INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 22, ISSUE 1, 2025, 12074 – 12090
DOI: https://doi.org/10.15282/ijame.22.1.2025.10.0927

RESEARCH ARTICLE

Multiobjective Optimization of Three-Pass Perforated Muffler Design for Improved Acoustic Performance and Reduced Fluid Pressure Drop Using Genetic Algorithms

Suprayitno* and Muhammad Yandi Pratama

Department of Mechanical and Industrial Engineering, Universitas Negeri Malang, Malang 65145, Indonesia

ABSTRACT – Noise pollution is a serious problem as the vehicle population increases every year. The vehicle exhaust system is a major contributor to noise pollution, while mufflers play a vital role in reducing it. Among various designs, a three-pass perforated is a muffler design that is often used to reduce noise in the vehicle exhaust system. However, a good muffler design should also consider minimizing the pressure drop, where these two requirements conflict. To solve this problem, a multiobjective optimization approach was applied using a non-dominated sorting genetic algorithm (NSGA-II) to find the optimal muffler design solution. Analysis of Variance (ANOVA) was also presented in this study as a statistical tool to determine the muffler design parameters that have a significant effect. To predict the acoustic transmission loss (TL) and fluid pressure drop (PD) inside the muffler, the three-pass perforated was simulated and experimentally verified. The results present two optimal muffler designs that were selected and discussed. The best designs are TL and experiment no.26. The best design TL, produced a muffler with a noise reduction capability (TL) better than the initial design by 9 dBA or 48%, with a PD improvement of 87.3 Pa or 2%. Experimental design no. 26 offers mufflers with noise reduction capability (TL) better than the initial design by 3.2 dBA or 18%, with an improvement in PD of 19.9 Pa or 0.5%. These results offer an alternative muffler design solution that has better noise reduction capability with a small increase in PD. ANOVA results with a significance level of 0.05 show that the design hole diameter parameter has a significant influence on TL performance, as evidenced by a p-value smaller than 0.05. Meanwhile, the ANOVA results for PD performance concluded that none of the design parameters or their interactions had a significant influence on PD performance. Only the design parameter center width and its squared interaction are assumed to have a significant influence, considering the p-value is close to 0.05.

ARTICLE HISTORY

Received	:	01st June 2024
Revised	:	24th Sep. 2024
Accepted	:	02nd Dec. 2024
Published	:	26th Feb. 2025

KEYWORDS

Multiobjective Optimization
Three-Pass Perforated Muffler
Transmission Loss
Pressure Drop
NSGA-II

1. INTRODUCTION

The past decade has dramatically increased the number of motor vehicles; consequently, noise pollution and exhaust gas emissions have become a serious problem [1]. Noise pollution is a disturbing noise that needs to be reduced for comfort purposes [2]. Motor vehicles, as the main means of transport in urban areas, have become a source of disturbing noise and have a negative impact on health [2]. The engine exhaust system accounts for approximately 32 percent of the total noise sources [1], [3]. It occurs when high-pressure engine exhaust gas passes through the exhaust pipe and flows out into the surrounding normal atmospheric pressure. As a result of changes in pressure, a noise phenomenon occurs which we often hear when a motor vehicle engine is operating [4]. Thus, optimizing muffler design has become an important focus area in recent years to improve engine exhaust system performance. Among various muffler designs, the three-pass perforated muffler design is often used in engine exhaust systems because it reduces noise with reasonable back pressure [5]–[7]. However, these dual objectives conflict and require a multiobjective optimization approach.

Multiobjective optimization refers to an approach in finding the optimal solution to a problem. The basic difference between single-objective and multiobjective lies in the objective function, where each objective function conflicts with each other. So, this approach will produce optimal solutions that do not dominate each other [8]. Noise and back pressure are two contradictory things, and a multiobjective optimization approach is suitable for finding the optimal solution to this muffler problem. Acoustic transmission loss is a performance parameter that is often used to represent the ability of a muffler to reduce noise [9]–[11]. It is very important to reduce noise pollution, which has a negative impact on humans and the environment [2], [12], [13]. Meanwhile, fluid pressure drop, also known as backpressure, is the extra pressure exerted by the muffler on the engine, which needs to be minimized in the design stage because it can increase fuel consumption and reduce engine power [14], [15].

Research with a multiobjective optimization approach using evolutionary algorithms such as genetic algorithm has been widely used to optimize various types of muffler designs [14], [16]–[18]. The results show that this approach is efficient and effective for optimizing muffler designs that emphasize on criteria and constraints that conflict with each

***CORRESPONDING AUTHOR | Suprayitno|** ✉ suprayitno@um.ac.id

other. However, research that really focuses on three-pass perforated tube mufflers is still limited, even though this type is often used in vehicle engine exhaust systems [5]–[7]. These limitations indicate that there is a significant gap for further research in exploring the optimal potential of this commercial muffler design. Therefore, to fill this lacuna, this current research aims to optimize the three-pass perforated tube muffler design to improve acoustic transmission loss performance and reduce fluid pressure drop with a multiobjective optimization approach using an NSGA-II.

2. MUFFLER DESIGN PROBLEM

There are two types of mufflers: reactive mufflers and dissipative mufflers. Reactive mufflers adopt the principle of sound wave cancellation to reduce engine noise. Reactive mufflers consist of chambers, partitions and plates with inlets and outlets that allow the incoming sound waves to reflect off each other and sound cancellation occurs [19]. This muffler is preferred because of its durability compared to dissipative mufflers, which use an absorbent material installed inside the muffler to reduce the sound waves. This absorbent material generally has a short-term service life [20], [21]. Besides, engine exhaust gas generally has a low frequency, so reactive mufflers have suitable characteristics that reduce this noise [16]. Therefore, for a more sustainable solution, reactive mufflers are preferred.

Three-pass perforated tube muffler is a type of reactive muffler that is often chosen for use in engine exhaust systems because of its ability to reduce noise with reasonable back pressure [5]–[7]. Reducing noise and backpressure are two opposing issues in the muffler design process. Research results by Siano et al. [14] show that when the muffler design can reduce noise, the resulting back pressure tends to be high, and vice versa. High back pressure can increase fuel consumption and reduce engine power. Meanwhile, noise also needs to be maximally suppressed. The sound quality of a vehicle is important in today's modern car era because it can be a differentiator between vehicles, giving an overall impression of the vehicle’s quality[14].

The ability of the muffler to reduce engine noise is related to the acoustic performance of the muffler as an acoustic filter in the engine exhaust system. Among the various ways to evaluate muffler performance, transmission loss (TL) is the most frequently used method in many studies, considering its ease of analysis theoretically and numerically [9]. TL is the ratio between the incoming sound power to the transmitted sound power [10], [11], [22]. Mathematically, we can predict TL using Eq. (1), where d is the inlet/outlet diameter, D is the muffler diameter, L is the length of the muffler chamber, and k is the number of waves, as presented in Figure 1. However, this equation can be used only for simple muffler designs, not for complex muffler designs such as three-pass perforated designs. Thus, there are many studies that use a numerical simulation approach to predict TL [1], [14], [18].

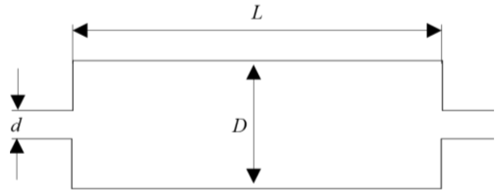


Figure 1. Muffler simple design

$$\mathrm{TL} = 10\log_{10}\left[1 + \frac{1}{4}\left(\frac{(0.4\,\pi\,d^2)}{(0.4\,\pi\,D^2)} - \frac{(0.4\,\pi\,D^2)}{(0.4\,\pi\,d^2)}\right)^2 sin^2 kL\right] \tag{1}$$

In reducing engine exhaust gas noise, the muffler causes a large pressure drop (PD) [23]. Because the deflected exhaust gas flow follows the muffler flow to reduce noise, it causes a large pressure to drop in the exhaust system. This pressure drop causes muffler back pressure towards the engine. Like TL, PD can be predicted using mathematical calculations, such as Eq. (2). Where, ρ is exhaust gas density (kg/m^3), U is the mean flow velocity (m/s), $\boldsymbol{K}$ is obtained using Eq. (3), where this value depends on the geometry of the muffler, then d is the inlet/outlet diameter (m), D is the muffler diameter, and L is the length of the muffler expansion section (m) [10]. However, this equation also cannot be used in complex designs such as three-pass perforated mufflers. Some researchers prefer to use numerical simulation [14], [24]–[26].

$$PD = \frac{1}{2}\rho\, U^2\, \boldsymbol{K} \tag{2}$$

$$\boldsymbol{K} = 0.981 + \frac{0.0346L}{(d - D)\left[\frac{d^2}{d^2 - D^2}\right]^2} \tag{3}$$

PD is the difference between the pressure at the exhaust manifold and the cross-section at the exhaust outlet [27]. The amount of PD that occurs in the system will be in line with the muffler back pressure to the engine. Therefore, this parameter is often used in several studies on mufflers to predict the back pressure that occurs [16], [28]. TL and PD are two parameters of muffler performance in terms of noise reduction and minimizing back pressure that conflict with each other. Therefore, a multiobjective optimization approach is used to solve this muffler design problem to find the right design.

