Research Article

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# A novel method for constructing large-scale industrial noise maps based on open source data

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**Abstract:** This study proposed a method of obtaining the type and quantity of equipment in factories by inquiring environmental impact assessment reports, which greatly improves the efficiency of gathering factory information. Thereafter, by combining on-site measurement and numerical modelling, the noise maps of an automobile industrial area were constructed. The exposed population under different noise levels were evaluated using the noise maps. The results indicated that noise pollution at nighttime in the study area was more severe than that during daytime, with 523 people (1.08%) and 1,357 people (2.81%) exposed to excessive noise levels during daytime and nighttime, respectively. In addition, this study also constructed a low-frequency industrial noise map. The methods and results of the present study can provide novel technical path for construction and analysis of large-scale industrial noise map.

**Keywords:** environmental impact, factory, numerical modelling, equipment, CadnaA

## 1 Introduction

According to global industrial and economic development data released by The World Bank, the world gross industrial product in 2022 was USD 16188.86 billion, increased by 0.66% compared to the previous year [1]. Even after the significant impact of COVID-19, the global industrial development has remained stable. Although the industrial economy is an important factor in promoting and enhancing regional economic development, it also brings a series of noise pollution problems. Industrial noise can cause negative effects such as hearing loss [2–5], decline of memory [6], sleep disorders [7–9], and mental health [10,11]. Therefore, constructing an industrial noise map is particularly important for reducing the harm caused by industrial noise.

With the continuous development of computer technology, more and more researchers are using numerical simulation software to construct industrial noise maps [12–15]. Common environmental noise simulation softwares include CadnaA, SoundPlan and Predictor LimA. For example, Raina *et al.* [16] studied the impact of hilly terrain on noise attenuation in cement factories and the results showed that noise was attenuated throughout the entire valley and changed according to the terrain of the valley. del Mar Durán del Amor *et al.* [17] assigned different noise sources into different groups and conducted normalized frequency analysis on the most relevant sources, to determine the contribution of different noise sources. Deaconu and Cican [18] constructed noise maps under the influence of two different turbojet engines and evaluated the impact of turbojet engine noise on adjacent residential areas.

In current scientific open literature, large-scale noise mapping researches were generally conducted in the fields of traffic, aircraft, and railway noise [19,20]. In fact, there is not much research on large-scale industrial noise mapping, mainly because the construction of numerical models for industrial noise maps often requires large amount of factory equipment information, and researchers usually only can obtain these relevant data from the particular factory department. Bozkurt and Demirkale [12] constructed a noise map of an industrial area with different factory's door opening ratios through on-site observation and investigation. They evaluated the noise exposed population and area based on the industrial noise map. Paschalidou *et al.* [21] developed the strategic noise maps and action plans for the "agglomeration of Piraeus," which involved railway, port, road traffic and industrial noises. Licitra *et al.* [22] proposed predominance maps for the port areas in environmental acoustic, which involved road traffic, railway, port, and industrial noises. In summary, obtaining accurate factory equipment data are a major challenge in constructing industrial noise maps. Based on this challenge, this study adopted a new approach to construct a high precision

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industrial noise map. Environmental impact assessment reports issued by the government usually listed the models and quantities of various industrial equipment. Based on these information, this study collected the noise parameters of each equipment from open source data to determine their noise levels. Therefore, this approach can construct industrial noise maps effectively at a lower cost.

## 2 Methodologies

The method used in this study is shown in Figure 1. First, the relevant data of the factory's equipment were obtained through environmental impact assessment reports and academic papers. Second, information on the buildings and population were obtained through literature review and field observation. Then, a trial traffic and industrial noise model of the study area was constructed using CadnaA software. The accuracy of the trial traffic and industrial noise model was verified through field measurement data. Finally, an industrial noise map was developed based on the validated noise model.

### 2.1 Study area

According to a report from the government of Panyu District of Guangzhou City [23], Panyu Automobile City produced 530,000 vehicles with industrial output value of RMB101.9 billion in 2022, where an increment of 37.3% was archieved compared to 2021. Therefore, to reflect the impact of industrial noise in real life and to better control the impact of industrial noise pollution, Panyu Automobile City was selected as the study area in the present study. The factories, residential areas, schools, and other buildings in Panyu Automobile City are shown in Figure 2. Panyu Automobile City is located in the northeast of Panyu District and at the core central of the Guangdong-Hong Kong-Macao Greater Bay Area. It is also one of the four major industrial development platforms in Panyu District. The study area in the present works is approximately 17.8 km$^2$ with total of 40 active factories (Figure 2), 11 villages, and 4 residential areas. The study area belongs to subtropical marine monsoon climate, with annual average temperature of 23.4 °C [24].

### 2.2 Basic information of the noise model

It is necessary to determine the basic information of the noise model to construct a noise map of the study area:
1) Software: CadnaA software (Version 2020 MR2).
2) Time frame: 6:00 to 22:00 is defined as daytime; 22:00 to 6:00 is defined as nighttime [25].
3) Meteorological data: Temperature and relative humidity were obtained from the official website of Guangzhou

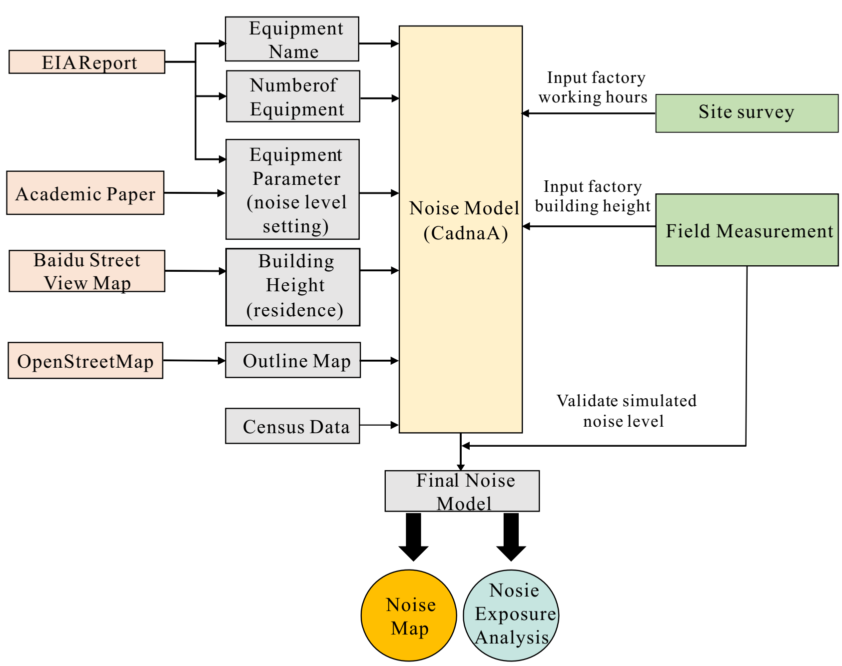


**Figure 1:** Methodologies for constructing industrial noise map.

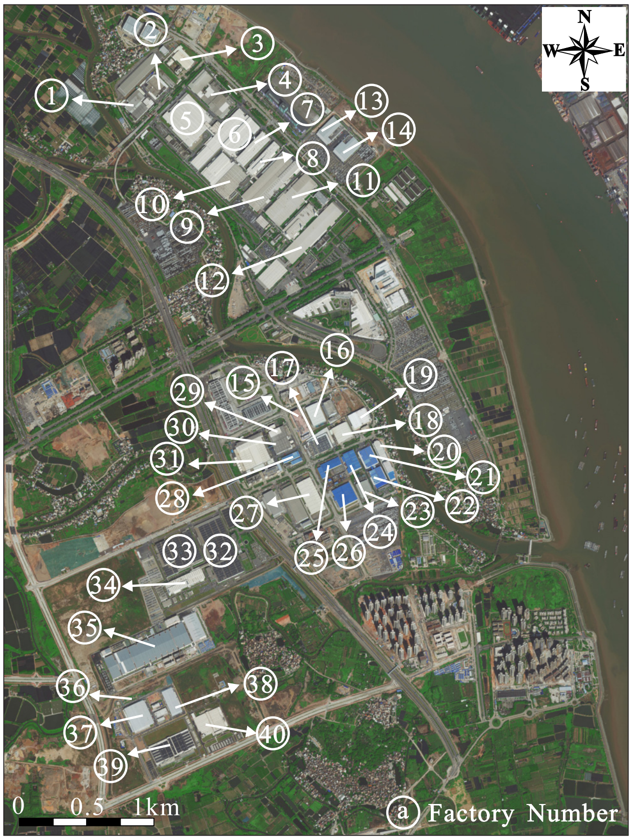


**Figure 2:** Study area.

Meteorological Bureau [26]. Average temperature and average relative humidity of the measurement day were used in the noise model.

4) Terrain data: Through on-site observation, it was found that the terrain in the study area is relatively flat, so the impact of altitude differences was not considered in the noise model.
5) Height of receiver: The microphone needs to be placed at least 1.2 m above the ground according to the relevant requirements of China national standards [27]. Therefore, in current study, the height of the receiver in the noise map was set at 1.5 m [12,17,28,29].

