Research Paper

Optimization System to Minimize Exposure to Occupational Noise

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This research deals with the development of an optimization system to minimize employee noise exposure in the work environment. It is known from the literature that continuous exposure to high noise levels can cause heart overload, stress, fatigue, and increase accident numbers at a production line. Thus, it is necessary to develop acoustic solutions at an industrial level that could minimize failures and accident occurrences. The rules that regulate occupational noise exposures allow an assessment of the degrees of exposure and subsequent corrections of working conditions. It is observed that the exposure is necessary for further evaluation and correction. Therefore, this research proposes to simulate occupational noise exposure conditions through mathematical models implemented in C++, using the GUROBI linear optimization package and to act previously to minimize ONIHL (Occupational Noise-Induced Hearing Loss). One of this work results is based on Doses Values, TWA (Time Weighted Average) and Distances Covered, using these three factors simultaneously through the optimization, it obtains a route that minimizes exposure and avoids ONIHL. Although there is a need for balanced doses between employees, to this end, the Designation Problem was implemented. Thus, with the routes obtained by optimization, an efficient allocation task was made for the maintenance crew, resulting in minimized and balanced doses. This model was applied to a real industrial plant that will not be identified, only methodology and results obtained will be presented.

Keywords: acoustics; noise; optimization; dosimetry

1. Introduction

The lack of industrial noise control should lead to more adverse consequences to companies, e.g. financial or/and investments in worker's healthcare system. NIOSH (n.d.) indicates that Occupational Noise-Induced Hearing Loss (ONIHL) is one of the most frequent occupational injuries in the United States. It affects approximately 22 million workers, who are exposed to dangerous noise levels during their working hours, and is responsible for an estimated $242 million in annual expenses on labor claims. Thus, the ONIHL causes the worker's life quality deterioration, with a high social and economic cost in labor liabilities.

WSZOŁEK (2017) points out the problem of the lack of detailed regulations regarding the formal approach and the methodology for assessing noise levels. The author reports basic legal conditions for calculating cumulative noise levels in the environment. An analysis of the case studies in the industry is presented.

Current solutions to problems of continuous exposure and its harmful effects on human health do not currently exist. As reported above, companies choose to pay large amounts of severance pay to workers. After the exposure that caused an injury, the worker is investigated, diagnosed and removed. Thus, an earlier assessment is not made to predict where overexposure may occur and how to avoid it. This research aims to fill this gap in the control of industrial noise. Through the developed optimization procedure, it is possible to simulate various inspection routes and choose routes that minimize noise exposure. If, after the optimization procedure, the doses are still above the appropriate legal value, an additional acoustic treatment procedure is performed on the sources that most contribute to the exposure to mitigate the noise exposure. After performing these two procedures, a route is obtained with adequate exposure doses in accordance with the values of regulatory standards and preventing the occurrence of hearing loss.

The simulation was performed with the modeling system named Vehicle Routing Problem (VRP) using the real plant data. At this first stage, only routing was considered, to minimize exposure dose. At another stage, the optimization was also added to the acoustic treatment procedure, since the exposure doses were still above the permitted values. After the acoustic treatment, the exposure doses were within the permitted values.

With the L_{Aeq} (level of continuous noise equivalent to the sound produced over a period measured with the frequency filter at "A" weighting) maps, equivalent sound level, the probabilities of time on the route, and variability of the sound power levels of the sources are identified, the virtual dosimetry procedure consists of:

1) Initialize the dose of the homogeneous group equal to zero.
2) A position in the plant is randomly generated for each minute of the day labor, and the corrected L_{Aeq} value at that position, by the statistical variations in the sound power levels of the sources.
3) Calculate the exposure time for that point. If the route time at that point is greater than 1 minute, the time is one minute, otherwise, the time will be the current route time for that point.
4) Update the route time map, i.e., subtract the value of the time used in the route time from the point.
5) Calculate the dose and accumulate.
6) Repeat steps 2–5 until the homogeneous group's workday is complete.
7) Repeat steps 1–6 until 2000 doses are completed. By the statistical Monte Carlo Method, a high number of doses is used to improve the quality of the result obtained.
8) Calculate average sample dose and confidence intervals.

Figure 1 shows an example of a virtual dose, where you can see the contribution of the various regions of

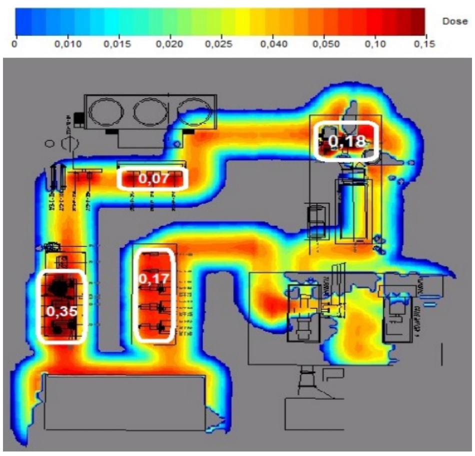

Fig. 1. Example of virtual dose map.

the route in the total dose value of the homogeneous group.