3. MULTIOBJECTIVE OPTIMIZATION USING NSGA-II

When an optimization problem consists of one objective, it is called single-objective optimization. Meanwhile, if the optimization problem consists of more than one objective, then it is called multiobjective optimization. However, the fundamental difference in multiobjective optimization is that each objective conflicts with each other [8]. The genetic algorithm (GA) is a search algorithm whose working method is inspired by Darwin's ideas about natural selection and evolution [18]. It was originally proposed by Holland [29] in 1975 and until now has been widely used in various fields of study to solve optimization problems [30]. NSGA-II, developed by Deb [31], is a multiobjective optimization algorithm that implements an elite maintenance strategy and is an explicit mechanism for maintaining diversity. Like conventional GA, NSGA-II starts by randomly creating a population of individuals representing the design parameters, which then uses selection, crossover, and mutation processes to form a population of offspring. In contrast to conventional GA, which selects solutions based on fitness function values, NSGA-II performs selection based on non-domination ranking and crowd distance.

In general, the basic stages of multiobjective optimization are presented in Figure 2 [8]. The first step is formulating the optimization problem, including the function, optimization objectives, and specified boundaries. In this section, we must have functions or equations to complete the optimization goal. After getting the function, optimizer software can conduct the optimization process computationally. The optimizer software will generate multiple trade-off solutions or Pareto fronts. These multiple trade-off solutions are optimal solutions that do not dominate each other or optimal muffler design solutions that do not dominate each other's TL or PD objectives. The second step is to select a solution based on higher-level information [8].

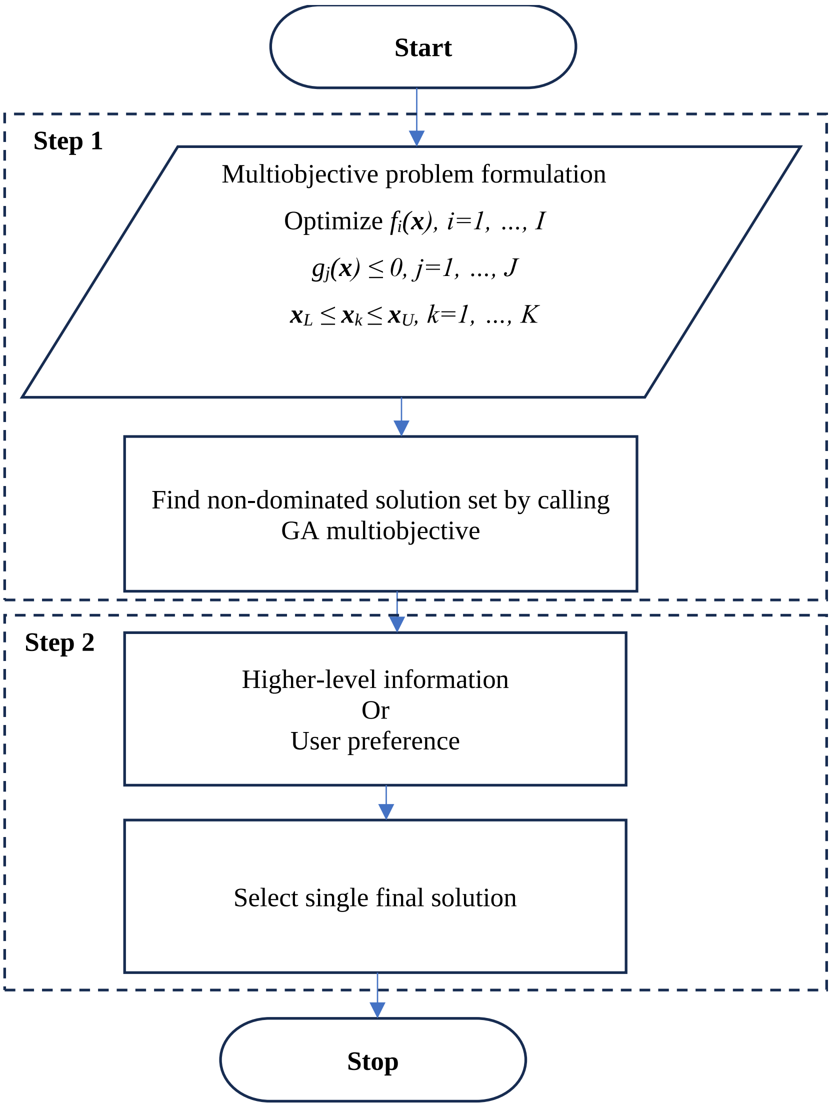


Figure 2. Two steps multiobjective optimization

4. MULTIOBJECTIVE OPTIMIZATION PROBLEM FORMULATION

A multiobjective optimization problem has a number of objective functions which are to be minimized or maximized [8]. Mathematically, the multiobjective optimization problem formulation for a three-pass perforated muffler design is described in Eq. (4). The objective function is to maximize TL and minimize PD, which means that the desired muffler design has high noise reduction capability (maximum TL) and a low-pressure drop (minimum PD). The limits used are the design parameter size limits presented in Table 1 and Figure 3, which indicate the location of each design parameter. Based on the objective function and constraints described, the program is then written. NSGA-II is used as a search algorithm to find the optimal muffler design solution that provides maximum transmission loss and pressure drop [31], [32]. The flowchart of the NSGA-II algorithm and its implementation process is shown in Figure 4. In the calculation, the population size is set to 200, with a selection function using a tournament size of 4. The crossover fraction is 0.8, utilizing a two-point crossover function, and the mutation function is constraint-dependent. The migration direction is set to forward, and the distance crowding measure uses the default setting. The stopping criterion, or maximum number of iterations, is set to 100 times the number of variables, resulting in a maximum of 500 iterations.

$$\begin{gathered}\text{Maximize } TL = f(M_d, F_w, C_w, R_w, H_d) \\ \text{Minimize } PD = f(M_d, F_w, C_w, R_w, H_d) \\ \text{Subject to} 110 \leq M_d \leq 170 \\ 80 \leq F_w \ \leq 120 \\ 170 \leq C_w \leq 210 \\ 80 \leq R_w \leq 120 \\ 4 \ \leq H_d \leq 8\end{gathered} \tag{4}$$

Table 1. Design parameters

Design Parameters (mm)	Lower Bound	Upper Bound
Muffler diameter (M_d)	110	170
Front width (F_w)	80	120
Centre width (C_w)	170	210
Rear width (R_w)	80	120
Hole diameter (H_d)	4	8

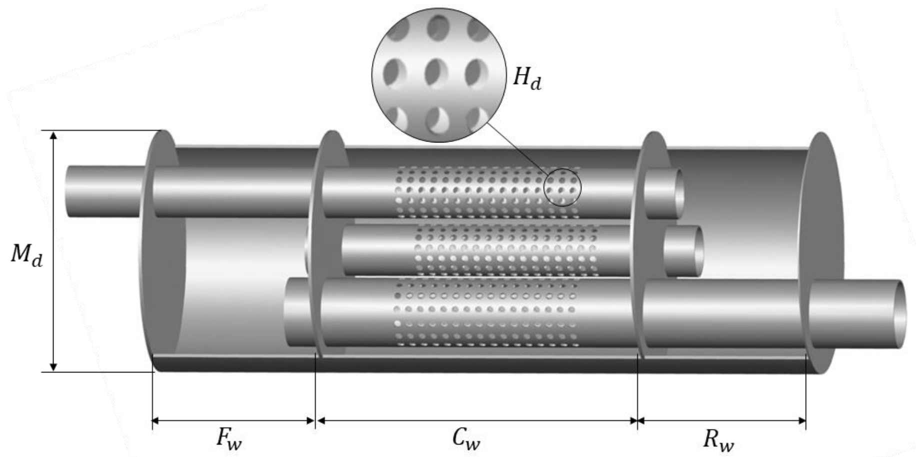


Figure 3. Design parameters for 3D three-pass perforated tube muffler visualization