## 2.3 Outline map of the study area

The map of the study area was imported from OpenStreetMap into CadnaA software to obtain a contour map of the study area. However, the preliminary contour map obtained was incomplete and lacked of some contents such as factories and residential buildings. Therefore, by combining the latest satellite image from Google Earth and geographic information from Amap, the map of the study area was improved to obtain a complete outline map as shown in Figure 3.

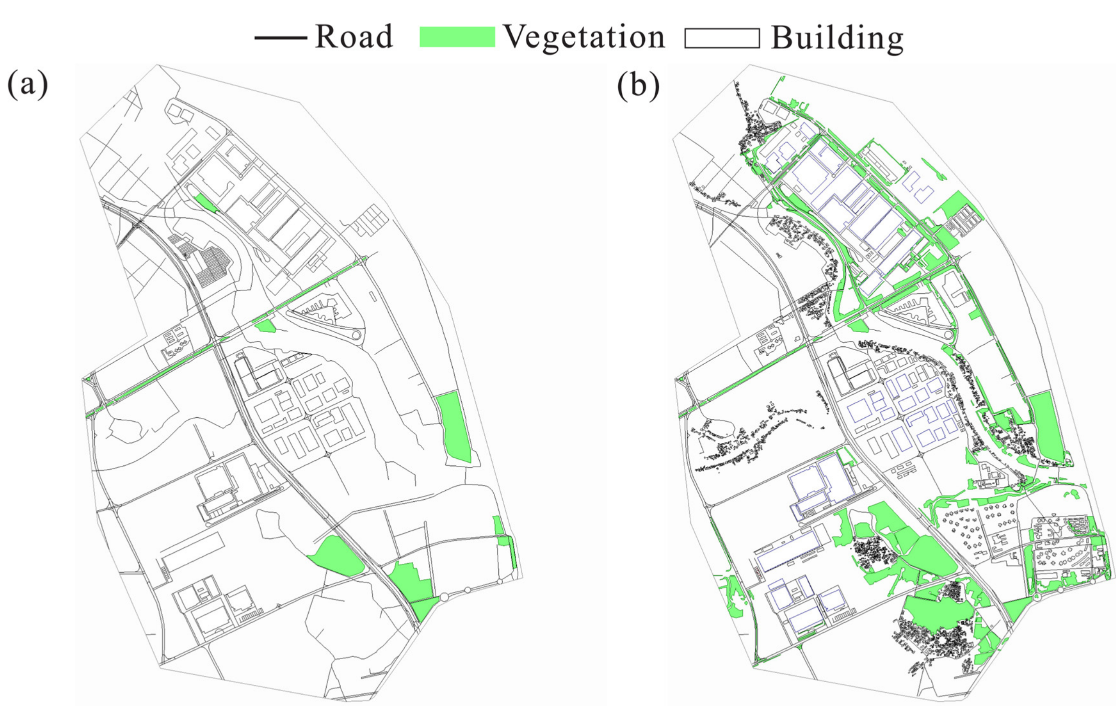


**Figure 3:** (a) Incomplete outline map and (b) complete outline map.

## 2.4 Boundary condition of the factory

Each factory needed to be modelled after the outline map of the study area was obtained. The modelling method by assuming each equipment as a point sound source is very complex due to large number of equipment in each factory. Therefore, the outer surfaces of the factory (excluding the bottom surface) was simplified as area sound source as shown in Figure 4. Assuming that the sound power level was uniformly distributed within the factory, the steps and equation for establishing the factory model are presented here.

1) This study summarized the equipment types and equipment quantities of each factory based on the environmental impact assessment report of the factory (Table A1 in the Appendix). The working h of each factory was obtained through on-site observation and survey. Then, the mean room sound absorption coefficient of each factory was determined based on the type of factory [30,31] (metal processing and non-metal processing factories) as shown in Table A2 in the Appendix. The noise spectrum or sound power level of the equipment was obtained through previous relevant research studies and some environmental impact assessment reports as shown in Tables A3 and A4 in the Appendix. Finally, the area sound sources for each factory were constructed based on the actual size of the factory's external surface using the information from Tables A1–A4.
2) The interior sound pressure level in the room ($\mathrm{SPL}_i$) corresponding to each area sound source was calculated using Equation (1) [32], where PWL is the sound power level of all noise sources (equipment), $A$ is the equivalent sound absorption area, $\alpha$ is the mean absorption coefficient of the room surfaces, and $S$ is the area of the room surfaces.

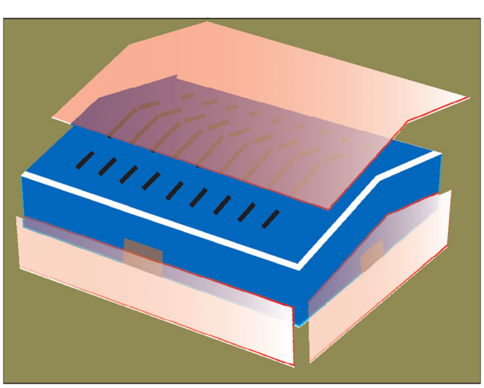

Figure 4: Area sound source of a factory.

$$\begin{aligned}\mathrm{SPL}_i &= \mathrm{PWL} - 10\lg\left(\frac{A}{m^2}\right) + 6\ \mathrm{dB} \\ &= \mathrm{PWL} - 10\lg\left(\frac{\alpha \cdot S}{m^2}\right) + 6\ \mathrm{dB}.\end{aligned} \tag{1}$$

3) To include the effect of transmission loss from indoor to outdoor, it is necessary to input the weighted sound reduction index ($R_\mathrm{w}$) of the factory surface material before computing the sound power level of each area sound source. This study found that the exterior walls and roofs of most factories were made by colour steel plates through on-site observation. Therefore, the $R_\mathrm{w}$ of colour steel plate was used as the $R_\mathrm{w}$ of factory's exterior walls and roofs (Table A5 in the Appendix). Finally, the sound power level of each area sound source was obtained.

## 2.5 Building height and its wall sound absorption coefficient

Through on-site observation, beside factories, it was found that the buildings in the study area are mainly composed of villages and residential areas. Some areas in the villages and residential communities have consistent building height.


Figure 5: 14 small areas with the same building height.

Therefore, this study categorized 10 villages and 4 residential areas within the study area into 14 small areas with similar building heights [33] (Figure 5). Then, the number of floors of buildings in each small area was determined based on Baidu Street View Map [34]. Finally, the height of each building was estimated based on the number of floors and floor height (the floor height in Panyu Motor City is about 3 m), where building height = floor height × number of floors [12,35]. The height of buildings in each area are shown in Table 1. In addition, it was found that the height of some buildings are much higher or lower than their adjacent buildings. Therefore, the height of all factories (Figure 2), some logistics parks and some office buildings (red areas in Figure 5) were evaluated separately and their building heights are shown in Table 2. Based on the on-site observation, it was found that most of the buildings in the study area are composed by masonry walls with balconies. Therefore, in this study, the sound absorption coefficient of these building's walls were set to 0.4 [35]. In addition, the wall sound absorption coefficient of some empty factories and logistics parks were set to 0.15 [30].

## 2.6 Grid independency study

Figure 6 shows the sound pressure levels that computed from the production base of Gac Motor using the grid sizes of 4 m × 4 m and 10 m × 10 m, to explore the impacts of grid size on simulation results. The results indicate that the trends of the two grids are similar with an average error of approximately 0.23 dBA. However, the computational time for grid sizes of 4 m × 4 m and 10 m × 10 m are 18 h and 8 h, respectively. Therefore, in this study, gird size of 10 m × 10 m was chosen to construct an accurate industrial noise map with lower computational cost.

**Table 1:** Building height of the 14 small areas

| Number | Number of floors | Building height (m) |
|---|---|---|
| 1 | 2.5 | 7.5 |
| 2 | 3 | 9 |
| 3 | 3 | 9 |
| 4 | 3.5 | 10.5 |
| 5 | 2.5 | 7.5 |
| 6 | 3 | 9 |
| 7 | 3 | 9 |
| 8 | 3 | 9 |
| 9 | 3 | 9 |
| 10 | 2 | 6 |
| 11 | 30 | 90 |
| 12 | 29 | 87 |
| 13 | 23 | 69 |
| 14 | 25 | 75 |

**Table 2:** Building height that need to be evaluated separately

| Number | | Building height (m) | Number | | Building height (m) |
|---|---|---|---|---|---|
| Area number | 1 | 23 | Factory number | 18 | 15 |
| | 2 | 15 | | 19 | 8 |
| | 3 | 26.5 | | 20 | 20 |
| | 4 | 20 | | 21 | 16 |
| | 5 | 25 | | 22 | 16 |
| | 6 | 35 | | 23 | 14.15 |
| Factory number | 1 | 11 | | 24 | 18 |
| | 2 | 19 | | 25 | 18 |
| | 3 | 16 | | 26 | 20 |
| | 4 | 15 | | 27 | 20 |
| | 5 | 17.5 | | 28 | 18 |
| | 6 | 9.3 | | 29 | 18 |
| | 7 | 9.3 | | 30 | 17 |
| | 8 | 9.3 | | 31 | 15 |
| | 9 | 11.5 | | 32 | 10 |
| | 10 | 9.3 | | 33 | 12.5 |
| | 11 | 22 | | 34 | 10.5 |
| | 12 | 9.3 | | 35 | 23 |
| | 13 | 16 | | 36 | 9 |
| | 14 | 16 | | 37 | 10.5 |
| | 15 | 30 | | 38 | 10.5 |
| | 16 | 8 | | 39 | 16 |
| | 17 | 16 | | 40 | 7.5 |