Nowakowski *et al.* (2019) report experimental research carried out to minimize noise generated by trams in urban areas. Some design strategies affecting tram noise quality were presented. The main noise sources were discovered and characterized. As the result, the wagon acoustic properties and its side covers were reconstructed to minimize noise propagation, which constitutes a new adopted application.

Korbiel *et al.* (2017) point out the influence of noise on people's lives, which impacts on the quality of life and health. The authors present the laws on noise exposure and investigate the influence of noise exposure on people's daily lives.

Dudarewicz *et al.* (2017) assess the auditory threshold of employees exposed to noise generated by low-frequency ultrasonic welding devices. It can be concluded that differences in the auditory threshold for the groups of employees studied may occur due to differences in the spectral composition of the noise. Thus, there is a need to continue the studies carried out to assess the impacts of noise exposure.

Abbasi *et al.* (2019) conducted a study of the correlation between blood pressure and noise exposure in a group of employees in the textile industry with exposures to high noise levels. As a result, it can be said that exposure to occupational noise alone combined with other factors of work and individual characteristics are associated with increased blood pressure.

According to (Morais *et al.*, 2004) continuous exposure to high-level noises can generate physical and psychological stress, pulse acceleration, increase blood pressure, heart overload, narrowing blood vessels, and abnormal secretions of hormones that cause muscle tension and hearing damage. Argalasova *et al.* (2016) present a study of sound exposure impacts due to different noise sources on human health. The study shows a need for prevention and intervention to avoid permanent hearing loss.

Noise reduces attention and maximizes reaction time of an individual concerning stimuli, which can cause an increase of failures numbers, accidents that impact the quality of life and productivity at work according to the National Institute of Safety and Hygiene in Work (2006).

Costa *et al.* (2018) assess noise impact on public school teachers. Thus, noise, above limits established by legislation, in classrooms can cause psychological and behavioral problems to teachers.

Cordeiro (2005) investigates whether exposure to noise is a significant risk factor for occupational accidents. The method used was the population-based case-control study, totaling 94 cases. A multiple logistic regression model was used, whose independent variable is noise exposure, controlled by covariates of interest. It can be concluded that exposure to noise is a significant risk factor for accidents at work and the investment in research to minimize exposure to occupational noise is justified.

Fagundes Neto (2017) points out in his thesis the harmful effects of continuous exposure to noise. The author reports that the exposure causes the organism to be in a constant state of alert, in a stressful situation, to protect itself from an alleged "attack". The brain of the affected people accelerates and the muscles work is agitated. As a result, these people have increased blood pressure, disruption of the stomach and intestine, problems with skin irritation and sexual impotence.

Mikos (2003) states that more than 12 million people have hearing loss in Brazil. However, the majority of this group is made up of workers who acquired ONIHL due to inadequate working conditions.

Silva (2018) carried out a study of exposure to noise among employees in food and nutrition units located in a food court. From the results obtained, it was inferred that for all the units analyzed, the employee's exposure was above law recommendations for an 8-hour labour day. Another aggravating factor in this situation is the fact that none of the study employees used PPE (Personal Protective Equipment) despite the high exposure to noise.

Oliveira *et al.* (2015) point out the impact of exposure to high-level noises for workers. A case study was carried out with workers from mobile support units. Results show that there are auditory and non-auditory symptoms presented by these workers. Among the auditory symptoms, the occurrence of tinnitus was 38.9% and the intolerance to loud sounds – 27.8%. As for non-auditory symptoms, irritation was shown in 47.2% of employees, followed by headaches with 38.9%.

MEDSEG (2018) reports that in Europe more than 33% of workers are exposed to high noise levels during at least a quarter of their working hours. The author points out that exposure to high noise levels can cause accidents at work, due to the difficulty of hearing the workers and consequent lack of understanding of the work instructions, and the possibility of non-audibility of warning/emergency signs. With exposure to loud noises, the workers may present other symptoms, such as sexual impotence, cardiovascular problems, psychological problems, and gastritis.

Façanha and Azevedo (2018) conducted a study on employee's knowledge about the importance of using PPE. The case study was carried out with 70 employees in the operational area of a beverage company. From the results obtained, it is observed that 57.1% of the employees do not use the PPE and only 21.4% underwent hearing tests. The study points out that 78.5% do not realize noise's impact on human health. Thus, it can be concluded with the study, that most research workers do not use PPE and do not understand what noise is and its consequences for the human health.

The Regulatory Standard No. 15 (1978) presents the limits of exposure to noise for workers in order to protect them from hearing damage. In Regulatory Standard No. 15 (1978) the causes of ONIHL are described as prolonged exposure to noise above 85 dB for 8 hours per day. The symptoms presented by the employees are hearing difficulties. As a preventive measure, the Ordinance provides for the use of collective and/or individual hearing protection, reduction of working hours, creation of regular breaks, change of function, and use of less noisy equipment. The Regulatory Standard No. 15 (1978) provides the concepts of continuous or intermittent noise (85 dB) and impact noise (120 dB). In the event of these occurrences, the law provides for an unhealthy allowance of 20% of the minimum wage to be paid to the employee, as this unhealthy work is characterized as medium.