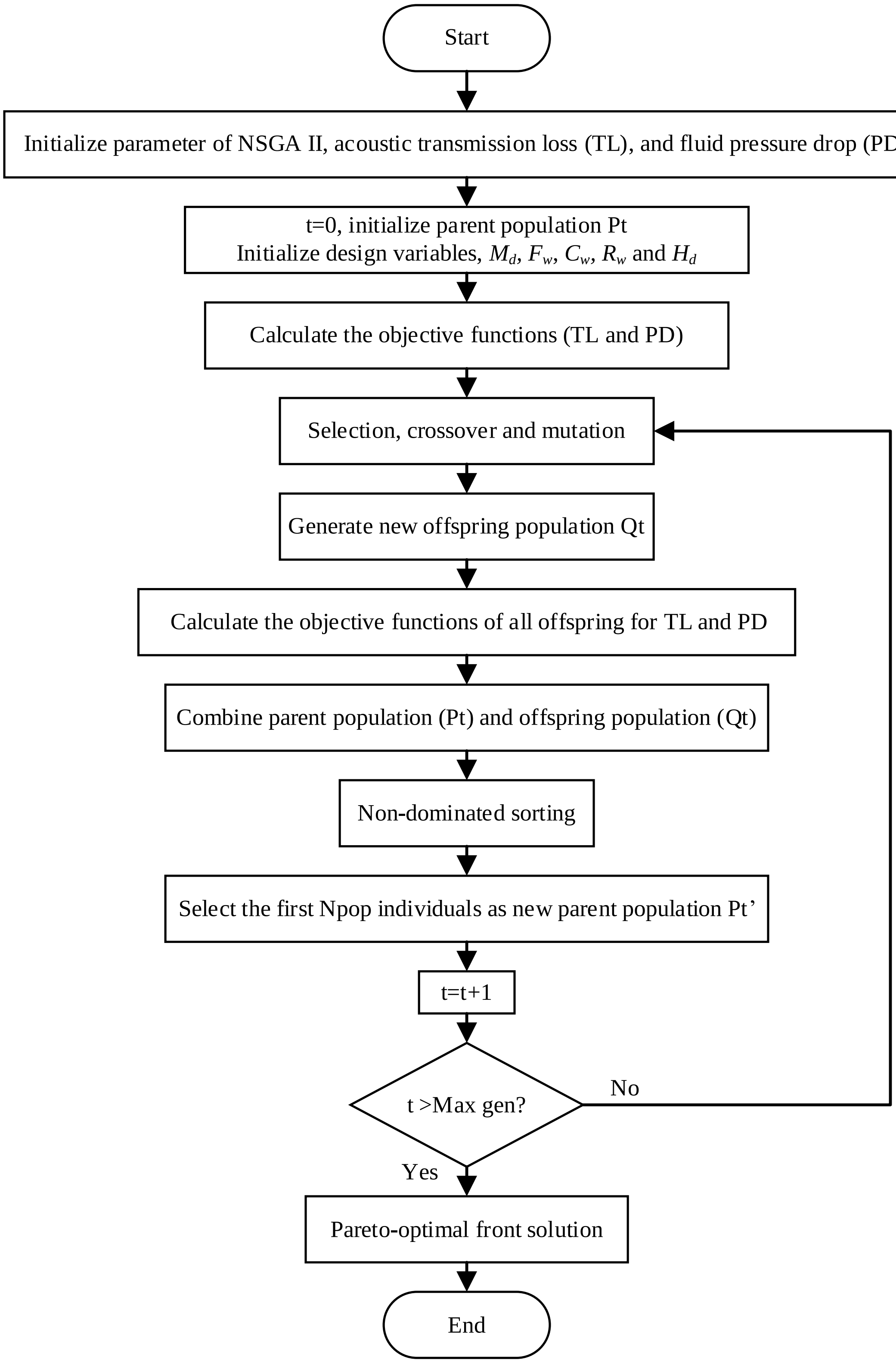


Figure 4. Flowchart of the NSGA-II algorithm

5. RESEARCH FLOWCHART

In general, the flow of this research is visualized in the form of a flowchart in Figure 5. A more detailed explanation of the flowchart stages is as follows. The muffler design process begins with creating a 3D three-pass perforated muffler using CAD software, followed by simulation using commercial software to obtain Transmission Loss (TL) and Pressure Drop (PD) values. These simulated values are compared with experimental results to verify the accuracy of the simulation model. If the simulation results align with the experimental data, the research progresses; otherwise, the simulation settings are adjusted.

An experimental design is then formulated using the Central Composite Design (CCD) model, which involves five design parameters at three levels, resulting in 27 muffler design experiments. These designs are simulated to gather TL and PD values, which are used to create a polynomial regression model. This model serves as the fitness function for optimization through NSGA-II, which generates a Pareto front of non-dominated solutions for both TL and PD. The optimal designs identified are verified experimentally to assess their real-world performance. Finally, ANOVA is applied to the regression equations using Minitab software to identify significant design parameters, providing valuable insights for future research and more accurate muffler design.

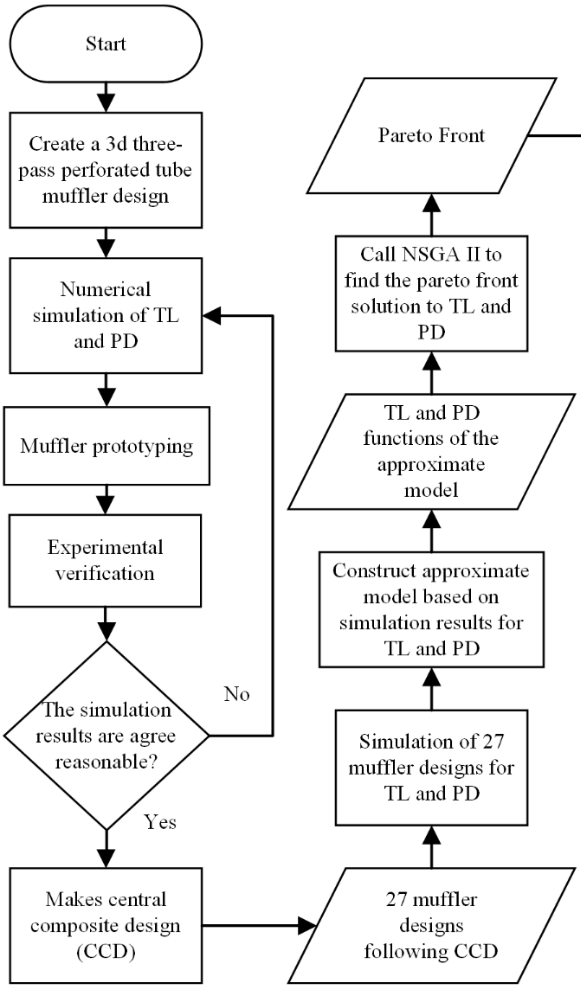


Figure 5. Research Flowchart

5.1 Simulation and Experimental Verification

TL and PD simulations using commercial software have been carried out in several studies [5], [27]. The assumptions set in the simulation are limited to conditions that occur at an engine speed of 1000 rev/min. It refers to the stationary rotation of a vehicle and the vehicle noise measurement standard according to ISO [33]. The exhaust gas temperature is set at 172° C, the pressure before the muffler is set at 4100 Pa, and the broadband noise function is activated with the sound speed set at 346 m/s. These measurements are obtained from experimental measurement results. The K-epsilon model was chosen because it accurately represents engineering turbulence for industrial applications. Most engineering flows are turbulent, including engine exhaust systems [34]. After the simulation process is complete, a real muffler is made and then verified experimentally. The engine used is a commercial car engine with the engine specifications shown in Table 2.

Special tools are needed to measure TL experimentally, and it tends to be difficult to implement with improvised tools. Therefore, the insertion loss (IL) measurement scheme was chosen in this study because it is relatively easier to implement. To calculate TL with the *IL* measurement, the scheme is presented in Eq. (5). Where *r* is the distance from the sound source to the measuring instrument, *IL* is the difference in sound power at the same point with and without using a muffler [1].

$$TL = IL + 10_{\log}(4\pi r^2) \tag{5}$$

Table 2. Engine specification

Engine parameters	Specifications
Power	94 HP at 6000 rev/min
Torque	118 Nm at 4800 rev/min
Displacement	1.242 cc / 1.2 l
Cylinders	4 Cylinder
Bore and Stroke	73 mm and 74.2 mm
Compression ratio	11:1
Fuel	Gasoline

The IL measurement scheme was adopted from several studies, as shown in Figure 6. The standard followed is the Internal Combustion Engine Exhaust Muffler Measurement Method from China Standards, Beijing, China [1], [35]. Other relevant research using a similar scheme is shown in [18], [36]. The numbers show 1) engine, 2) thermometer, 3) fluid manometer, 4) muffler, 5) sound level meter, and 6) computer. The measurement procedure was conducted with the following steps: 1) operating the engine with a stable engine speed until the engine reaches engine operating temperature; 2) noise measurements are carried out using a sound level meter at a distance of 0.5 m, at an angle of 45° and at a height parallel to the muffler; 3) in the same way, measure the noise again without using a muffler and only using a straight pipe that has the same diameter and length. The location of the sound level meter and muffler must always be kept in the same position [35].