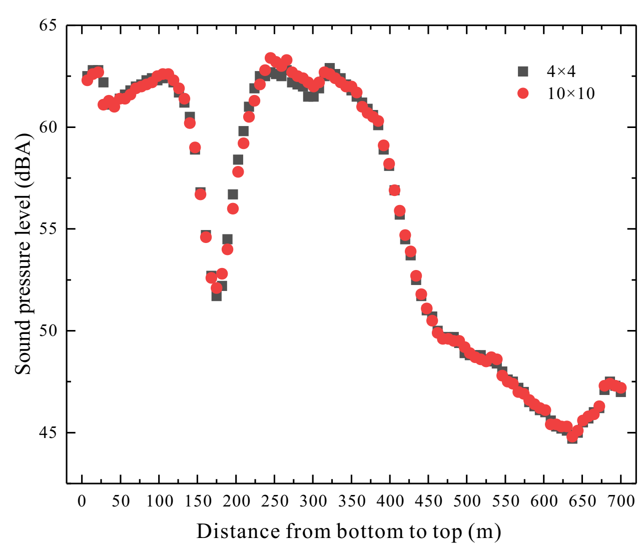


**Figure 6:** Comparison between 4 m × 4 m and 10 m × 10 m grids' simulation results.

## 2.7 Census data

The total population of the study area is about 48,249 people based on the relevant reports of the People's Government of Panyu District [36,37]. The total population was allocated to each residential building based on its geometric dimensions (building area and height).

## 2.8 Validation experiment

Four days field measurements were conducted from 3th to 6th July 2023 to verify accuracy of the trial day road traffic and industrial noise model as shown in Figure 7. Totally there were 39 measurement points (Figure 8). First, the measurement points were selected at the location without the interference of the road traffic noise. Second, some factories are located on side of some roads, so the measurement points of these factories were arranged to simultaneously measure the road traffic noise and industrial noise. Finally, a measurement point was arranged to each arterial road to measure the road traffic noise separately. The measurement process was carried out from 6:00 to 22:00 with measurement time of 15 min at each point based on China national standard (GB 3096-2008) [25]. GB 3096-2008 requires that during the daytime measurement period, the equivalent sound level must be measured for at least 10 min at each measurement point. The date of the measurement process should avoid holidays and non-working days. The measurement time of many researchers were less than 15 min [38–40]. Therefore, 15 min measurement time in the present study complied with China national standard and consistent with the practices of other researchers over the world. The microphone and calibrator used for measuring traffic and factory noises in the present study met the requirements of China national standards GB/T 3785.1 [41] and GB/T 15173 [42], respectively. The microphone was fixed on a tripod at a distance of 1.5 m from the ground and at a distance of 1m or more than 1 m from the fence of factories. In addition, the measurement process was carried out in good weather without rain, snow, or lightning with wind speed below 5 m/s [27]. The average temperature and average relative humidity on the measurement day were 31.1 °C and 78%, respectively [26].

Among the 39 noise measurement points, 20 of these points were located near to the main road (points 2–4, 7, 8, 16–28, 30, and 31). Therefore, these points need to include road traffic data measurement in addition to noise measurement. The data were used to generate the trial day traffic and industrial noise model which included: road


Figure 7: Measurement of the traffic and industrial noise.


Figure 8: Measurement points.

width, traffic flow, vehicle type ratio, vehicle speed, and road surface type. The actual width of the road was obtained using the distance measurement function of Amap (satellite map). Vehicle flows and types were measured based on the categories of small-size, mid-size and large-size cars [43]. Vehicle speeds were measured based on the categories of cars and trucks (15 each), and their average values were computed. The hand-held radar speedometer used for measuring vehicle speed in the present study met the requirements of China national standard JJG 771 [44]. In addition, asphalt concrete was selected as the road surface type through on-site observation.

## 3 Results and discussion

### 3.1 Comparison between simulation and measurement results

The road traffic and industrial noise map of the study area is shown in Figure 9. The measurement and simulation results at the 39 measurement points are compared as shown in Table 3. The results show that about 80% of the measurement points have errors less than 3 dBA, with an average error of 1.9 dBA. Therefore, the error in this study is relatively small if compared with other similar studies with an average error of approximately 6.1–6.5 dBA [12,13]. In this study, there are two significant errors in 2 measurement points, namely, 4.6 dBA and 5.4 dBA. These large errors are due the fact where the factory equipment near the measurement point shut down intermittently during the measurement process, which resulting in higher simulation values if compared to measurement values.

In addition, a good correlation between the measurement and simulation results is found with a determination coefficient of 0.847 as shown in Figure 10. Therefore, it is proved that the simulation results of this study are accurate. It indicates that the methodologies and industrial noise model in the present study are reliable.

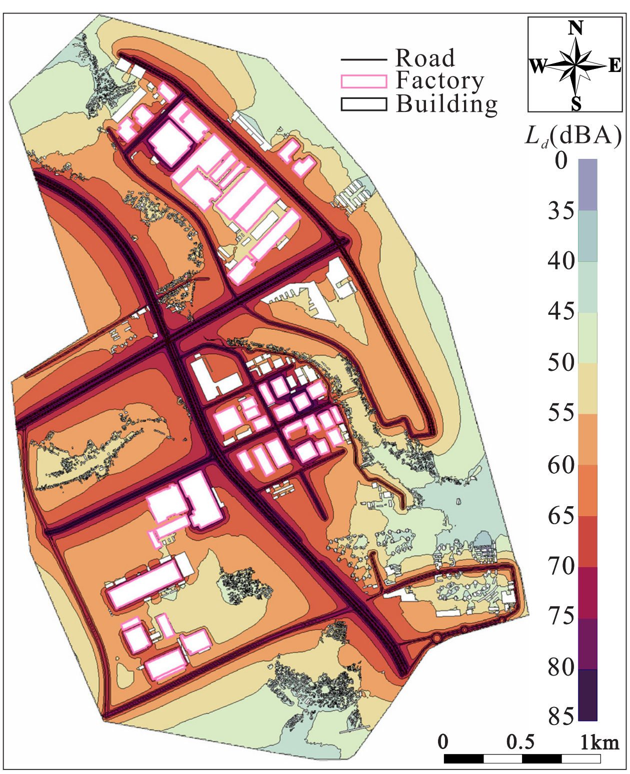


**Figure 9:** Day road traffic and industrial noise map.

### 3.2 Industrial noise map

The industrial noise maps for three time periods in Panyu Automobile City was computed after accuracy of the traffic and industrial noise model was verified. The three industrial noise maps are day, night, and day–night noise maps as shown in Figures 11–13. During daytime, the noise levels of most factory areas (35/40) remain within the range of 55–64.5 dBA. According to the environmental noise limit in Table A6 in the Appendix, industrial production area belongs to Class 3 functional area and thus, the noise level around the factory area needs to be controlled below 65 dBA. Consequently, it can be concluded that the sound environment quality of most factories in the study area meets the requirement of China national standard. However, some residential areas which located near the industrial production areas are affected by industrial noise where their noise levels are above 55dBA (residential area belongs to Class 1 functional area with noise limit of 55dBA). These areas are mainly distributed in parts of Zhansha Village and all staff dormitory buildings as shown in Figure 14(a).