The work (Giampaoli *et al.*, 2001) from FUNDACENTRO consists of procedures for assessing occupational noise exposure. FUNDACENTRO is a research institute that conducts studies on safety, hygiene, and occupational medicine, linked to the Ministry of Labor. In this standard, the concept of exposure level is presented, to quantify and characterize occupational exposure, called dose, to continuous or intermittent noise. Also, there is the alternative of using integrating meters and instant readings.

The Regulatory Standard No. 9 (1978) mentions that every company must have an Environmental Risk Prevention Program (ERPP) and a Hearing Conservation Program (HCP). Thus, the legislation obliges companies and professionals in the area of Occupational Health and Safety to carry out the implementation and control of hearing loss prevention programs.

Tavares (n.d.) describes as the main consequences of ONIHL, the decrease in productivity, loss of ability to concentrate and communicate, physical and psychological stress, and a greater possibility of accidents with the decrease in the worker's attention. The author also presents eight measures for the implementation of a hearing loss prevention program, as described below:

- Conduct an HCP consisting of an audit to verify what is appropriate or not regarding the compliance of the legislation.
- Monitoring noise exposure and identifying workers exposed to noise levels equal to or greater than 85 dB on average during 8 hours of work.
- Implementation of safety engineering controls, so that there is no exposure to noise levels equal to or greater than 85 dB on average during 8 hours of working hours. To achieve this, the rotation of employees and noise control devices are needed.
- Education and training of employees, so that the employee can identify when additional protection is needed and inform the responsible area.

- Maintenance of system records for at least two years. Evaluation of the hearing conservation program for eventual corrections of the parts that do not work properly and maintenance of the activities that presented good results.

2. Material and methods

This work is a continuation of a research line of the Laboratory of Acoustics and Vibrations (LAV) of the Faculty of Mechanical Engineering (FEMEC) of the Federal University of Uberlândia (UFU), which aims to develop acoustic methods and solutions at an industrial level for ONIHL. In his thesis, Oliveira Filho (2011) developed a methodology that uses prior mapping and identification of noise sources in the workplace, and the route of the employee to predict the dose of exposure to occupational noise. This work proposes to develop an optimization system to minimize the exposure of employees to occupational noise, that is, to simulate the conditions of exposure to occupational noise previously in order to avoid the occurrence of ONIHL. In the first phase of the work, the objective was to find the optimal routes for employees. The routing problem was modelled as Traveling Salesman Problem (TSP), and as VRP.

Oliveira Filho (2011) reports the use of an average speed of 0.8 m/s on the route between inspection points. However, the author explains that this speed value can be changed due to who performs the inspection route at the factory, which alters employee's exposure. This fact increases the relevance of the developed optimization system.

At first, modeling was used for one factor at a time. In the second phase of the work, an optimization model was developed that considered the three factors simultaneously: doses, Time Weighted Average (TWA) data, and distances covered for optimization. For the execution of this work, it was necessary to develop concepts of acoustics and fundamentals. After obtaining the optimal routes, there was a need for a balance between the doses of the employees. As the routing problems do not deal with the doses separately, but with the optimization of the total dose of the employees, a new approach was necessary to continue this work.

After a bibliographic review of Operational Research, Linear Programming, the adequacy of the problem of efficient allocation of employees to maintenance tasks with the Designation Problem was verified. With the optimized routes obtained by the VRP modeling, the Designation Problem was implemented which, allowed the balance between doses.

For the created optimization system validation, a real plant was used, which will not be identified for reasons of industrial secrecy. The methodology used in the plant and the results obtained will be presented.

2.1. Mathematical modeling – designation problem

For Hillier and Lieberman (2006), the Designation Problem can be defined as a special type of Linear Programming problem, in which those designated are indicated for the execution of tasks. Thus, the Designation Problem applies to employees responsible for performing maintenance tasks on machines in an industrial plant, that is, each machine must be assigned to an employee. Implementations of the Designation Problem must respect the five assumptions described below.

The first hypothesis is that the number of assignees and the number of tasks must be the same. It is worth noting that this hypothesis can be adapted with the creation of virtual "ghost" employees for the allocation of maintenance tasks. The second hypothesis concerns the assignment of each assignee to a task. The third hypothesis ensures that each task is performed by exactly one designated person. The fourth hypothesis works with the idea of the cost associated with the designated i $(i = 1, 2, ..., n)$ for the execution of task j $(j = 1, 2, ..., n)$. The goal of the fifth hypothesis is to determine how to make the n assignments in order to minimize the total cost. System 1 presents the mathematical model for the Designation Problem:

$$\begin{gathered} \text{minimize} \sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}, \\ \sum_{j=1}^{n} x_{ij} = 1 \quad \forall i, \\ \sum_{i=1}^{m} a_{ij}x_{ij} \quad \text{maximum dose} \quad \forall j, \\ x_{ij} \in 0, 1 \quad \forall i, j. \end{gathered} \tag{1}$$