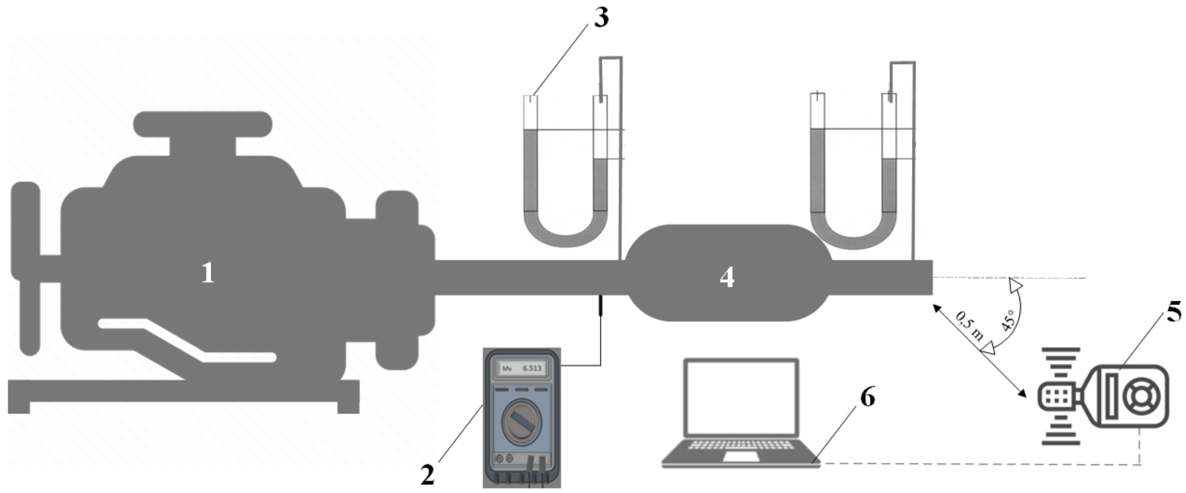


Figure 6. Schematic of test bench

5.2 Experimental Verification Analysis

As presented in Table 3, The difference between the simulated TL and the experimentally measured TL shows a difference of 0.6 dBA or 4.7%. Meanwhile, the difference between the simulated PD and the PD measured experimentally shows a difference of 278 Pa or 8%. Errors that occur can be caused by material and manufacturing factors in the muffler manufacturing process. The percentage difference between the simulation and experimental results is still in the normal category [1], [19].

Table 3. Comparison of TL and PD experiments and simulations

Description	Standard Deviation		Average	
	TL (dBA)	PD (Pa)	TL (dBA)	PD (Pa)
Experiments	0.8	122.2	12.7	3456
Simulations	-	-	13.3	3734

5.3 Approximate Model

The idea behind approximate models is to create an engineering method used as an explicit model to evaluate the objective function [18]. Although TL and PD values can be evaluated through computer simulation, processing all muffler designs still takes a long time. In this research, a computer, model 30BEA01AID, equipped with an Intel(R) Xeon(R) W-2145 CPU @ 3.70 GHz, 16 GB of RAM, and operating system Windows 10 Pro 64-bit, was used to carry out these simulations and run the NSGA-II algorithm. Given the standard specifications of this setup, processing times were still substantial, making it necessary to develop an approximate model. A polynomial equation was created to evaluate TL and PD, and CCD was chosen as the design to distribute each experiment. This design is often used in research that aims to create approximate models based on polynomial equations [37]. In Table 4, CCD designs with a total of 27 muffler designs have been created, with 26 non-center point designs and one center point. There is no repetition of running the experiment at the center point because this is a simulation that has the same value for each measurement, in contrast to real experimental measurements, which are closely subject to variance [38].

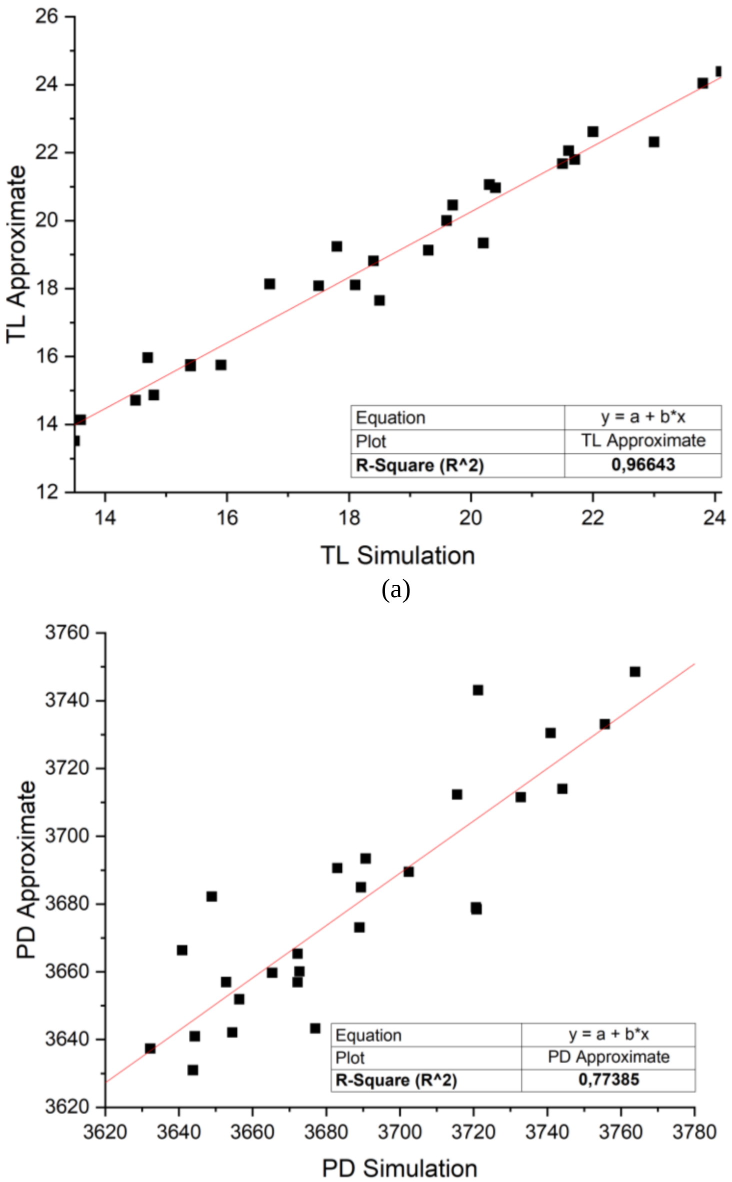
Table 4. Central composite design

Runs	Muffler diameter	Front width	Centre width	Rear width	Hole diameter	Simulation	
						TL (dBA)	PD (Pa)
1	110	80	170	80	8	22.0	3672.2
2	110	80	170	120	4	15.4	3690.7
3	110	80	210	80	4	21.5	3763.8
4	110	80	210	120	8	19.6	3702.4
5	110	120	170	80	4	13.6	3672.2
6	110	120	170	120	8	20.3	3656.4
7	110	120	210	80	8	20.4	3755.6
8	110	120	210	120	4	15.4	3689.4
9	170	80	170	80	4	14.8	3665.3
10	170	80	170	120	8	24.1	3715.5
11	170	80	210	80	8	21.7	3732.8
12	170	80	210	120	4	15.9	3644.3
13	170	120	170	80	8	21.6	3672.7
14	170	120	170	120	4	14.5	3632.2
15	170	120	210	80	4	13.5	3643.8
16	170	120	210	120	8	23.8	3740.9
17	110	100	190	100	6	20.2	3683.0
18	170	100	190	100	6	17.8	3689.0
19	140	80	190	100	6	19.7	3652.8
20	140	120	190	100	6	19.3	3654.5
21	140	100	170	100	6	18.5	3744.1
22	140	100	210	100	6	16.7	3721.2
23	140	100	190	80	6	18.1	3648.9
24	140	100	190	120	6	17.5	3720.6
25	140	100	190	100	4	14.7	3677.0
26	140	100	190	100	8	23.0	3640.9
27	140	100	190	100	6	18.4	3720.8

When 27 experiments have been simulated, and the TL and PD values have been obtained for each experiment, the next step is to create an approximate polynomial equation model to replace the simulation model in calculating TL and PD for the five design parameters. Further, in Montgomery [38], it is possible to show how to create approximate models from existing data. The approximate polynomial equation model that has been built is presented in Eq. (6) and Eq. (7). This approximate model needs to be checked for the coefficient of determination (R^2), it is the amount of error between the value predicted by the approximate model and the value obtained using simulation. (R^2) values for both TL and PD are presented in Figure 7. R^2 for TL is 0.96, then for the R^2 PD value, the value is 0.77. The greater the R^2 value, it indicates the level of accuracy. Therefore, it can be concluded that the approximate models are close to simulation models, so simulation models can be replaced with approximate models. This approximate polynomial equation model will be used as a fitness function in the optimization process using NSGA-II.

