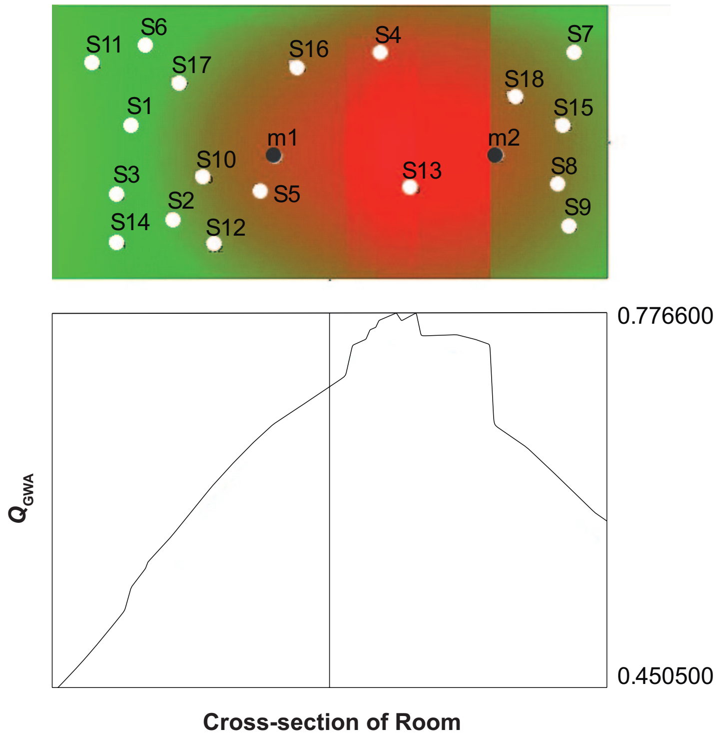


**Figure 6. Location of workstations after optimization, without changes in the location of power generators CMI C-G2000 (Eurmate, Germany) and NT250Up and the distribution of global index of acoustic assessment of machines $Q_{GWA2}$ in a cross-section of an industrial room at the height of 1 m after optimization.** *Notes.* m1 = power generator CMI C-G2000 (Eurmate, Germany); m2 = power generator NT250Up (Nutool, UK); S1–S18 = measurement points.

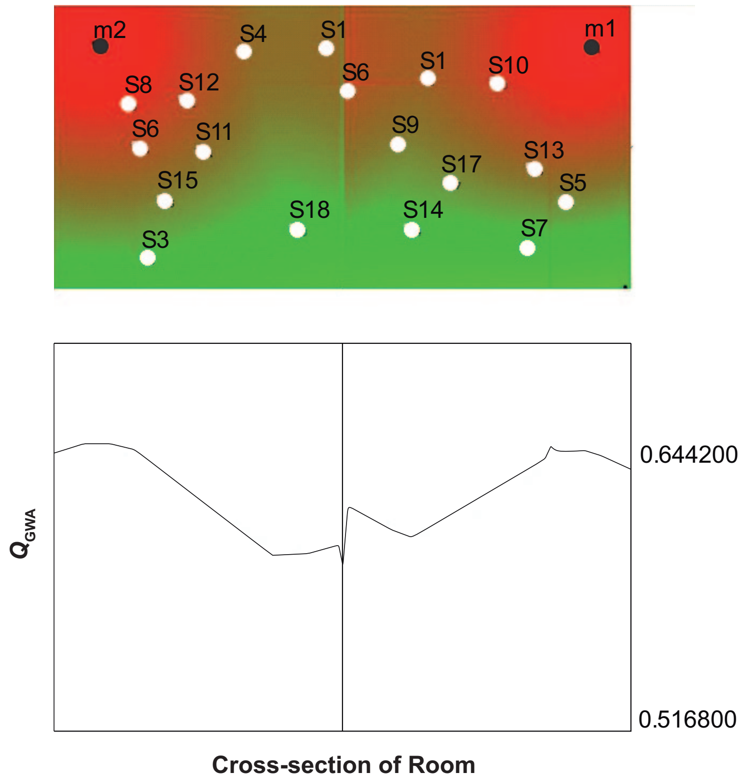


**Figure 7. Location of power generators CMI C-G2000 (Eurmate, Germany) and NT250Up and workstations after the optimization of their location and the distribution of global index of acoustic assessment of machines $Q_{GWA3}$ in a cross-section of an industrial room at the height of 1 m after optimization.** *Notes.* m1 = power generator CMI C-G2000 (Eurmate, Germany); m2 = power generator NT250Up (Nutool, UK); S1–S18 = measurement points.

The results of the last series of simulation tests, i.e., optimization of the location of both noise sources and workstations, showed a decrease in $Q_{GWA}$ for 15 workstations as well. At the same time these values were lower than the ones resulting from an optimization of the location of workstations only. The difference shows that the last of the optimizations resulted in the greatest improvement in the acoustic comfort at workstations.

## 5. SUMMARY

The results presented in the paper demonstrate that the developed $Q_{GWA}$ and genetic algorithms can be used as optimization tools and can be useful in supporting measures aimed at noise reduction at workstations.

The developed software for noise prediction in industrial rooms and for optimizing the location of machines and workstations makes it possible to

- determine the distribution of $Q_{GWA}$ in sections of limited cubicoid areas, i.e., a typical shape of an industrial room, by using statistics to predict SPL in an industrial room;
- visualize the working conditions to assess partial indices influencing the value of $Q_{GWA}$, taking into account several machines at the same time;
- use genetic algorithms to optimize the location of machines and workstations to minimize the harmful effects of noise, and use the value of the global index to calculate adaptation.

The values of $Q_{GWA}$ and the distribution of SPL can be determined with software using statistical methods in any cross-section of an industrial room. The analysis of the results obtained with the software and during experimental tests shows that the differences between predicted SPL and actual values in principle do not exceed 0.5 dB.

The simulation tests of the optimization of the location of machines and workstations demonstrated that the adopted objective function of a minimum product of global indices of acoustic assessment was correct. The best results, i.e., the greatest reduction in $Q_{GWA}$, is obtained by optimizing the location of machines and workstations at the same time.

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