System 1 is composed of four equations. Equation (2) represents the objective function of the problem, in which x is the problem decision variable, that is, 0 is assigned if the employee does not execute any service on the equipment or 1 when the employee does service on the equipment to perform maintenance:

$$\text{minimize} \sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij}. \tag{2}$$

The restriction in Eq. (3) ensures that a single employee enters the operating station where the equipment is located, performs maintenance, and leaves the operating station:

$$\sum_{j=1}^{n} x_{ij} = 1 \quad \forall i. \tag{3}$$

Equation (4) is a constraint that establishes a maximum dose for each employee. This restriction allows the balance between the doses of the employees:

$$\sum_{i=1}^{m} a_{ij}x_{ij} \quad \text{maximum dose} \quad \forall j. \tag{4}$$

The constraint (5) guarantees that the problem decision variable is binary, that is, it receives 0 if the employee does not go to the equipment or receives 1 when the employee goes to the equipment to perform maintenance:

$$x_{ij} \in 0, 1 \quad \forall i, j. \tag{5}$$

2.2. Mathematical modeling – vehicle routing problem

According to (Lima *et al.*, 2015), the VRP solution must contain a set of routes to be used by a fleet of homogeneous vehicles. In this article, a certain number of employees must attend a set of customers (the equipment). Thus, it seeks to minimize operations time costs (noise exposure). VRP is based on some premises: first, the routes must start and end at the same point in the operation, that is, in the same operating environment. The second premise is that each equipment piece must be inspected once and solved entirely by a single employee. The sum of demands of a route cannot exceed the capacity of each employee. It is known from the literature that problems of this magnitude are classified as NP-hard since the order of complexity is non-polynomial.

Laporte (1992) points out that in VRP the equipment's demands must be previously defined and that it must be fully met by a single employee. The capacity of the employees is homogeneous and must be defined in advance as well. The employees always start from the same marker (operating environment). There is a restriction at the vehicle capability which determines that the sum of equipment's demands at a unique route cannot exceed the employee's capacity.

In this article, the following modeling was proposed for the industrial power generation plant. Two employees were used, the capacity of each employee was defined as five pieces for each equipment. A total of ten pieces of equipment from the industrial plant must be inspected. Equation (6) represents the objective function to be minimized. In this equation, there are the dose values that each employee will be exposed to when moving between equipment i to equipment j. There is a binary decision variable that receives the value "1" if the employee moves between equipment i to equipment j or "0" otherwise. The act of the employee moving between various equipment will be considered the route to be taken. To facilitate the understanding of the formulas, the abbreviation "equip" was used to represent the set of available equipment:

$$\text{minimize} \sum_{i \in \text{equip}} \sum_{j \in \text{equip}} d_{ij} x_{ij}. \tag{6}$$

The restriction in Eq. (7) requires that a single employee leaves equipment i only once on each route:

$$\sum_{j \in \text{equip}} x_{ij} = 1 \quad \forall i \in \text{equip} \mid i \neq 1. \tag{7}$$

The restriction imposed by Eq. (8) ensures that a single employee goes to the equipment only once on each route travelled:

$$\sum_{i \in \text{equip}} x_{ij} = 1 \quad \forall j \in \text{equip} \mid j \neq 1. \tag{8}$$

The restrictions in Eqs (9) and (10) work together to avoid the formation of sub-routes. A sub-route would be a route on which an employee does not inspect all factory equipment assigned to him before returning to the starting marker. Flow represents the act or effect of flowing, of moving continuously, and continuous traffic of employees. The decision variable represents the flow between equipment i and j, the flow that enters a node j (equipment j) must be a larger unit than the flow that leaves the same node j.

This way, an employee must leave a flow unit in each visited equipment, allowing the mathematical model to differentiate the inspected equipment from the non-inspected. The maximum flow is limited to the maximum number of nodes to prevent employees from being able to travel any sub-route using the excess flow. The demand represents the need for the equipment to be inspected in time, that is, a demand equal to 6 means that a machine needs 6 minutes to be inspected. In this simulation, the time equal to 1 dimensionless unit was used:

$$\sum_{i \in \text{equip}} f_{ij} - \sum_{i \in \text{equip}} f_{ji} = \text{demand}_j \quad \forall j \in \text{equip} \mid j \neq 1, \tag{9}$$

$$f_{ij}\, x_{ij} \text{ capacity} \quad \forall i, j \in \text{equip}. \tag{10}$$

The term capacity that appears in Eq. (10) represents the time available to inspect all machines.