$$\begin{aligned} TL = -29.3 - 0.337M_d - 0.867F_w + 1.134C_w + 0.109R_w - 0.74H_d + 0.000527M_d^2 + 0.00244F_w^2 \\ - 0.00231C_w^2 - 0.00181R_w^2 + 0.081H_d^2 + 0.000594M_dF_w - 0.000594M_dC_w \\ + 0.001406M_dR_w + 0.01677M_dH_d + 0.000109F_wC_w + 0.001547F_wR_w \\ + 0.01453F_wH_d - 0.000734C_wR_w - 0.01641C_wH_d + 0.00672R_wH_d \end{aligned} \tag{6}$$

$$PD = 7779 - 1.78M_d + 9.3F_w - 45.5C_w - 0.9R_w - 39.0H_d + 0.0038M_d^2 - 0.0722F_w^2 + 0.1253C_w^2 + 0.0055R_w^2 - 5.90H_d^2 - 0.0013M_dF_w - 0.0150M_dC_w + 0.0149M_dR_w + 0.319M_dH_d + 0.0151F_wC_w + 0.0087F_wR_w + 0.202F_wH_d - 0.0205C_wR_w + 0.209C_wH_d + 0.110R_wH_d \quad (7)$$



(a)

(b)

Figure 7. Determination coefficient ($\boldsymbol{R^2}$) of approximate model TL (a) and PD (b)

6. RESULT AND DISCUSSION

6.1 Optimization Result

NSGA-II will produce optimal muffler design solutions for TL and PD. We strive to obtain mufflers with high noise-reduction capabilities and low-pressure drops. However, these two things contradict each other. NSGA-II will produce optimal solutions that consider both aspects. These solutions are points that will form a pattern of optimal trade-off solutions or Pareto fronts in Figure 8 [39]. The Pareto front is a set of optimal solutions in the case of multiobjective optimization where these solutions do not dominate each other in their respective objective functions. [40]. In Figure 8, TL and PD trends showed contradictory patterns. When the muffler design solution has a high TL value, the PD value is also high. Meanwhile, if the muffler design solution has a low PD value, the TL value is also in line.

Meanwhile, we expect results with high TL and low PD. However, these solutions are the most optimal solutions for this case, where these solutions are not dominated by each other in both objectives. The next step is to choose based on higher-level information. Choosing based on higher-level information refers to selecting a solution with various high-level non-technical and qualitative considerations [41]. As a result, three selected designs and one standard design, which became the initial design before being optimized, are displayed in Table 5.

Figure 8 and Table 5 present the initial design, the selected, and the best TL and PD. The initial design was a standard commercial three-pass perforated exhaust design. The initial design is displayed to see the position or condition of the initial muffler design before optimization. The best TL design (solution 28) has the highest TL value of the 70 muffler design solutions offered. Compared with the initial design, this design can increase the reduction value by 11 dBA. Meanwhile, the best PD design has the best PD value of the 70 solutions offered. Compared with the initial design, this design can reduce pressure by 58 Pa. Then, the final option is a selected design. This design offers an increased reduction value of 8 dBA with a constant pressure drop. The selected design was chosen because it also considered the size of the muffler. The selected design has the smallest size compared to the best TL and PD designs. In Figure 8 and Table 5, the initial design, the selected optimum, the best TL, and the best PD designs are presented. The initial design was a standard commercial three-pass perforated exhaust design displayed to show the position or condition of the muffler before optimization. The best TL design (solution 28) has the highest TL value among the 70 muffler design solutions offered. Compared with the initial design, this design achieves an 11 dBA increase in noise reduction. Meanwhile, the best PD design offers the lowest pressure drop among the 70 solutions, reducing the pressure drop by 58 Pa compared to the initial design.

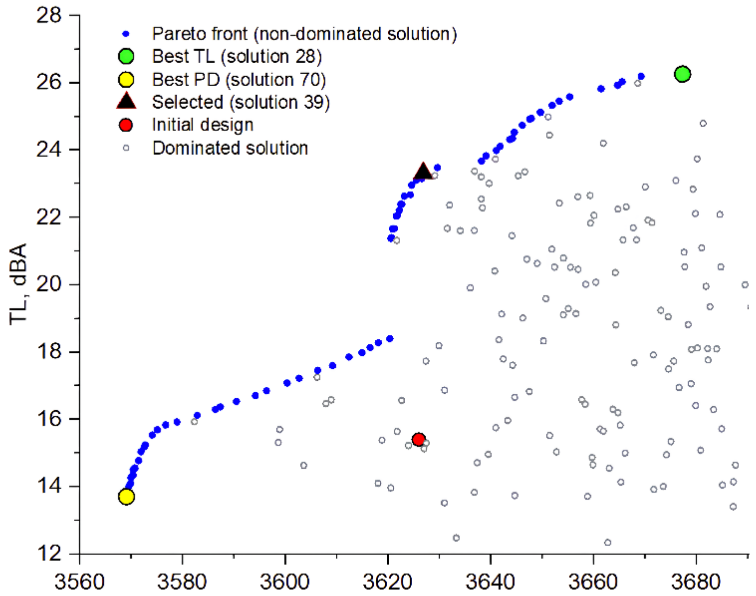


Figure 8. Pareto front

Table 5. List of the muffler parameters for the initial, selected, best TL and PD solutions

Configuration	Muffler Diameter	Front Width	Centre Width	Rear Width	Hole Diameter	TL (dBA)	PD (Pa)
Initial design	140	110	190	110	4	15.4	3626.8
Best TL (sol. 28)	170	120	179	120	8	26.3	3677.3
Best PD (sol. 70)	170	120	188	82	4	13.7	3569.1
Selected (sol. 39)	111	80	186	98	8	23.3	3626.8

The selected optimum was determined by identifying a design that maintains the same PD value as the initial design while improving TL performance. This approach was inspired by the method used by Siano et al. (2013), which emphasizes selecting a solution from the Pareto front where the pressure drop does not deteriorate, yet the TL performance is enhanced. Unlike other solutions that achieve high TL values at the expense of a worsening PD, the selected optimum balances both objectives effectively. Specifically, the selected design offers an 8 dBA increase in noise reduction while maintaining a constant pressure drop and is further preferred due to its smaller size compared to the best TL and PD designs. Acoustic elements such as future mufflers will need to meet the needs of higher noise reduction, lower back pressure, and smaller muffler volumes [42]. Considering that the solution obtained above is based on an approximate model built based on simulation results, the design must be verified to get the actual value.

6.2 Verification of Optimum Designs

Verification of the results is intended to validate the optimum design predictions provided by NSGA-II. The three best optimal designs are TL, PD, selected and experiment no. 26, standard design as initial design, created and simulated using commercial software. In this section, the TL and PD results of each design are compared with each other to determine the optimal non-dominated design. Table 6 compares the best PD design with the initial design, where the initial design dominates PD's best design objectives. Therefore, the best PD design is not included as a non-dominated optimal solution.

Non-dominated solutions relate to solutions that are not dominated or superior to other solutions [8]. Then, a comparison between selected and experiment no. 26, where experiment no. 26 dominates both selected objectives. Therefore, the selected is not included as an optimal non-domination solution.

From the previous comparison results, three optimal non-dominated designs were found. There are initial designs, best TL, and experiment no.26. An interesting fact is that the initial design is included in the non-dominated optimal design because its PD value is the best compared to other solutions. Another solution, TL's best design, offers a muffler design with noise reduction capabilities that are better than the initial design by 9 dBA or 48% but with an increase in PD of 87.3 Pa or 2%. Meanwhile, experimental design no. 26 offers a muffler with noise reduction capabilities that are better than the initial design by 3.2 dBA or 18%, with an increase in PD of 19.9 Pa or 0.5%.

Each optimal design has advantages in each TL and PD, neither dominating nor outperforming each other. The initial design is good in terms of PD value, but it is bad in terms of TL value. Meanwhile, The best TL is good in terms of TL value but bad in terms of PD value. Then, experiment no. 26 is good in terms of TL compared with the initial design but bad in terms of PD values. Compared with the best TL, it is bad in terms of TL value but good in terms of PD value. That is the concept of non-dominated solutions, where each solution is not dominated by other solutions [8], [41].

Table 6. Optimum design verification result

Configuration	Muffler diameter	Front width	Centre width	Rear width	Hole diameter	TL (dBA)	PD (Pa)
Initial design	140	110	190	110	4	17.8	3621.0
Best TL (sol. 28)	170	120	179	120	8	26.4	3708.3
Best PD (sol. 70)	170	120	188	82	4	17.7	3646.2
Selected (sol. 39)	111	80	186	98	8	20.6	3673.5
Experiment no. 26	140	100	190	100	8	23.0	3640.9

If studied more deeply, the best TL solution is the muffler with the best TL performance. However, based on its dimensions, this muffler has a large size or volume, which means it also has a large weight. Meanwhile, future muffler designs are expected to have smaller designs [42]. Meanwhile, experiment no. 26 has a lower TL value than the best TL design. However, this design is better in terms of PD value and has a smaller muffler size, which means it has a smaller weight. Therefore, this design is preferred for a more sustainable solution [42]. The design is not much different from the initial design. This design does not require modification when used directly on a vehicle. Then, ANOVA was performed to determine whether each design parameter had a statistically significant influence on TL and PD performance.