The noise levels around the factory areas at nighttime decrease about 1.8–5.7 dBA compared to daytime noise level (compare Figures 11 and 12). However, the noise limit of industrial production area during nighttime is tighter (below 55 dBA). Therefore, many factories (13/40) cannot meet the requirement of the national standard during nighttime. Besides, the residential areas that affected by nighttime industrial noise ($L_n$ > 45 dBA) are distributed in some areas of Sisha Village and Liusha Village in addition to Zhansha Village and staff dormitory building

**Table 3:** Error between the measurement and simulation results. Error = $|L_{d,m} - L_{d,s}|$

| Measurement ponit | $L_{d,m}$ (dBA) | $L_{d,s}$ (dBA) | Error (dBA) | Measurement ponit | $L_{d,m}$ (dBA) | $L_{d,s}$ (dBA) | Error (dBA) |
|---|---|---|---|---|---|---|---|
| 1 | 69.0 | 70.5 | 1.5 | 21 | 69.0 | 72.4 | 3.4 |
| 2 | 61.3 | 64.9 | 3.6 | 22 | 72.0 | 77.4 | 5.4 |
| 3 | 64.8 | 67.5 | 2.7 | 23 | 70.8 | 73.3 | 2.5 |
| 4 | 72.9 | 74.0 | 1.1 | 24 | 66.5 | 65.5 | 1.0 |
| 5 | 60.7 | 63.8 | 2.1 | 25 | 68.2 | 69.9 | 1.7 |
| 6 | 68.1 | 70.0 | 1.9 | 26 | 62.0 | 64.4 | 2.4 |
| 7 | 63.1 | 65.2 | 2.1 | 27 | 59.6 | 60.8 | 1.2 |
| 8 | 66.0 | 66.6 | 0.6 | 28 | 64.6 | 68.0 | 3.4 |
| 9 | 61.1 | 63.3 | 2.2 | 29 | 69.0 | 68.7 | 0.3 |
| 10 | 63.1 | 64.4 | 1.3 | 30 | 71.0 | 74.2 | 3.2 |
| 11 | 60.5 | 61.1 | 0.6 | 31 | 71.5 | 72.1 | 0.6 |
| 12 | 67.1 | 66.5 | 0.6 | 32 | 62.8 | 64.6 | 1.8 |
| 13 | 71.1 | 74.1 | 3.0 | 33 | 61.5 | 60.7 | 0.8 |
| 14 | 64.0 | 65.4 | 1.1 | 34 | 64.0 | 62.4 | 1.6 |
| 15 | 70.1 | 70.4 | 0.3 | 35 | 62.1 | 65.4 | 3.3 |
| 16 | 68.2 | 67.1 | 1.1 | 36 | 65.0 | 67.5 | 2.5 |
| 17 | 69.0 | 73.6 | 4.6 | 37 | 70.8 | 70.4 | 0.4 |
| 18 | 72.4 | 74.1 | 1.7 | 38 | 65.2 | 67.2 | 2.0 |
| 19 | 69.5 | 69.1 | 0.4 | 39 | 65.8 | 66.3 | 0.5 |
| 20 | 66.9 | 69.8 | 2.9 | | | | |

(Figure 14(b)). In conclusion, the sound environment quality at nighttime in Panyu Automobile City is far inferior to that during daytime.

This study uses standard of the US Department of Housing and Urban Development (HUD) [45] to classify day–night noise level since there is no relevant China regulations on day–night noise limit. HUD groups the noise level into four groups: (i) clearly acceptable: $L_{\mathrm{eq}} \leq 49$ dBA, (ii) normally acceptable: $49 < L_{\mathrm{eq}} \leq 62$ dBA, (iii) normally unacceptable: $62 < L_{\mathrm{eq}} \leq 76$ dBA, and (iv) clearly unacceptable: $L_{\mathrm{eq}} > 76$ dBA. By comparing Figures 12 and 13, the areas covered during day–night are significantly larger than at

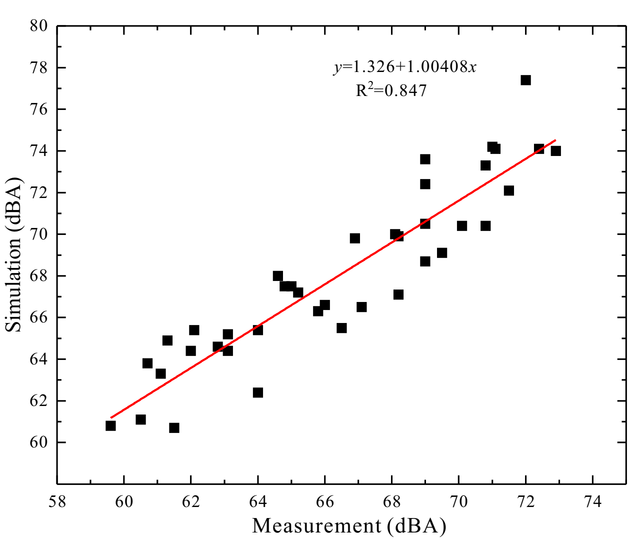


**Figure 10:** Correlation analysis between the measurement and simulation results.

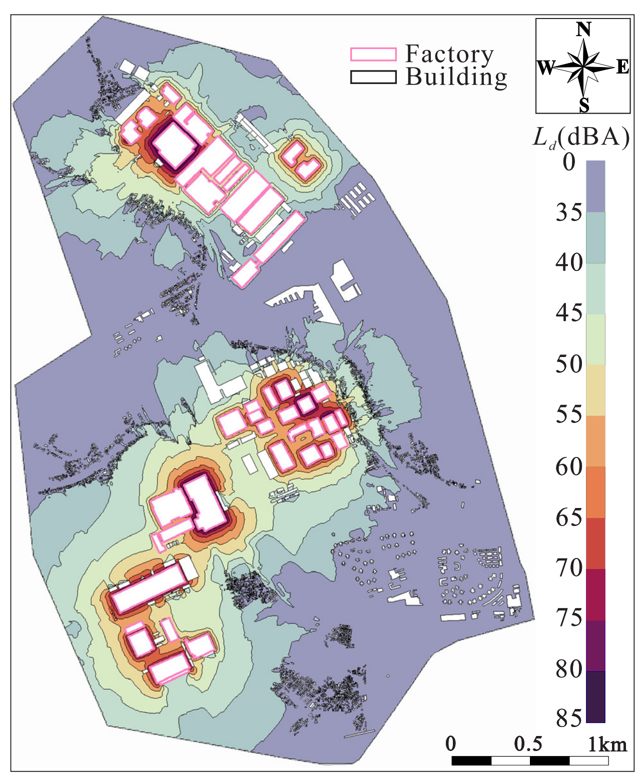


**Figure 11:** Day industrial noise map.

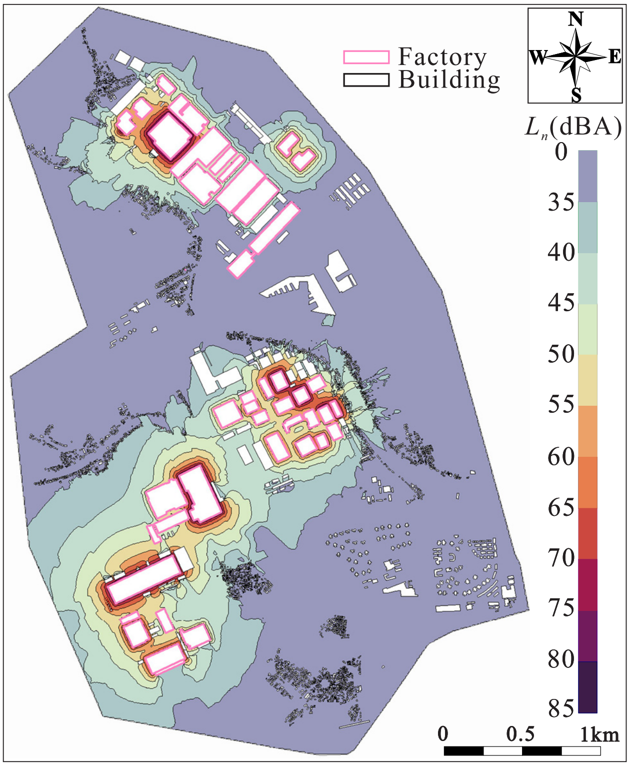


Figure 12: Night industrial noise map.

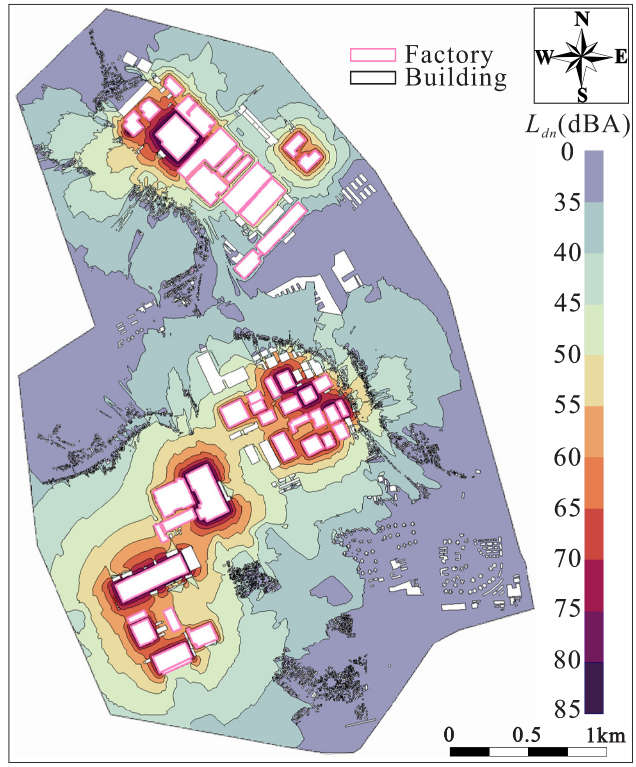


Figure 13: Day–night industrial noise map.

nighttime for industrial noise level higher than 40 dBA. At the same time, some residential buildings are exposed to noise levels of 62–76 dBA during day–night, which is unacceptable based on the standard of HUD. It was found that these residential buildings are distributed in some areas of Zhansha Village and all staff dormitories as shown in Figure 14(c). By comparing Figure 14(b) and (c), it can be seen that the residential areas affected by industrial noise during day–night are significantly lesser than those at nighttime. Therefore, this reflects that the sound environment quality at nighttime is not as good as that during day–night.