In Eq. (11), it is observed that the number of employees leaving the maintenance, should be the same as that entering for equipment inspection, that is, 6 employees enter, 6 employees leave, $i = 1$ and $j = 1$:

$$\sum_{j \in \text{equip}} x_{1j} = \sum_{j \in \text{equip}} x_{j1}. \tag{11}$$

Besides, it is a binary decision variable that receives the value 1 if the employee moves between equipment i and equipment j or 0 otherwise, and the flow is a non-negative integer according to Eq. (12):

$$\begin{aligned} x_{ij} &\in 0, 1 \quad \forall i, j \in \text{equip}, \\ f_{ij} &0 \quad \forall i, j \in \text{equip}. \end{aligned} \tag{12}$$

2.3. Industrial plant

The optimization system developed in a real plant was implemented, which will not be presented due to industrial secrecy reasons. The methods used, the implementation, and the results obtained will be discussed. The real plant consists of thirteen floors and fifty-five pieces of equipment. The first floor consists of the briefing room, in which the maintenance team of only two employees for the whole plant work. They are designated for daily instructions and information before starting their maintenance routine that consists of 3 pieces of equipment per day. An 8-hour day was considered for the two employees, with one-hour break.

Due to the existence of multiple floors in the real plant, it was necessary to implement the VRP instead of the Designation Problem since there is a displacement between floors, which there was not for the virtual power generation plant with a single floor. This VRP model includes distance factor, balance factor between employee doses, and the factor variation of employee's service capacity regarding dose exposure.

Through the usage of SAFETYNOISE software, the acoustic treatment optimization for the real industrial plant was developed. SAFETYNOISE is a software developed by Laboratory of Acoustics and Vibrations from Faculty of Mechanical Engineering from the Federal University of Uberlândia. Using the virtual dosimetry module, SAFETYNOISE calculates the doses. In this concept, SAFETYNOISE considers Virtual Dosimetry to computationally estimate an interval and confidence for the dose of exposure value to occupational noise for a given homogeneous group, considering not only the work routine but also the possible deviations from it, such as attendance to stops, clearance of area and service, changes in the route due to renovations or maintenance, differences in the work pace of each worker belonging to the analyzed group, among other possible altered variables.

Seven steps were performed to acquire acoustics optimization. In the first step, 10 dBA attenuation was acquired for one machine. The second step concerns the optimization of 10 dBA for two machines, and so on until the last step includes the optimization of 10 dBA for ten machines. Thus, the number of machines, to be optimized in this problem, was varied. The initial value of the capacity factor value considered in the simulations was 0.093. This value must be considered to prevent the program from responding to an unviable solution since a minimum starting value is required to solve the problem. In order to reduce the search region in the space of viable solutions, the step size of 0.001, also known as increment, was used. This scan of the search space for viable solutions continues up to the maximum dose limit of one (1). The capacity factor refers to an employee who received a dose when he stops walking and starts performing machine inspection.

Figure 2 shows a map of the industrial plant with the L_{Aeq} map, generated by SAFETYNOISE, showing the estimated L_{Aeq} levels for the area in the current situation before the optimization and acoustic treatment procedure.

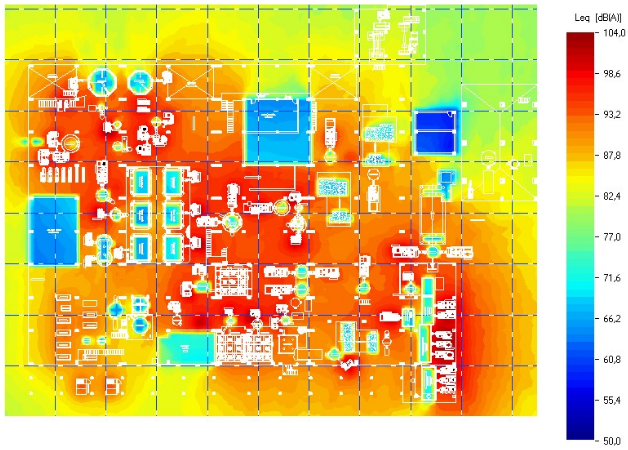

Fig. 2. Map of the current industrial plant situation before treatment procedures.

As shown in Fig. 2 analysis, most of the graph area with the equipment to be inspected, the central area has an exposure of approximately 93 to 104 dB.

3. Results and discussion

This section presents results obtained from the real plant with the modeling of the problem, using Vehicle Routing Problem. VRP considers employee's balance of doses, besides minimizing them it also uses distance factors, based on an automatic balance factor dose. The algorithm starts from a starting marker of the capacity value, which was defined as a minimum value. It searches for the solution in the neighborhood space, it was set up an increment step size of 0.001, for scanning. Therefore, if a minimum value calculated based on the doses of the real plant were not set up, the program would return an unviable solution. This implementation was based on the optimization theory presented by Lobato and Steffen Jr. (2008) in order to use a more efficient methodology to reduce the search space.

The algorithm was implemented on a workstation computer with a professional processor and also in a personal computer (PC) to compare its processing time. The technical configurations of each computer can be seen in Table 1. In addition, the real plant processing time of both computers and its acquisition costs are shown.

It can be seen from Table 1 that the workstation has a processing time of 76% faster compared to the processing time of the PC, i.e. the workstation can process the whole problem and solve it in 76% of the time spent by the PC performing the same action. On the other hand, the cost of purchasing a workstation is five times the cost of purchasing the PC for home use. Because of this, the workstation features a 40 GB memory, that is, 5.7 times bigger than the PC memory. Besides, the workstation processor has 8 cores of

Table 1. Workstation and PC configurations.