6.3 Analysis of Variance

Analysis of Variance (ANOVA) is a popular method used to carry out statistical tests in experiments involving two or more groups [43]. With ANOVA, researchers can find out the muffler design parameters that significantly influence TL or PD. These results will be helpful for future research in determining which design parameters need to be given more attention or considered. In this research, Minitab software was used to ANOVA muffler data on TL and PD with a significance level of 0.05. The results of the respective TL and PD ANOVA are presented in Table 7 and Table 8.

For the TL, of the five design parameters, only the H_d design parameter has a P-value smaller than 0.05 or rejects H_0. Meanwhile, the four design parameters have a P-value greater than 0.05 or accept H_0. Then, the interaction between parameters shows that the interaction of design parameters M_dH_d has a significant influence on TL. This means that statistical testing with a significance level of 0.05 concludes that the design parameters H_d and the interaction M_dH_d have a significant influence on the TL value [38]. These results align with Fan and Ji [7], showing that adding holes to the components inside the muffler can affect the resonance and shift it to a higher frequency. Shifting the resonance to a higher frequency can reduce the noise coming out of the muffler because the engine exhaust noise is at a low frequency [16].

Table 7. ANOVA TL

Source of Variation	DOF	Sum of Squares	Mean Squares	P-Value
Model	20	249015	12451	0.01
Linear	5	190989	38198	0.00
M_d	1	0.03	0.03	0.90
F_w	1	8405	8405	0.05
C_w	1	0.76	0.76	0.49
R_w	1	0.03	0.03	0.90
H_d	1	181769	181769	0.00
Square	5	5385	1077	0.62
M_d^2	1	0.55	0.55	0.56
F_w^2	1	2320	2320	0.25
C_w^2	1	2095	2095	0.27
R_w^2	1	1288	1288	0.38
H_d^2	1	0.26	0.26	0.69
2-Way Interaction	10	52641	5264	0.06
M_dF_w	1	2031	2031	0.28
M_dC_w	1	2031	2031	0.28
M_dR_w	1	11391	11391	0.03
M_dH_d	1	16201	16201	0.02
F_wC_w	1	0.03	0.03	0.89
F_wR_w	1	6126	6126	0.08
F_wH_d	1	5406	5406	0.10
C_wR_w	1	1381	1381	0.36
C_wH_d	1	6891	6891	0.07
R_wH_d	1	1156	1156	0.40
Error	6	8604	1434	
Total	26	257619		

Further research by Fan and Ji [6] refers to more specific components, the same as this research. Considering changes to the perforation area or number of holes in the muffler inlet or outlet can move the resonance to a higher frequency, resulting in a lower sound coming out of the muffler than before. Huang et al [5] also revealed the same thing, where decreasing the perforation area or holes in the muffler channel can reduce the resonance to a lower frequency, and increasing the perforation area can move the resonance to a higher frequency. Visually, the influence of the design parameter H_d on the TL value is presented in the form of a 3D surface plot in Figure 9, by setting the plot position of other design parameters at the midpoint. In Figure 9, it can be seen that changes in size in H_d significantly affect the TL value compared to changes in size in other design parameters.

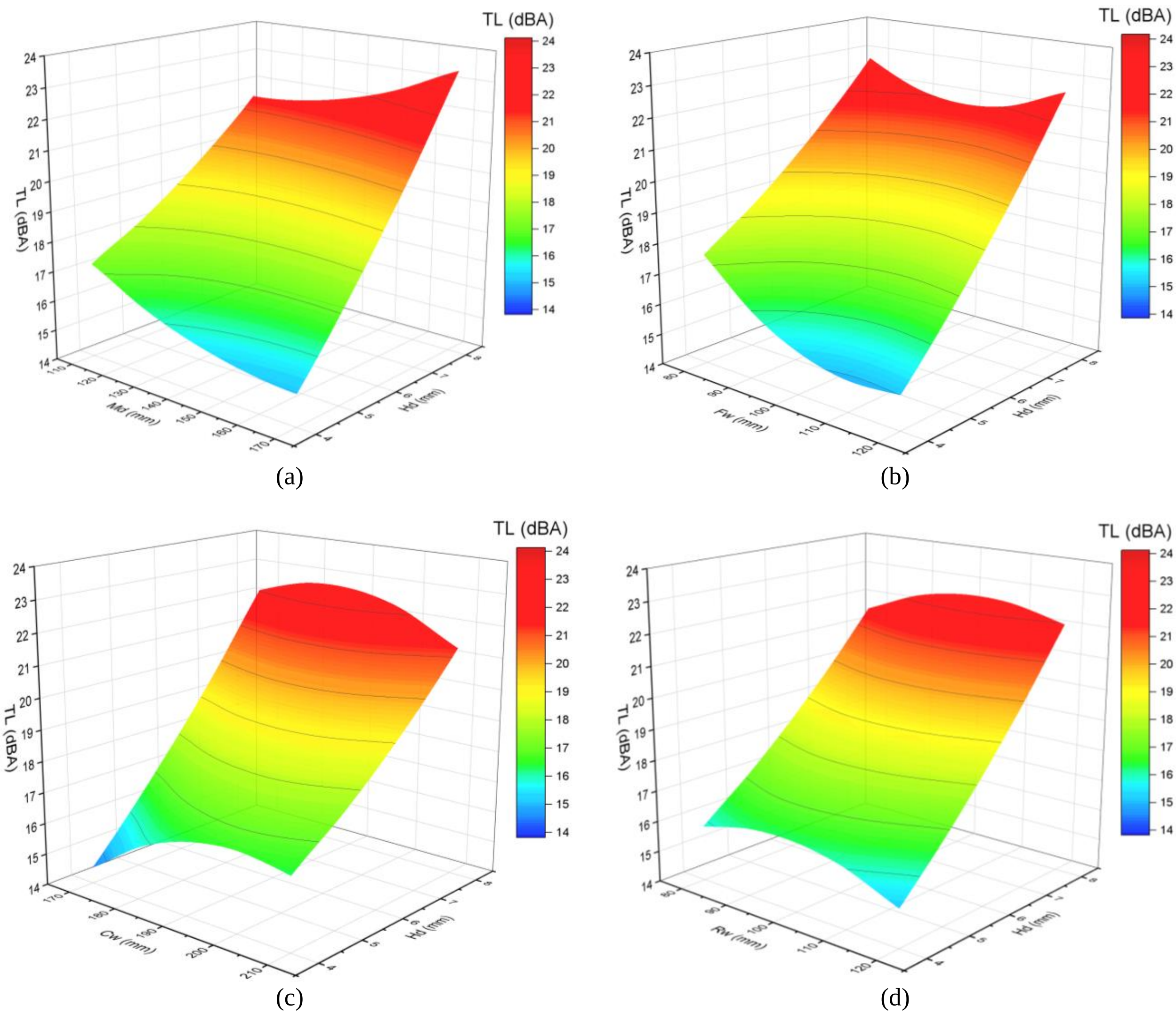


Figure 9. 3D surface graphs $\boldsymbol{H_d}$ design parameters with others

The ANOVA results for TL are different from those for PD. The PD ANOVA results, as shown in Table 8, show that there are no design parameters, either inter, that are stated to significantly influence PD. However, the design parameter C_w and its square C_w^2 have the smallest value and are close to a p-value of 0.05, which means that this design parameter has quite an influence on the PD value. Changing the size of the design parameter C_w will affect the number of holes in that area. This causes an increase in the movement of exhaust gas from the channel to the chamber, which influences the PD value, which is in line with Siano et al. [14], which revealed that an increase in the perforated area in the pipe affects the decrease in pressure in the muffler because it causes an increase in the transfer area between the channel and the chamber. Fan and Ji [6] show that the holes in the channels inside the muffler can affect the exhaust gas flow velocity inside, where changes in the exhaust gas flow velocity inside the muffler affect the back pressure [44]. Back pressure and PD are two things that are the same. In several previous studies, the PD parameter was used to represent the back pressure generated in the muffler [16], [28]. Visually, the influence of C_w on the PD value is presented in the form of a 3D graphic surface in Figure 10, by setting the plot position of other design parameters at the midpoint.

In Figure 10 (a) and (b), it can be seen that changing the size of the design parameter, C_w produces an up and down response which forms a curved surface. This is different from changes in the design parameters, M_d and R_w regarding the PD response, where there is no meaningful change in the PD value. Then, in Figure 10 (b) and (d), changing the size of the design parameter C_w produces a more varied and wavy response compared to the previous image and it can be seen that there is a significant change in PD from low to high. The changes in response seen from varying muffler design parameters demonstrate the importance of understanding how each parameter affects the acoustic and pressure performance of the muffler. To gain further insight, it is also important to review the key parameters that have been identified in previous studies as significant factors in improving muffler performance. The study conducted by Chao et al. [16] showed that increasing dimensions such as length, width, and height and reducing the duct diameter resulted in better acoustic performance and pressure drop. In another study, Siano et al. [14] show that a design that compromises the best acoustic performance and pressure drop can be achieved by reducing the size of the center chamber width and inlet and outlet diameters and increasing the perforated area of each chamber.