## 3.3 Population under different noise levels

This study evaluates the population that exposed to different noise levels based on day, night, and day–night noise maps as shown in Table 4. The results show that 523 people and 1,357 people are exposed to noise levels (noise limits) of $L_d$ > 55 dBA and $L_n$ > 45 dBA during daytime and nighttime, respectively, accounting for 1.08 and 2.81% of the total population in the study area. The population that is suffered with industrial noise is higher during nighttime due to the fact that most factories (37/40) in Panyu Automobile City are still engaged in production activities at nighttime and the noise limit during nighttime is much tighter ($L_n$ < 45 dBA, Table A6). Based on the classification of HUD on day–night noise quality, the noise level within the range of 62 dBA < $L_{dn}$ < 76 dBA is classified as normally unacceptable, which also reflects that 357 people are staying in the area with severe noise pollution.

Figure 15 shows the proportion of population under different noise levels during daytime and nighttime. The results indicate that the population in Panyu Automobile City is mainly living under the noise level of 45 dBA < $L_{eq}$ < 50 dBA during both daytime and nighttime. In addition, the proportions of population in noise levels ranging from 45 dBA to more than 65 dBA during nighttime are slightly lower than that during daytime.

## 3.4 Low-frequency industrial noise map

Recently, low-frequency noise has been classified as an environmental problem by the World Health Organization [46]. However, compared to high-frequency noise, there are lesser researches done on the impact of low-frequency noise on health. Some studies had shown that low-frequency noise could cause health problems such as sleep disorders [47] and headaches [48]. Therefore, this study uses dBC-dBA


**Figure 14:** Residential areas that affected by industrial noise. (a) Daytime, (b) nighttime, and (c) day–night.

and 15 dB as the indicator and threshold [29,49,50], respectively, to evaluate the low-frequency noise in Panyu Automobile City. If the difference between dBC-dBA at a certain location is greater than 15 dB ($L_{c-a}$ > 15 dB), the particular location is considered to be exposed to the risk of low-frequency noise.

The results for daytime and nighttime are shown in Figures 16 and 17, respectively. The results indicate that the

**Table 4:** Population under different noise levels

| Time period | $L_{eq}$ (dBA) | Population |
|---|---|---|
| Day-time | $L_d > 45$ | 2,415 |
| | $L_d > 50$ | 1,118 |
| | $L_d > 55$ | 523 |
| | $L_d > 60$ | 238 |
| | $L_d > 65$ | 93 |
| Night-time | $L_n > 45$ | 1,357 |
| | $L_n > 50$ | 748 |
| | $L_n > 55$ | 378 |
| | $L_n > 60$ | 173 |
| | $L_n > 65$ | 79 |
| Day-night | $L_{dn} < 49$ | 46,140 |
| | $49 < L_{dn} < 62$ | 1,752 |
| | $62 < L_{dn} < 76$ | 357 |
| | $L_{dn} > 76$ | 0 |

areas affected by low-frequency noise during daytime and nighttime are distributed far away from industrial production areas and are mainly distributed in some areas of Shanhai Liancheng Community (orange marked area in Figures 16 and 17). However, unlike the daytime situation, the areas affected by low-frequency noise at nighttime are also distributed in some areas of Zhilian Automobile Town, and Jiaotang Village (red and purple marked areas in Figure 17, respectively). In addition, $L_{c-a}$ values in some areas are distributed within the range of 14–15 dB. These areas are also far from industrial production areas and are also distributed in some areas of Shanhai Liancheng Community, Zhilian Automobile Town, and Jiaotang Village (see all grey marked areas in Figures 16 and 17). The proportion

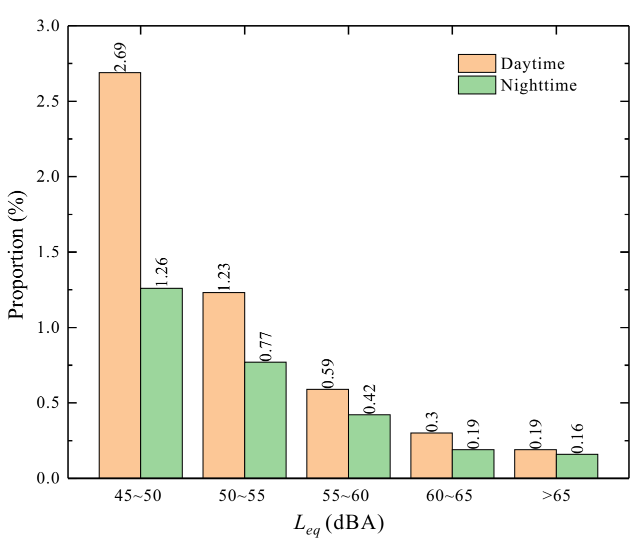


**Figure 15:** Proportion of the population under different noise levels during daytime and nighttime.

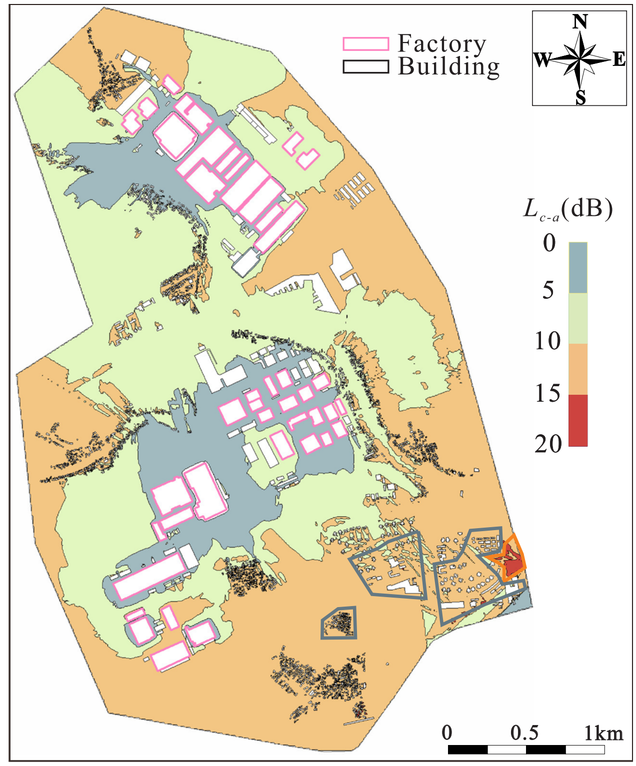


**Figure 16:** Day low-frequency industrial noise map.

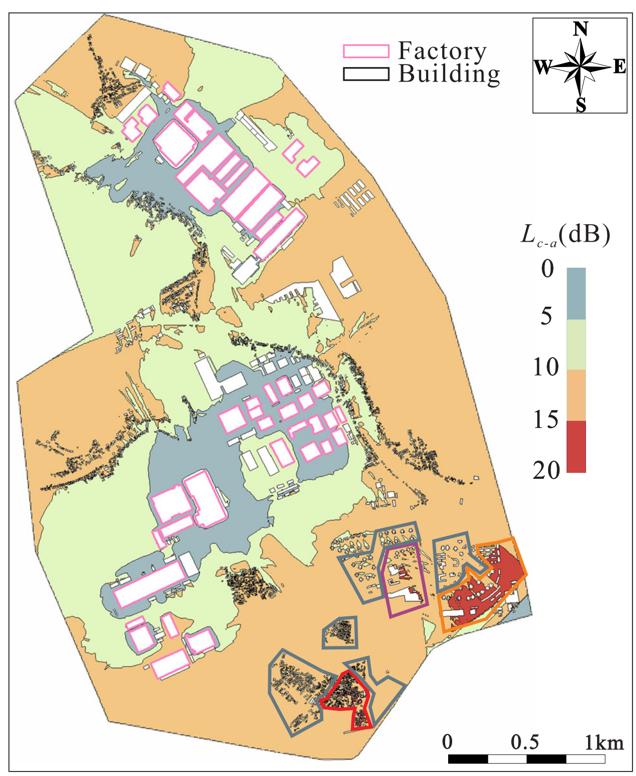


**Figure 17:** Night low-frequency industrial noise map.

of the low-frequency industrial noise is shown in Figure A1 in the Appendix. It is found that 0.25 and 1.36% of the areas are exposed to low-frequency noise level greater than 15dB during daytime and nighttime, respectively.

## 4 Conclusions

The traditional construction method of industrial noise map often consumes high costs in term of manpower and time as it requires obtaining data from relevant departments of government and factories. To overcome the shortcoming of the traditional method, this study obtained the types and quantities of equipment in each factory through environmental impact assessment reports. Thereafter, the noise levels of each equipment were summarizes through open-source data, thus eliminating the need to obtain data from factory managers, greatly improves the efficiency in obtaining factory equipment information. Finally, with the combination with on-site observation, measurement, and numerical modelling, the industrial noise map of Panyu Automobile City was constructed at different time periods. The average error between the measurement and the simulation results at all measurement points was 1.9 dBA, which is lower than the errors of other similar studies. Therefore, the noise map of this study can accurately reflect the actual industrial noise level in the study area.