Equipment	Workstation	Desktop
Type	Professional	Domestic use
Processor	Intel Xeon E5-1620 v2 @ 8x 3.9 GHz	Intel Core i5 650 @ 4x 3.333 GHz
Threads	8 of 3.9 GHz	4 of 3.3 GHz
Memory	40 GB	7 GB
Processing time	10 hours	13 hours
Purchase cost	US$ 1 164.47	US$ 230.59

3.9 GHz compared to 4 cores of 3.3 GHz in the PC. Thus, the workstation allows a performance gain by the company.

Table 2 presents the results obtained for VRP with an automatic capacity factor of 0.4 for two employees. The time to resolve the problem was approximately 300 seconds. The doses for employee "A" and "B" were 1.2 and 1.2, respectively.

Table 2. Automatic VRP results of the real plant for two employees.

Capacity factor	0.4
Number of employees	2
Worker "A" route	1 → 12 → 44 → 28 → 7 → 8 → 14 → 32 → 20 → 40 → 4 → 29 → 5 → 46 → 51 → 42 → 17 → 9 → 16 → 38 → 30 → 53 → 18 → 2 → 11 → 19 → 1
Worker "B" route	1 → 15 → 36 → 52 →34 → 33 → 3 → 27 → 31 → 25 → 24 → 43 → 13 → 39 → 26 → 37 → 6 → 41 → 22 → 45 → 10 → 55 → 23 → 47 → 21 → 54 → 50 → 48 → 49 → 35 → 1
Worker "A" dose	1.2
Worker "B" dose	1.2

According to the obtained doses from optimization, the presented values were above the allowed value, thus the second stage of the method of this work was carried out, that is, the acoustic treatment. Simulations were developed for acoustic treatment of one machine, two machines, and so on, up to ten machines. With this last treatment, an adequate dose was obtained for both employees, according to Table 3.

The L_{Aeq} map, generated by SAFETYNOISE, shows the estimated L_{Aeq} levels for the area after the treatments (Fig. 3).

It can be seen from Fig. 2 analysis that most of the graph area is acoustically compromised and has the equipment to be inspected, the central area has an exposure of approximately 93 to 104 dB. On the other hand, it can be seen in Fig. 3 that the exposure after the Procedure of Routes of Inspection and Acoustic Treatment is approximately 82 dB.

Table 3. VRP results with acoustic treatment for two employees.

Capacity factor	1.0
Number of employees	2
Worker "A" route	1 → 14 → 12 → 38 → 37 → 44 → 31 → 39 → 27 → 36 → 29 → 46 → 35 → 42 → 30 → 40 → 33 → 43 → 26 → 34 → 47 → 11 → 23 → 8 → 9 → 7
Worker "B" route	1 → 45 → 28 → 41 → 32 → 49 → 48 → 53 → 51 → 54 → 50 → 52 → 24 → 25 → 15 → 22 → 19 → 21 → 10 → 18 → 16 → 17 → 13 → 20 → 7
Worker "A" dose	0.9
Worker "B" dose	1.0

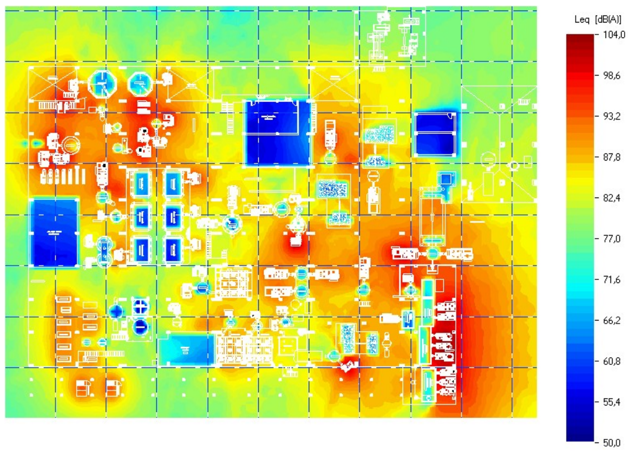

Fig. 3. Map of the industrial plant situation after acoustic treatment.

According to obtained data by the Routing Inspection and Acoustic Treatment Procedure through the algorithms, an exposure dose reduction of approximately 67% was acquired. This new dosage enabled the routing of the industrial plant by two employees with an adequate dose. Therefore, the analysis of the L_{Aeq} maps generated by SAFETYNOISE and the generated results by the optimization system allows us to conclude that there was a significant minimization of noise exposure, making the work environment adequate and healthy for the worker.