Table 8. ANOVA PD

Source of Variation	DOF	Sum of Squares	Mean Squares	P-Value
Model	20	29376	1469	0.53
Linear	5	8736	1747	0.40
M_d	1	1237	1237	0.39
F_w	1	828	828	0.48
C_w	1	4138	4137	0.14
R_w	1	68	68	0.84
H_d	1	2466	2466	0.24
Square	5	7882	1576	0.45
M_d^2	1	29	29	0.89
F_w^2	1	2040	2040	0.28
C_w^2	1	6139	6139	0.08
R_w^2	1	12	12	0.93
H_d^2	1	1360	1360	0.37
2-Way Interaction	10	12758	1276	0.58
M_dF_w	1	10	10	0.94
M_dC_w	1	1289	1289	0.38
M_dR_w	1	1282	1282	0.38
M_dH_d	1	5845	5845	0.09
F_wC_w	1	583	583	0.55
F_wR_w	1	195	195	0.73
F_wH_d	1	1043	1043	0.43
C_wR_w	1	1079	1079	0.42
C_wH_d	1	1122	1122	0.41
R_wH_d	1	310	310	0.66
Error	6	8558	1426	
Total	26	37935		

In addition, some further studies highlighted the importance of using perforated sections in improving acoustic performance at certain frequencies. For example, Fan and Ji [6], [7] found that the addition of a hollow section to the tube can improve acoustic attenuation at certain frequencies, while Huang et al. [5] showed that a rigid inlet or outlet tube inside the center chamber can eliminate the tip resonator and improve acoustic attenuation in the mid-frequency range. Interestingly, Mohammad et al. [4] emphasized that the perforated parameter is the most recommended factor in muffler noise reduction. Based on these findings, some of the key parameters that are significant for improving the acoustic performance and pressure drop of mufflers include the physical dimensions (length, width, height), channel diameter, the use of perforated tubes, and the configuration of the center chamber and inlet/outlet. A deep understanding of these parameters' influence is critical in designing efficient and effective mufflers in the future.

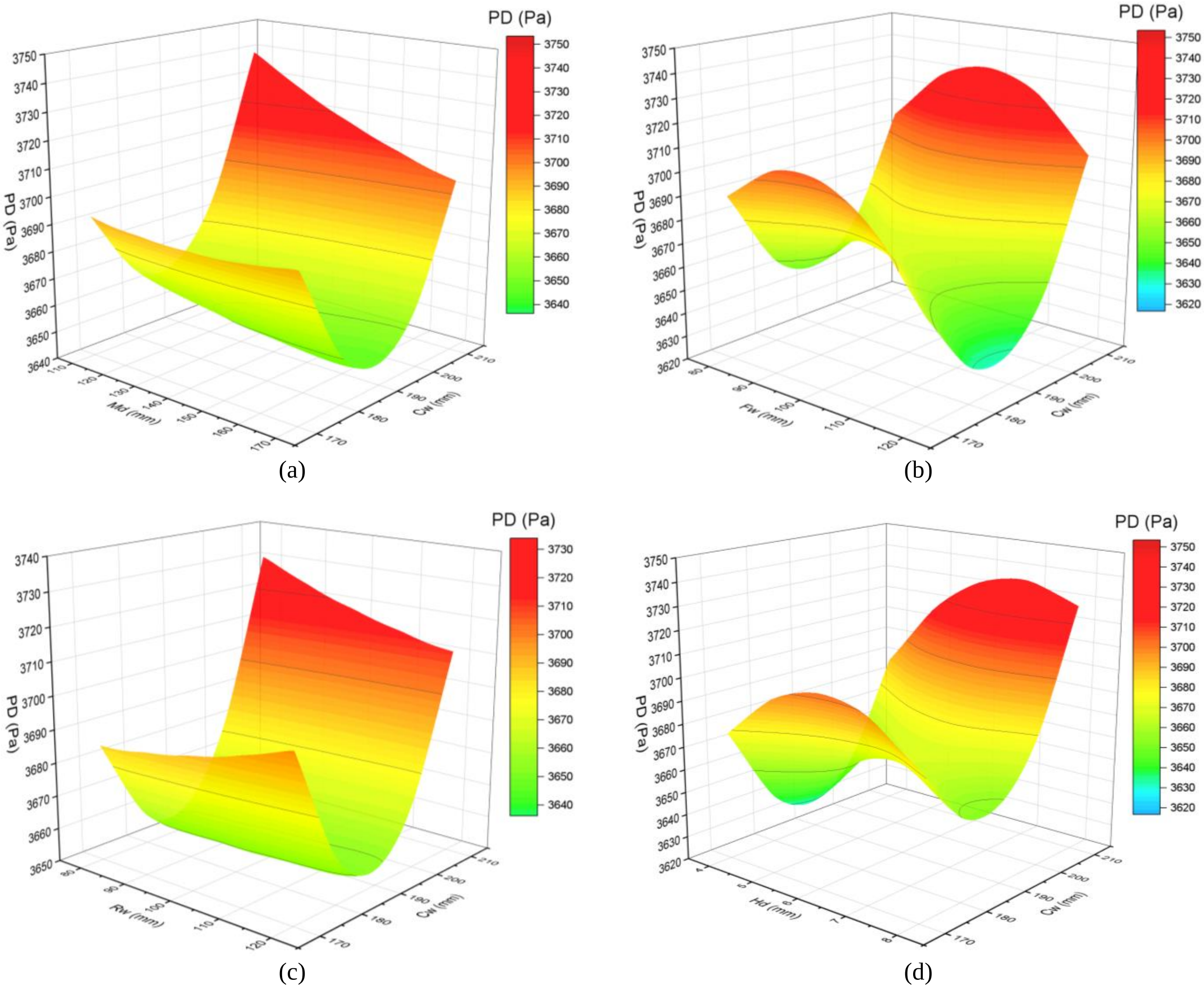


Figure 10. 3D surface graphs $\boldsymbol{C_w}$ design parameters with others

7. CONCLUSION

This research involves problem-solving in the three-pass perforated muffler design, which has trade-off conditions for reducing noise and minimizing backpressure solved using a multiobjective optimization approach using NSGA-II. This research uses the TL and PD muffler evaluation method using commercial software, and the results are validated experimentally. The results show values that are not much different from the simulation. CCD was chosen as the experimental design model, which resulted in 27 different muffler designs to be simulated. An approximate polynomial regression model was built based on simulation results from 27 muffler designs. This approximate model is used as a fitness function in the optimization process using NSGA-II.

NSGA-II produces a series of optimal muffler design solutions for TL and PD of around 70 muffler design solutions. Several optimal muffler design solutions are selected, verified, and compared with the initial or standard design. The optimal muffler solutions are the best design TL, and the experimental design no. 26. The best design, TL, offers a muffler with better noise reduction capabilities than the initial design of 9 dBA or 48% but with an increase in PD of 87.3 Pa or 2%. Experimental design no. 26 offers a muffler with noise reduction capabilities that are better than the initial design by 3.2 dBA or 18%, with an increase in PD of 19.9 Pa or 0.5%. These results offer an alternative muffler design solution with better noise reduction capabilities and a small increase in PD. Then, ANOVA results with a significance level of 0.05 show that the design parameter hole diameter (H_d has a significant influence on TL performance. This is proven by the p-value being smaller than 0.05. Meanwhile, the ANOVA results for PD performance conclude that none of the design parameters or their interactions significantly influenced PD performance. Only the design parameter C_w and its quadratic interaction is felt to have a significant influence because the p-value is close to 0.05.

ACKNOWLEDGEMENT

This research was funded through an internal grant from the State Universitas Negeri Malang with research contract numbers No. 5.4.878/UN32.20.1/LT/2023 and 4.4.281/UN32.14.1/LT/2024.

REFERENCES

[1] J. Fu, W. Chen, Y. Tang, W. Yuan, G. Li, and Y. Li, "Modification of exhaust muffler of a diesel engine based on finite element method acoustic analysis," *Advances in Mechanical Engineering*, vol. 7, no. 4, p. 1687814015575954, 2015.

[2] D. Singh, N. Kumari, and P. Sharma, "A review of adverse effects of road traffic noise on human health," *Fluctuation and Noise Letters*, vol. 17, no. 1, pp. 1–12, 2018.

[3] S. Chivate, P. Hujare, R. Askhedkar, D. Hujare, and S. Chinchanikar, "A review on acoustic performance analysis of reactive muffler," *Materials Today: Proceedings*, vol. 63, pp. 613–622, 2022.

[4] M. Mohammad, M. M. A. Buang, A. A. Dahlan, M. H. Khairuddin, and M. F. M. Said, "Simulation of automotive exhaust muffler for tail pipe noise reduction," *Jurnal Teknologi (Sciences & Engineering)*, vol. 79, no. 7–4, pp. 37–45, 2017.