The industrial noise maps indicated significant differences in the noise pollution level in Panyu Automobile City at different time periods. Therefore, this study evaluated the exposed population under different noise levels. The results showed that during daytime and nighttime, 1.08 and 2.81% of the populations were exposed to excessive noise levels (over the noise limits of national standard), respectively. It can be seen that the industrial noise pollution level at nighttime is more severe than during daytime because the noise limit at nighttime is much stricter than that during daytime. In addition, noise maps with $L_{c-a}$ were constructed for both day and night, to investigate the impact of low-frequency noise on Panyu Automobile City. The results showed that low-frequency noise had little impact on the city. For future work, this study will adopt effective noise reduction measures based on the pollution level of Panyu Automobile City to reduce the impact of industrial noise on the residential areas.

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# Appendix

**Table A1:** Factory information

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| 1 | Rubber plant [51] | Open mill | 3 | 24 h |
| | | Internal mixer | 2 | |
| | | Rubber filter machine | 1 | |
| | | Chiller | 1 | |
| | | Extruder | 14 | |
| | | Cutting machine | 48 | |
| | | Foaming machine | 4 | |
| | | Perforating machine | 4 | |
| | | Sealing strip flocking | 3 | |
| | | Compressor | 3 | |
| | | Injection molding machine | 17 | |
| 2 | Seat manufacturing [52] | Forming machine | 2 | 8:00–24:00 |
| | | Dryer | 2 | |
| | | Chiller | 2 | |
| | | Riveting machine | 1 | |
| | | Spot welding machine | 6 | |
| | | Welding robots | 14 | |
| | | Spot welding robot | 3 | |
| | | Laser welding machine | 2 | |
| | | Axial flow fan | 2 | |
| | | Glue spraying cabinet | 1 | |
| | | Compressor | 3 | |
| 3 | Interior manufacturing [53] | Foaming machine | 3 | 8:00–24:00 |
| | | Foaming machine | 2 | |
| | | Punching machine | 6 | |
| | | Cutting machine | 1 | |
| | | Thermoforming machine | 1 | |
| | | Glue spray machine | 2 | |
| | | Ultrasonic welder | 25 | |
| | | Friction welding machine | 2 | |
| | | Injection molding machine | 5 | |
| | | Flame treatment machine | 1 | |
| | | Compressor | 2 | |
| | | Generator | 1 | |
| 4 | Engine manufacturing [54] | CNC | 109 | 8:00–24:00 |
| | | Ultrasonic washer | 12 | |
| | | Press-fitting machine | 16 | |
| | | Tightening machine | 15 | |
| | | Lathe | 4 | |
| | | Grinding machine | 10 | |
| | | Glue coating machine | 6 | |
| | | Chiller | 1 | |
| | | Buffing machine | 1 | |
| | | Engine heat test bench | 4 | |
| 5 | Press shop [55] | Mechanical press | 40 | 8:00–24:00 |
| | | Rectifier welding machine | 1 | |
| | | Pedestal grinder | 1 | |
| | | Research and matching press | 2 | |
| | | Bench drill machine | 1 | |
| | | Mold cleaning machine | 1 | |
| | | Forklift | 6 | |
| 6 | Welding shop [55] | Spot welding machine | 53 | 8:00–24:00 |

*(Continued)*

**Table A1:** *Continued*

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| | | Spot welding Robot | 189 | |
| | | $CO_2$ arc welding machine | 14 | |
| | | Crop shear | 28 | |
| | | Stud welding machine | 9 | |
| | | Riveting robot | 69 | |
| | | Glue dispensing robot | 11 | |
| | | Roller hemming robot | 9 | |
| | | Robotic stud welding | 7 | |
| 7 | Welding shop [55] | Spot welding machine | 14 | 8:00–24:00 |
| | | Spot welding robot | 23 | |
| | | $CO_2$ arc welding machine | 4 | |
| | | Crop shear | 7 | |
| | | Stud welding machine | 2 | |
| | | Air hoist | 7 | |
| | | Riveting robot | 18 | |
| | | Glue dispensing robot | 3 | |
| | | Roller hemming robot | 2 | |
| | | Robotic stud welding | 2 | |
| 8 | Welding shop [55] | Spot welding machine | 12 | 8:00–24:00 |
| | | Spot welding robot | 20 | |
| | | $CO_2$ arc welding machine | 3 | |
| | | Crop shear | 6 | |
| | | Stud welding machine | 2 | |
| | | Air hoist | 6 | |
| | | Riveting robot | 15 | |
| | | Glue dispensing robot | 2 | |
| | | Roller hemming robot | 2 | |
| | | Robotic stud welding | 2 | |
| 9 | Assembly shop [55] | Car interior line | 1 | 8:00–24:00 |
| | | Car chassis line | 1 | |
| | | Car exterior assembly line | 1 | |
| | | Instrument assembly line | 1 | |
| | | Powertrain production area | 1 | |
| | | Door subassembly | 1 | |
| | | Test line | 1 | |
| 10 | Welding shop [55] | Spot welding machine | 40 | 8:00–24:00 |
| | | Spot welding robot | 67 | |
| | | $CO_2$ arc welding machine | 11 | |
| | | Crop shear | 21 | |
| | | Stud welding machine | 7 | |
| | | Air hoist | 19 | |
| | | Riveting robot | 52 | |
| | | Glue dispensing robot | 8 | |
| | | Roller hemming robot | 7 | |
| | | Robotic stud welding | 5 | |
| 11 | Paint shop [55] | Kiln | 4 | 8:00–24:00 |
| | | The wax room | 1 | |
| | | Painting robot | 4 | |
| | | Spraying robot | 4 | |
| 12 | Battery testing [55] | Charge and discharge tester | 8 | 8:00–24:00 |
| | | Transfer robot | 2 | |
| 13 | Metal products [56] | Uncoiler | 2 | 8:00–24:00 |
| | | Crop shear | 2 | |
| | | Welding machine | 1 | |
| | | Compressor | 3 | |

*(Continued)*

**Table A1:** *Continued*

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| | | Water pump | 2 | |
| | | Bridge crane | 3 | |
| 14 | | Axial flow fan | 6 | |
| | | Skin pass mill | 1 | |
| | | Roll coater | 1 | |
| | | Stretching straightener | 1 | |
| | | Coiler | 2 | |
| | | Furnace anneal | 1 | |
| 15 | Parts manufacturing [57] | Injection molding machine | 9 | 8:00–24:00 |
| | | Crusher | 3 | |
| | | Buffing machine | 3 | |
| | | Heating furnace | 1 | |
| | | Kiln | 2 | |
| | | Painting robot | 12 | |
| 16 | Parts manufacturing [58] | Mechanical press | 20 | 24 h |
| | | Spot welding machine | 22 | |
| | | Leveling machine | 2 | |
| | | Oil press | 16 | |
| | | Cutting machine | 5 | |
| | | Bending machine | 2 | |
| | | Bench drill machine | 6 | |
| | | Chiller | 4 | |
| | | Double head saws | 9 | |
| | | Welding robots | 13 | |
| 17 | Interior decoration [53] | Foaming machine | 2 | 8:00–17:20 |
| | | Injection molding machine | 5 | |
| | | Punching machine | 9 | |
| | | Ultrasonic welder | 25 | |
| | | Flame treatment machine | 1 | |
| | | Foaming machine | 3 | |
| | | Friction welding machine | 2 | |
| | | Cutting machine | 1 | |
| | | Compressor | 3 | |
| | | Oil press | 1 | |
| | | Cooler | 1 | |
| | | Nitrogen generator | 1 | |
| | | Generator | 1 | |
| 18 | Parts manufacturing [59] | Mechanical press | 48 | 8:00–24:00 |
| | | Compressor | 3 | |
| | | Hydraulic press | 6 | |
| | | Hydraulic pipe bender | 4 | |
| | | Lathe | 21 | |
| | | Shearing machine | 4 | |
| | | Automatic pipe cutting machine | 4 | |
| | | Double head multi boring machine | 4 | |
| | | Welding robots | 26 | |
| | | Spot welding machine | 10 | |
| | | $CO_2$ arc welding machine | 41 | |
| | | TIG welding | 2 | |
| | | Buffing machine | 2 | |
| 19 | Metal components [60] | 3D laser cutting machine | 3 | 8:00–24:00 |
| | | CNC | 1 | |
| | | OTC robotic arm | 10 | |
| | | Compressor | 3 | |
| | | Cutting machine | 1 | |