4. Conclusions

This section presents the main conclusions of this work:

1) It can be concluded that the SAFETYNOISE software generates the sound pressure level values for all points of the plant in order to simulate the exposure to industrial noise. This data-set allows the assessment of the contribution of each machine to occupational exposure, intending to verify the overall effect.
2) From this data, a spreadsheet is generated to obtain the best route through the optimization system. It is possible to obtain the best route for the inspector/lubricator. This optimization procedure presents full usability for companies. If the industrial plant has just one floor, an efficient routing must be developed followed by Designated Problem (DP) implementation.
3) Although, in an industrial plant that has more than one floor, it is necessary to consider the displacement between plant floors and implement the VRP directly. From the data set generated, it is possible to obtain the best route for the employee. Thus, the optimization system developed in this research is fully usable for companies that need to optimize the dose of occupational exposure.
4) After changing from one to five noise sources, it did not imply a significant dose reduction (background noise). So it stopped optimization with ten iterations of acoustic treatment. There are two L_{Aeq} maps, generated by SAFETYNOISE, in this article, one showing the estimated L_{Aeq} levels for the area in the current situation, and the other after treatments that shows the optimization efficiency of the acoustic treatment. Thus, the acoustic treatment proves to be an excellent tool for cases in which, after the optimization procedure, the dose is still high. After routes optimization, and doses still being above the permitted values, it is possible to optimize the choice of noise sources to be treated and obtain adequate doses. The optimization of the acoustic treatment of noise sources, that were most impacting the dose, was performed.
5) By analyzing the generated maps from SAFETYNOISE with the equipment to be inspected, the central area had an exposure of approximately 93 to 104 dB. On the other hand, it appears that after the Procedure of Routes of Inspection and Acoustic Treatment the exposure is approximately 82 dB. Due to the results obtained by the Inspection Routes and Acoustic Treatment Procedure, there was a reduction of approximately 67% of the two employees' exposure dose values, which enabled the routing of the industrial plant by two employees with adequate doses. Thus, it can be concluded that there was a mitigation of noise exposure, making the work environment adequate and healthy for the worker.
6) The optimization procedure has great applicability. Code adaptations can be made according to the number of sources, equipment, and the number of floors that the industrial plant has.

It is possible to list some possibilities of continuity for this research at the master's and/or doctorate level. Among these, we can mention:

a) The optimization system applicability developed in this article could be applied to other companies and adaptations of the codes according to the number of machines, equipment, and the number of floors that the company has.
b) After the implementation of the Inspection Routes Optimization Procedure in an industrial plant, a survey with the employees should be taken. So, it could verify the effect of the mitigation procedure of the noisiest sources on the perception and quality of life of the worker.
c) This article suggests that measurements should be taken after industrial plant implementation of the Inspection Routes Optimization Procedure, to ascertain the actual exposure values to minimize the possibility of measurement inconsistencies. This action must be provided for in the Hearing Conservation Program (HCP).
d) In future works, it is possible to develop a survey of auditory and non-auditory symptoms resulting from exposure. Thus, differentiate them and verify their correlation with the workers' acoustic psychological perception.

References

1. Abbasi M. *et al.* (2019), Assessment of role of job components and individual parameters on the raised blood pressure in a noisy industry, *Archives of Acoustics*, **44**(3): 575–584, doi: 10.24425/aoa.2019.129272.
2. Argalasova L. *et al.* (2016), The risks of social noise exposure in the vulnerable population in Slovakia, *Archives of Acoustics*, **41**(3): 535–541, doi: 10.1515/aoa-2016-0052.
3. Cordeiro R., Clemente A.P.G., Diniz C.S., Days A. (2005), Occupational noise as a risk factor for work-related injuries, *Revista Saúde Pública at the Botucatu Medical School of UNESP*, **39**(3): 461–466, doi: 10.1590/S0034-89102005000300018.
4. Costa M.T.D. *et al.* (2018), The ergonomic impact of noise on public school, *Research, Society and Development*, **7**(5): e775160-e775160, doi: 10.17648/rsd-v7i5.249.
5. Dudarewicz A. *et al.* (2017), The hearing threshold of employees exposed to noise generated by the

low-frequency ultrasonic welding devices, *Archives of Acoustics*, **42**(2): 199–205, doi: 10.1515/aoa-2017-0022.