[5] H. Huang, Z. Ji, and Z. Li, "Influence of perforation and sound-absorbing material filling on acoustic attenuation performance of three-pass perforated mufflers," *Advances in Mechanical Engineering*, vol. 10, no. 1, p. 1687814017748012, 2018.

[6] Y. Fan and Z. Ji, "Three-pass mufflers with perforated inlet/outlet tubes," *Applied Acoustics*, vol. 156, pp. 217–228, 2019.

[7] Y. Fan and Z. Ji, "Three-pass perforated tube muffler with perforated bulkheads," *Advances in Mechanical Engineering*, vol. 8, no. 11, p. 1687814016676767, 2016.

[8] K. Deb, *Multi-Objective Optimization using Evolutionary Algorithms*. John Wiley & Sons, Inc., 2001.

[9] J. K. Lee, K. S. Oh, and J. W. Lee, "Methods for evaluating in-duct noise attenuation performance in a muffler design problem," *Journal of Sound and Vibration*, vol. 464, p. 114982, 2020.

[10] D. A. Bies, C. H. Hansen, and C. Q. Howard, *Engineering Noise Control*, Fifth., vol. 3, no. 1. New York: Taylor & Francis Group, 2018.

[11] M. . Munjal, *Acoustics of Ducts and Mufflers*, Second. India, 2014.

[12] E. Okokon, A. Turunen, S. Ung-Lanki, A.-K. Vartiainen, P. Tiittanen, and T. Lanki, "Road-Traffic Noise: Annoyance, risk perception, and noise sensitivity in the finnish adult population," *International Journal of Environmental Research and Public Health*, vol. 12, no. 6, pp. 5712–5734, 2015.

[13] T. Bodin, J. Björk, J. Ardö, and M. Albin, "Annoyance, sleep and concentration problems due to combined traffic noise and the benefit of quiet side," *International Journal of Environmental Research and Public Health*, vol. 12, no. 2, pp. 1612–1628, 2015.

[14] D. Siano, F. Bozza, and F. Auriemma, "Acoustic and fluid-dynamic optimization of an automotive muffler," *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, vol. 227, no. 5, pp. 735–747, 2013.

[15] D. Neihguk, M. L. Munjal, and A. Prasad, *Pressure drop characteristics of perforated pipes with particular application to the concentric tube resonator*, no. 2015-01-2309, SAE Technical Paper, 2015.

[16] S. Chao and H. Liang, "Comparison of various algorithms for improving acoustic attenuation performance and flow characteristic of reactive mufflers," *Applied Acoustics*, vol. 116, pp. 291–296, 2017.

[17] X. L. Xie, F. Gao, X. Y. Huang, C. Huang, and J. Li, "Numerical optimization of flow noises for mufflers based on the improved BP neural network," *Journal of Vibroengineering*, vol. 18, no. 4, pp. 2626–2640, 2016.

[18] S. Zuo, K. Wei, and X. Wu, "Multi-objective optimization of a multi-chamber perforated muffler using an approximate model and genetic algorithm," *International Journal of Acoustics and Vibration*, vol. 21, no. 2, pp. 152–163, 2016.

[19] P. P. Hujare, V. R. Mote, A. R. Mache, D. P. Hujare, and S. S. Kore, "Analysis for effect of pores on acoustic performance of reactive muffler," *Noise Vib. Worldw.*, vol. 52, no. 9, pp. 285–292, 2021.

[20] A. Selamet, F. D. Denia, and A. J. Besa, "Acoustic behavior of circular dual-chamber mufflers," *Journal of Sound and Vibration*, vol. 265, no. 5, pp. 967–985, 2003.

[21] P. Daniel, "Design principles for an automotive muffler," *International Journal of Applied Engineering Research*, vol. 9, no. 4, pp. 483-489, 2014.

[22] S. Bilawchuk and K. R. Fyfe, "Comparison and implementation of the various numerical methods used for calculating transmission loss in silencer systems," *Applied Acoustics*, vol. 64, no. 9, pp. 903–916, 2003.

[23] H. Lu, T. Wu, S. Bai, K. Xu, Y. Huang, W. Gao et al., "Experiment on thermal uniformity and pressure drop of exhaust heat exchanger for automotive thermoelectric generator," *Energy*, vol. 54, pp. 372–377, 2013.

[24] C. P. O. A. Guhan, G. Arthanareeswaran, K. N. Varadarajan, and S. Krishnan, "Exhaust system muffler volume optimization of light commercial vehicle using CFD simulation," *Materials Today: Proceedings*, vol. 5, no. 2, pp. 8471–8479, 2018.

[25] A. Elsayed, C. Bastien, S. Jones, J. Christensen, H. Medina, and H. Kassem, "Investigation of baffle configuration effect on the performance of exhaust mufflers," *Case Studies in Thermal Engineering*, vol. 10, pp. 86–94, 2017.

[26] C. P. Om Ariara Guhan, G. Arthanareeswaren, and K. N. Varadarajan, "CFD study on pressure drop and uniformity index of three cylinder LCV exhaust system," *Procedia Engineering*, vol. 127, pp. 1211–1218, 2015.

[27] B. Mohamad, J. Karoly, A. Zelentsov, and S. Amroune, "A comparison between hybrid method technique and transfer matrix method for design optimization of vehicle muffler," *FME Transactions*, vol. 49, no. 2, pp. 494–500, 2021.

[28] Y. C. Chang, M. C. Chiu, and M. R. Wu, "Acoustical assessment of automotive mufflers using FEM, neural networks, and a genetic algorithm," *Archives of Acoustics*, vol. 43, no. 3, pp. 517–529, 2018.

[29] J. H. Holland, *Adaptation in Natural and Artificial Systems*. The MIT Press, 1992.

[30] K. F. De Lima, A. Lenzi, and R. Barbieri, "The study of reactive silencers by shape and parametric optimization techniques," *Appl. Acoust.*, vol. 72, no. 4, pp. 142–150, 2011.

[31] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," *IEEE Transactions on Evolutionary Computation*, vol. 6, no. 2, pp. 182–197, 2002.

[32] F. Zhu, Y. Liu, C. Lu, Q. Huang, and C. Wang, "Research on thermal energy management for PHEV based on NSGA-II optimization algorithm," *Case Studies in Thermal Engineering*, vol. 54, p. 104046, 2024.

[33] United Nations Economic Commission for Europe (UNECE), *ISO ECE R 51-01 Uniform Provisions Concerning the Approval of Vehicles with Regard to the External Noise*, pp. 6–9, 2017.

[34] M. A. Habib, A. U. Patwari, A. S. Anwar, S. Shadman, and O. H. Abir, "3D CFD based optimization technique for muffler design of a motorcycle," *Applied Mechanics and Materials*, vol. 860, pp. 52–57, 2017.

[35] T. Yasuda, C. Wu, N. Nakagawa, and K. Nagamura, "Predictions and experimental studies of the tail pipe noise of an automotive muffler using a one dimensional CFD model," *Applied Acoustics*, vol. 71, no. 8, pp. 701–707, 2010.

[36] R. Li, Y. Zhou, Y. Xue, and S. Han, "Local structural optimization method based on orthogonal analysis for a resistant muffler," *IEEE Access*, vol. 9, pp. 40560–40569, 2021.

[37] S. Bhattacharya, "Central composite design for response surface methodology and its application in pharmacy," in *Response Surface Methodology in Engineering Science*, IntechOpen, 2021.

[38] D. C. Montgomery, *Design and Analysis of Experiment*, Eighth edi. Tempe, Arizona: John Wiley & Sons, Inc., 2013.

[39] M. Akbari, P. Asadi, M. K. Besharati Givi, and G. Khodabandehlouie, "Artificial neural network and optimization," in *Advances in Friction-Stir Welding and Processing*, Elsevier, 2014, pp. 543–599, 2014.

[40] N. Gunantara, "A review of multi-objective optimization: Methods and its applications," *Cogent Engineering*, vol. 5, no. 1, p. 1502242, Jan. 2018.

[41] K. Deb, "Multi-objective optimisation using evolutionary algorithms: An introduction," L. Wang, A. H. C. Ng, and K. Deb, Eds. London: Springer London, 2011, pp. 3–34, 2011.

[42] F. Xue and B. Sun, "Experimental study on the comprehensive performance of the application of U-shaped corrugated pipes into reactive mufflers," *Applied Acoustics*, vol. 141, pp. 362–370, 2018.

[43] N. R. Smalheiser, "Chapter 11-ANOVA," in *Data Literacy*, Elsevier, 2017, pp. 149–155, 2017.

[44] V. Kumar, N. Prasad, M. K. Paswan, P. Kumar, and S. Biswas, "Design analysis and pressure loss optimization of automobile muffler," in *Intelligent Manufacturing and Energy Sustainability*, 2020, pp. 93–107, 2020.