*(Continued)*

**Table A1:** *Continued*

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| | | Oil press | 1 | |
| | | Cooler | 1 | |
| | | Nitrogen generator | 1 | |
| | | Heating furnace | 1 | |
| 20 | Parts manufacturing [61] | Forming machine | 2 | 24 h |
| | | Dryer | 2 | |
| | | Chiller | 2 | |
| | | Riveting machine | 1 | |
| | | Spot welding machine | 6 | |
| | | Welding robots | 14 | |
| | | Spot welding robot | 3 | |
| | | Laser welding machine | 2 | |
| | | Axial flow fan | 2 | |
| | | Glue spraying cabinet | 1 | |
| | | Compressor | 3 | |
| 21 | Parts manufacturing [62] | Welding robots | 20 | 8:00–24:00 |
| | | Spot welding robot | 90 | |
| | | Forklift | 8 | |
| | | Mechanical press | 6 | |
| | | Compressor | 3 | |
| | | Bridge crane | 2 | |
| 22 | Mold manufacturing [62] | Lathe | 2 | 8:00–24:00 |
| | | Milling machine | 4 | |
| | | Wire-cutting machine | 2 | |
| | | Electrical discharge machining | 6 | |
| | | CNC | 4 | |
| | | Grinding machine | 2 | |
| 23 | Parts manufacturing [63] | Plate shear | 1 | 8:00–17:20 |
| | | Mechanical press | 19 | |
| | | Bending machine | 1 | |
| | | Welding robots | 20 | |
| | | Spot welding machine | 6 | |
| | | Compressor | 1 | |
| 24 | Recycling processing [64] | Roller machine | 10 | 8:30–17:15 18:00–24:00 |
| | | Mechanical press | 4 | |
| 25 | | Packaging machine | 2 | |
| | | Bridge crane | 2 | |
| | | Forklift | 3 | |
| 26 | Steel processing [65] | Uncoiler | 1 | 8:00–24:00 |
| | | Plate shear | 1 | |
| | | Ultrasonic washer | 1 | |
| | | Leveling machine | 1 | |
| | | Forklift | 2 | |
| | | Bridge crane | 10 | |
| 27 | Steel processing [65] | Plate shear | 1 | 8:00–24:00 |
| | | Panel turnover machine | 1 | |
| | | Axial flow fan | 30 | |
| | | Compressor | 4 | |
| | | Generator | 1 | |
| | | Cold sawing machine | 2 | |
| | | Temper mill | 2 | |
| | | Straightening machine | 2 | |
| | | Leveling machine | 2 | |
| | | Coiler | 2 | |
| | | Packaging machine | 1 | |

*(Continued)*

**Table A1:** *Continued*

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| | | Uncoiler | 2 | |
| | | Roller machine | 2 | |
| 28 | Recycling processing [64] | Roller machine | 10 | 8:00–24:00 |
| | | Mechanical press | 4 | |
| | | Packaging machine | 2 | |
| | | Bridge crane | 2 | |
| | | Forklift | 3 | |
| 29 | Mold manufacturing [66] | Lathe | 3 | 8:00–24:00 |
| | | Milling machine | 6 | |
| | | Wire-cutting machine | 3 | |
| | | Electrical discharge machining | 9 | |
| | | CNC | 6 | |
| | | Grinding machine | 3 | |
| | | Driller | 3 | |
| 30 | Press shop [66] | Mechanical press | 11 | 8:00–24:00 |
| | | CNC | 8 | |
| 31 | Welding shop [66] | Stud welding machine | 30 | 8:00–24:00 |
| | | $CO_2$ arc welding machine | 52 | |
| | | Spot welding machine | 195 | |
| | | Welding robots | 398 | |
| 32 | Press shop [55] | Mechanical press | 40 | 8:00–24:00 |
| | | Rectifier welding machine | 1 | |
| | | Pedestal grinder | 1 | |
| | | Research and matching press | 2 | |
| | | Bench drill machine | 1 | |
| | | Mold cleaning machine | 1 | |
| | | Forklift | 6 | |
| 33 | Welding shop [55] | Spot welding machine | 118 | 8:00–24:00 |
| | | Spot welding robot | 199 | |
| | | $CO_2$ arc welding machine | 32 | |
| | | Crop shear | 62 | |
| | | Stud welding machine | 21 | |
| | | Air hoist | 57 | |
| | | Riveting robot | 154 | |
| | | Glue dispensing robot | 24 | |
| | | Roller hemming robot | 20 | |
| | | Robotic stud welding | 16 | |
| 34 | Paint shop [55] | Kiln | 4 | 8:00–24:00 |
| | | The wax room | 1 | |
| | | Painting robot | 4 | |
| | | Spraying robot | 4 | |
| 35 | Battery manufacturing [67] | Coating machine | 8 | 24 h |
| | | Roller machine | 8 | |
| | | Laser welding machine | 52 | |
| | | Assembly machine | 8 | |
| | | Industrial inkjet printer | 8 | |
| | | Compressor | 4 | |
| | | Nitrogen generator | 4 | |
| | | Refrigerating machine | 3 | |
| 36 | Semiconductor [68] | Ring cutting machine | 2 | 8:00–24:00 |
| | | Dicing machine | 4 | |
| | | Automatic welding machine | 2 | |
| | | Automatic bonding machine | 20 | |
| | | Automatic module mounting machine | 2 | |
| | | Automated assembly machine | 2 | |

*(Continued)*

**Table A1:** *Continued*

| Factory number | Factory type | Equipment | Number of equipment | Working time |
|---|---|---|---|---|
| | | Automatic packaging machine | 2 | |
| | | Compressor | 2 | |
| | | Chiller | 3 | |
| 37 | Interior manufacturing [69] | Painting robot | 12 | 8:00–24:00 |
| | | Punching machine | 33 | |
| | | Welding machine | 20 | |
| | | Injection molding machine | 4 | |
| | | Crusher | 1 | |
| | | Compressor | 4 | |
| | | Chiller | 3 | |
| 38 | Parts manufacturing [70] | Rotor assembly line | 5 | 8:00–24:00 |
| | | Stator assembly line | 5 | |
| | | Motor assembly line | 5 | |
| | | Gearbox assembly line | 5 | |
| | | Final assembly line | 5 | |
| | | Compressor | 5 | |
| 39 | Gearbox manufacturing [71] | CNC | 127 | 8:00–24:00 |
| | | Lathe | 19 | |
| | | Grinding machine | 19 | |
| | | Dryer | 58 | |
| | | Hydraulic press | 37 | |
| | | Compressor | 62 | |
| | | Ultrasonic washer | 35 | |
| | | Refrigerating machine | 1 | |
| | | Tightening machine | 40 | |
| 40 | Engine manufacturing [54] | CNC | 218 | 8:00–24:00 |
| | | Ultrasonic washer | 24 | |
| | | Press-fitting machine | 31 | |
| | | Tightening machine | 29 | |
| | | Lathe | 7 | |
| | | Grinding machine | 19 | |
| | | Glue coating machine | 11 | |
| | | Chiller | 2 | |
| | | Buffing machine | 1 | |
| | | Engine heat test bench | 8 | |

**Table A2:** The mean room absorption coefficient of each factory [30,31]

| Factory number | Mean room absorption coefficient | Factory number | Mean room absorption coefficient |
|---|---|---|---|
| 1 | 0.5 | 21 | 0.35 |
| 2 | 0.5 | 22 | 0.35 |
| 3 | 0.35 | 23 | 0.35 |
| 4 | 0.35 | 24 | 0.35 |
| 5 | 0.35 | 25 | 0.35 |
| 6 | 0.35 | 26 | 0.35 |
| 7 | 0.35 | 27 | 0.35 |
| 8 | 0.35 | 28 | 0.35 |
| 9 | 0.35 | 29 | 0.35 |
| 10 | 0.35 | 30 | 0.35 |
| 11 | 0.35 | 31 | 0.35 |
| 12 | 0.5 | 32 | 0.35 |
| 13 | 0.35 | 33 | 0.35 |
| 14 | 0.35 | 34 | 0.35 |
| 15 | 0.35 | 35 | 0.35 |
| 16 | 0.35 | 36 | 0.35 |
| 17 | 0.35 | 37 | 0.35 |
| 18 | 0.35 | 38 | 0.35 |
| 19 | 0.35 | 39 | 0.35 |
| 20 | 0.35 | 40 | 0.35 |