6. Façanha R.C., Azevedo G.R. (2018), The workers knowledge about the use of the equipment of individual protection for the health hearing [in Portuguese: O conhecimento dos trabalhadores sobre a importância do uso do equipamento de proteção individual para a saúde auditiva], *Revista Ceuma Perpectivas*, **31**: 78–85, doi: 10.24863/rccp.v31i1.183.
7. Fagundes Neto M.G. (2017), *Analysis of independent components applied in hermetic reciprocating compressors to mitigate noise sources* [in Portuguese: *Análise de componentes independentes aplicadas em compressores herméticos alternativo para mitigação das fontes de ruído*], Doctoral thesis, Federal University of Uberlândia, Faculty of Mechanical Engineering, doi: 10.14393/ufu.te.2018.7.
8. Giampaoli E., de Souza Duarte Saad I.F., de Ângelo da Cunha I., Domingos da Silca M. (2001), *NHO 01-Technical Procedure – Assessment of Occupational Exposure to Noise* [in Portuguese: NHO 01-Procedimento Técnico – Avaliação da Exposição Ocupacional ao Ruído], *FUNDACENTRO Occupational Hygiene Standard*, http://antigo.fundacentro.gov.br/biblioteca/normas-de-higiene-ocupacional/publicacao/detalhe/2012/9/nho-01-procedimento-tecnico-avaliacao-da-exposicao-ocupacional-ao-ruido, accessed on March 04, 2019.
9. Hillier F.S., Lieberman G.J. (2006), *Introduction to Operations Research*, Sao Paulo: Mc Graw Hill.
10. Korbiel T. *et al.* (2017), Recognition of the 24-hour noise exposure of a human, *Archives of Acoustics*, **42**(4): 601–607, doi: 10.1515/aoa-2017-0064.
11. Laporte G. (1992), The Vehicle Routing Problem: an overview of exact and approximate algorithms, *European Journal of Operational Research*, **59**(3): 345–358, doi: 10.1016/0377-2217(92)90192-C.
12. Lima S.J.A., Santos R.A.R., Araujo S.A. (2015), Optimization of the enabled vehicle routing problem using genetic algorithms and Gillett and Miller Heuristics and Downhill, *XXXV National Meeting of Production Engineering*.
13. Lobato F.S., Steffen Jr V. (2008), Luus-Jaakola algorithm applied to an inverse problem of fed batch fermentatio [in Portuguese: Algoritmo de Luus-Jaakola Aplicado a um Problema Inverso de Fermentação Batelada Alimentada], *Trends in Computational and Applied Mathematics*, **9**(3): 417–426, doi: 10.5540/tema.2008.09.03.0417.
14. MEDSEG (2018), Noise in the workplace, available at: https://www.medsegservice.com.br/single-post/ruido-ocupacional-avalia%C3%A7%C3%A3o-controle, accessed on April 10, 2020.
15. Mikos N. (2003), *Hearing loss can generate compensation for accident at work* [in Portuguese: *Perda de audição pode gerar indenização por acidente de trabalho*], available at: https://machadoadvogados.com.br/2003/06/18/perda-de-audio-pode-gerar-indenizao-por-acidente-de-trabalho, accessed on April 9, 2020.
16. Morais L.R., Nogueira R.C.C., Slama J.G. (2004), Fuzzy logic: environmental comfort assessment, *I Latin American Conference on Sustainable Construction*.
17. National Institute of Safety and Hygiene in Work (2006), *The protection of the health and safety of workers against the risks related to exposure to noise*, Royal Decree 2886/2006, Spain.
18. NIOSH (n.d.), *Work-related hearing loss – NIOSH* [in Portuguese: *Perda auditiva relacionada ao trabalho – NIOSH*] https://cmimafra.com.br/blog/perda-auditiva-relacionada-ao-trabalho-niosh, access April 09, 2020.
19. Nowakowski T., Firlik B., Staśkiewicz T. (2019), Developing assumptions for the tram noise attenuation passive system using the noise maps analysis method, *Archives of Acoustics*, **44**(4): 783–792, doi: 10.24425/aoa.2019.129733.
20. Oliveira Filho R.H.A (2011), *Methodology for the virtual assessment of the dose of exposure to noise in the workplace*, Doctoral thesis, Uberlândia – MG, Federal University of Uberlândia, Faculty of Mechanical Engineering.
21. Oliveira R.C., Santos J.N., Rabelo A.T.V., Magalhães M.C. (2015), The impact of noise exposure on workers in Mobile Support Units, *CoDAS*, **27**(3): 215–222, doi: 10.1590/2317-1782/20152014136.
22. Regulatory Standard No. 9, 1978. Brazil Ministry of Labour (1978), Ordinance No. 3,214, of June 8, 1978. Approves the regulatory standards – NR – of Chapter V, Title II, of the Consolidation of Labor Laws, related to Occupational Safety and Medicine. Federal Official Gazette, Executive Branch, Brasília, DF, Jun. 1978.
23. Regulatory Standard No. 15, 1978. Brazil Ministry of Labour (1978), Ordinance No. 3,214, of June 8, 1978. Approves the regulatory standards – NR – of Chapter V, Title II, of the Consolidation of Labor Laws, related to Occupational Safety and Medicine. Federal Official Gazette, Executive Branch, Brasília, DF, Jun. 1978.
24. Silva M.F. (2018), *Analysis of noises present in food and nutrition units in the food court of a shopping center in the municipality of Vitória de Santo Antão* [in Portuguese: *Análise de ruídos presentes em unidades de alimentação e nutrição na praça de alimentação de shopping center no município de Vitória de Santo Antão*], Bachelor's thesis, Federal University of Pernambuco.
25. Tavares J.C.R. (n.d.), *Noise at work: 8 adequate measures for worker protection* [in Portuguese: *Ruído no trabalho – 8 medidas adequadas para a proteção do trabalhador*], https://okup.com.br/seguranca-auditiva-no-trabalho-8-medidas-adequadas-para-protecao-do-trabalhador/, accessed on April 10, 2020.
26. Wszołek T. (2017), Cumulative industrial noise impact on the environment, *Archives of Acoustics*, **42**(2): 169–174, doi: 10.1515/aoa-2017-0019.