**Table A3:** Noise level (dBA) of equipment in 1/1 octave band

| Equipment | 63 Hz | 125 Hz | 250 Hz | 500 Hz | 1,000 Hz | 2,000 Hz | 4,000 Hz | 8,000 Hz |
|---|---|---|---|---|---|---|---|---|
| Open mill [72] | 82 | 91 | 96 | 95 | 92 | 80 | 75 | 66 |
| Mechanical press [73] | 95 | 99 | 105 | 107 | 110 | 117 | 115 | 110 |
| Internal mixer [72] | 84 | 87 | 88 | 91 | 90 | 81 | 72 | 62 |
| Chiller [74] | 80 | 86 | 88 | 92 | 86 | 80 | 74 | 62 |
| Extruder [72] | 92 | 93 | 94 | 91 | 92 | 88 | 83 | 78 |
| Cutting machine [75] | 72.1 | 71.4 | 72.0 | 70.9 | 68.8 | 68.4 | 68.5 | 66.9 |
| Axial flow fan [76] | 86 | 77 | 87 | 95 | 98 | 98 | 92 | 86 |
| Compressor [77] | 106.5 | 112 | 108 | 90 | 86 | 81 | 80.5 | 72.5 |
| Lathe [78] | 71.9 | 67.4 | 70.9 | 78 | 85.2 | 83.4 | 72.4 | 64 |
| Grinding machine [79] | 85 | 88 | 90 | 100 | 87 | 80 | 85 | 80 |
| Press-fitting machine [80] | 85.4 | 84.9 | 85.8 | 85.9 | 85.6 | 85.4 | 86.2 | 86.1 |
| CNC [81] | 60 | 68 | 78 | 78 | 85 | 81 | 78 | 75 |
| Bridge crane [82] | 75 | 80 | 95 | 110 | 92 | 115 | 108 | 80 |
| Glue pump [83] | 60 | 61 | 63 | 63 | 66 | 63 | 59 | 56 |
| buffing machine [75] | 78.7 | 77.4 | 77.0 | 77.5 | 81.4 | 79.2 | 76.9 | 75.1 |
| Kiln [84] | 93 | 94 | 96 | 99 | 93 | 92 | 94 | 83 |
| Finishing machine [85] | 62.2 | 70.5 | 73.5 | 78.9 | 83.2 | 85.5 | 90.5 | 88.6 |
| Milling machine [86] | 93 | 94 | 96 | 99 | 93 | 92 | 94 | 83 |
| Drille [87] | 93 | 94 | 96 | 99 | 93 | 92 | 94 | 83 |
| Cold sawing machine [88] | 80 | 83 | 94 | 104 | 110 | 106 | 100 | 91 |
| Refrigerating machine [89] | 71 | 75 | 75 | 80 | 86 | 94 | 100 | 95 |
| Crusher [90] | 65 | 68 | 69 | 111 | 118 | 99 | 90 | 78 |
| Water pump [83] | 88 | 89 | 91 | 91 | 94 | 91 | 87 | 81 |
| Generator [91] | 90 | 91 | 91 | 91 | 89 | 87 | 84 | 79 |

**Table A4:** Sound power level of equipment

| Equipment | PWL (dBA) | Equipment | PWL (dBA) |
|---|---|---|---|
| Roll forming machine | 96 [72] | Research and matching press | 90 [55] |
| Perforating machine | 80 [92] | Radial drilling machine | 86 [93] |
| Sealing strip flocking machine | 80 [94] | Mold cleaning machine | 106 [95] |
| Injection molding machine | 84 [96] | Forklift | 93 [97] |
| Dryer | 85.5 [98] | $CO_2$ arc welding machine | 81 [99] |
| Riveting machine | 90 [100] | Stud welding machine | 85 [101] |
| Spot welding machine | 89.9 [102] | Air hoist | 96 [103] |
| Welding robots | 80 [104] | Riveting robot | 80 [105] |
| Spot welding robot | 91 [101] | Glue dispensing robot | 80 [105] |
| Laser welding machine | 101.2 [106] | Roller hemming robot | 78 [107] |
| Glue spraying cabinet | 99.8 [108] | Robotic stud welding | 70 [109] |
| Foaming machine | 80 [110] | Car interior line | 71 [111] |
| Punching machine | 80 [112] | Car chassis line | 81 [111] |
| Thermoforming machine | 86 [113] | Car exterior assembly line | 81 [111] |
| Glue spray machine | 91 [114] | Instrument subassembly line | 81 [111] |
| Ultrasonic welder | 75 [99] | Powertrain production area | 81 [111] |
| Friction welding machine | 86 [115] | Door subassembly | 81 [111] |
| Flame treatment machine | 80 [115] | Test line | 71 [111] |
| Ultrasonic washer | 98 [116] | Spray booth | 85 [117] |
| Glue coating machine | 88 [118] | Spraying robot | 75 [119] |
| Engine heat test bench | 97.5 [54] | Painting robot | 85 [115] |
| Roller machine | 101 [64] | Charge and discharge tester | 70 [120] |
| Rectifier welding machines | 87 [121] | Transfer robot | 80 [122] |
| Pedestal grinder | 91 [123] | Uncoiler | 90 [124] |
| Crop Shear | 90.5 [98] | Nitrogen generator | 84 [60] |
| Welding machine | 82.7 [98] | Wire-cutting machines | 91 [125] |
| Roll coater | 85 [126] | Electrical discharge machining | 86 [125] |
| Stretching straightener | 102.7 [106] | Plate shear | 84 [121] |
| Coiler | 81.8 [127] | Packaging machine | 91 [65] |
| Furnace anneal | 81.7 [128] | Panel turnover machine | 80 [129] |
| Tightening machine | 80 [130] | Temper mill | 90.2 [127] |
| Heating furnace | 75 [60] | Straightening machine | 88 [131] |
| Leveling machine | 80 [132] | Coating machine | 93 [133] |
| Oil press | 90 [60] | Assembly machine | 70 [134] |
| Cutting machine | 79.7 [135] | Industrial inkjet printer | 75 [136] |
| Bending machine | 94 [137] | Ring cutting machine | 85 [138] |
| Bench drill machine | 85 [139] | Dicing machine | 88 [140] |
| Double head saws | 85 [59] | Automatic welding machine | 86 [68] |
| Welding robot | 70 [141] | Automatic bonding machine | 81 [68] |
| Hydraulic press | 100.9 [142] | Automatic module mounting machine | 76 [68] |
| Hydraulic pipe bender | 81 [59] | Automated assembly machine | 81 [68] |
| Shearing machine | 107 [143] | Automatic packaging machine | 81 [68] |
| Automatic pipe cutting machine | 83 [121] | Rotor assembly line | 70 [70] |
| Double head multi boring machine | 91 [59] | Stator assembly line | 70 [70] |
| TIG welding | 88.6 [59] | Motor assembly Line | 70 [70] |
| 3D laser cutting machine | 81 [60] | Gearbox assembly line | 70 [70] |
| OTC robotic arm | 96 [60] | Final assembly line | 70 [70] |
| Cooler | 88 [60] | Rubber filter machine | 80 [144] |

**Table A5:** $R_w$ of colour steel plate [145]

| Frequency (Hz) | 63 | 125 | 250 | 500 | 1,000 | 2,000 | 4,000 |
|---|---|---|---|---|---|---|---|
| $R_w$ (dBA) | 10 | 13 | 15 | 14 | 17 | 21 | 24 |

**Table A6:** Environmental noise limit [25]

| Functional area | Coverage | Noise limit | |
|---|---|---|---|
| | | Daytime (dBA) | Night (dBA) |
| Category 1 | Residential, nature reserve, school, administrative, hospital | 55 | 45 |
| Category 2 | Commercial, market | 60 | 50 |
| Category 3 | Warehousing, industry | 65 | 55 |
| Category 4a | Areas on both side of traffic artery | 70 | 55 |
| Category 4b | | 70 | 60 |

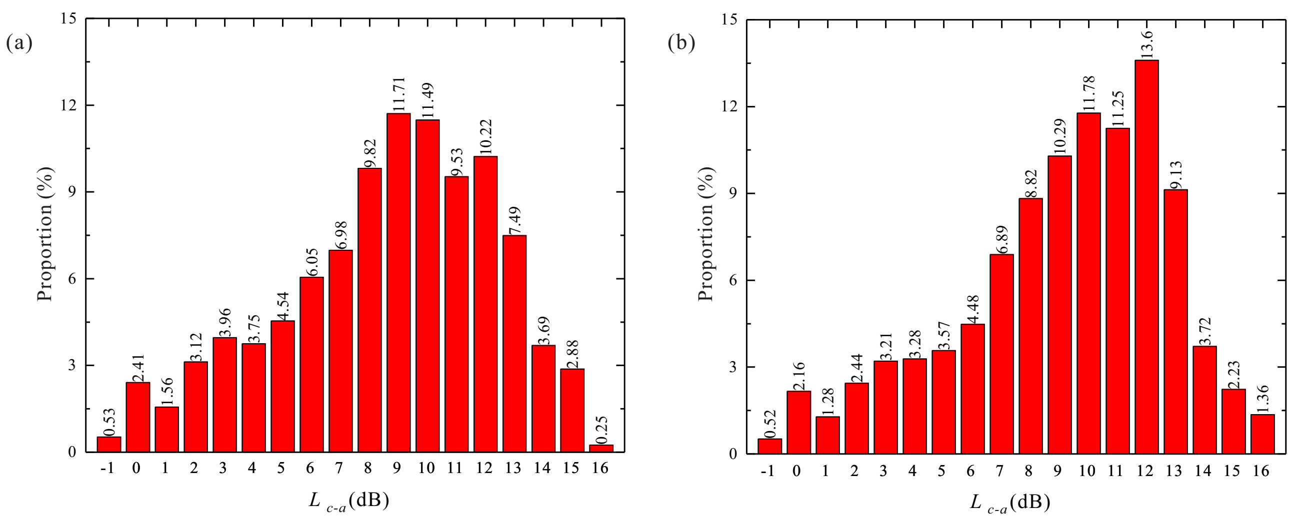


**Figure A1:** Proportion of the low-frequency industrial noise during (a) daytime and (b) nighttime.