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-Applied Acoustics-

Global sensitivity analysis for road traffic noise modelling

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ABSTRACT

Regulatory road traffic noise maps are based on input data that are sometimes incomplete, erroneous or non-existent. When designing them, it is therefore necessary to label and qualify these data by giving priority to certain sources of information and certain parameters over others. Beforehand, a sensitivity analysis of the sound prediction model to these input parameters should be carried out to concentrate efforts on the most influential inputs (either physical or configurational parameters). In this paper, an overall sensitivity analysis of the CNOSSOS-EU model is proposed using the Morris screening method. It is conducted using the open source software Noise Modelling, on a case study of a French city. The analysis is performed on 15 of its input parameters at 14343 receivers. The selection of the parameters and their ranges of variation were chosen to mimic those faced by an operator when producing monthly noise maps. Whether or not to consider diffraction at the horizontal edges appears to be the most influential parameter when estimating the number of people exposed to sound levels above 65 dB(A). However, a finer analysis by receiver shows how the influence of each parameter strongly depends on the source-receiver configuration.

Keywords: Noise mapping, Sensitivity analysis, Morris Method, Open-Source

1 INTRODUCTION

Strong relationships between noise levels and both annoyance and health effects are established [1]. Most people exposed to excessively high noise levels live in cities where road traffic is known to be the main sound contribution, hence the need to accurately quantify urban road traffic noise. The standardized methodology consists in a road traffic and geometric data collection, which feeds noise emission and propagation models to generate noise maps at different space scales, typically for cities or larger urban areas. These noise maps, based on aggregated long-term indicators, give access to noise exposure levels once crossed with the residential occupation [2].

The interest in relying on a standardized methodology is to enable the comparison of exposure levels of different cities, or the evolution over time of exposure levels of a given city. Thus the CNOSSOS-EU model was proposed to participate in this harmonization of calculation methods [3]. However, despite recommendations, some choices are left to the user in the modeling configurations (*i.e.* in the choice of physical and configurational parameters), which may possibly lead to uncertainty in the calculated exposure levels. Also, some physical parameters are sometimes difficult to obtain, uncertain or non-existent, requiring calculation assumptions that may influence

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41 the accuracy of the calculated sound exposure levels.

42 It is thus essential to be able to identify the most influential inputs (among all physical and
43 configurational parameters) to prioritize them in the data collection and modelling process. For road
44 traffic, noise emission models rely on inputs such as the mean flow rates and mean speeds per road
45 segment, along with the traffic composition (ratio of medium, heavy or two-wheels vehicles). The
46 sound propagation model determines for each pair emission point / receiver the attenuation based on
47 atmospheric inputs such as the temperature, humidity or wind conditions, geometrical configuration
48 such as the buildings location and their absorption coefficients, but also configurational parameters
49 such as the number of reflections or whether or not the horizontal and vertical diffractions are
50 considered in the calculation.

51 In order to add/associate uncertainty information to the results provided by the strategic noise
52 maps, one solution to test the relative importance of all these parameters while overcoming the high
53 computational costs is to analytically solve the noise model equations [4], [5]. However, these
54 methods can be difficult or even impossible in the case of a strongly non-linear model or with the
55 presence of discrete factors such as CNOSSOS-type models. It is also possible to study the
56 sensitivity by calculating the mapping for a large number of possible scenarios chosen by an
57 operator [6] or to test the impact of producing the same noise map by different research groups [7].
58 Nevertheless, these methods induce a high cost to prepare the scenarios and to calculate them which
59 limits the scope of the sensitivity analyses thus performed.

60 Statistical approaches dedicated to sensitivity studies are also used to understand the behavior of
61 model outputs against their input parameters. Numerous statistical and probabilistic tools exist, such
62 as regression, smoothing, statistical learning, etc. [8]. Monte Carlo screening, which consists of
63 doing a large number of calculations with random parameters, was used by [9]–[11]. Shilton et al.
64 carried out a series of error propagation and sensitivity tests on the XPS 31-133 and CRTN
65 (Calculation of Road Traffic Noise) models using two forms of analysis: a series of Monte Carlo
66 simulations were used to investigate error propagation in the non-geometric aspects of the methods,
67 as well as sensitivity tests based on a spatial noise model called *crisp* for geometrical aspects [12].
68 This work is part of the UK Department of Environment Food & Rural Affairs (DEFRA) research
69 project “Research Project NANR 93: WG-AEN's Good Practice Guide and The Implications for
70 Acoustic Accuracy”², which led to the publication of a guide (Annexes 4 and 5 on uncertainties)
71 [13], [14]. This guide has for example been applied to the city of Buenos Aires in 2019 [15].

72 Despite the interest of the studies cited above, results are dependent on the case study. A
73 parameter that is influential in one setting is not necessarily important in another and some receivers
74 or groups of receivers may be more sensitive to some parameters than others. This means that for
75 each new case study, the methodology may be replicated to determine the sensitivity of the model to
76 its input parameters. Unfortunately, the software often used for noise mapping do not have the
77 flexibility to perform all these necessary calculations, which hinders a wider use of sensitivity and
78 uncertainty studies for the estimation of urban road traffic noise.

79 In this study, a methodology for sensitivity analysis built on an open-source modeling framework,
80 is proposed. The sensitivity analysis follows the Morris method, which is a known method to
81 quickly converge to information on the sensitivity of the model to a set of input parameters [8]. The
82 sensitivity analysis presented is performed using the open source software Noise Modelling 3.0³
83 [16]. An open source framework offers high reproducibility of methods and results. The large
84 number of calculations required is made possible by recent development of the software, which
85 dissociates the different phases of the calculation that are known to be very different in calculation
86 time, namely the emission, pathfinding and propagation steps. The sensitivity of the model is
87 studied through the sound level values calculated at each of the receivers on the map as well as on
88 the percentage of the population exposed to a sound level higher than 65 dB(A).

89 Section 2 presents the sensitivity analysis method, called the Morris method, as well as the study
90 area and the tools that were used and developed for conducting this analysis. Section 3 presents the
91 results for the studied urban area. The influence of the input parameters on the ratio of the

² Available at <http://tiny.cc/nanr93>

³ <http://noise-planet.org/noisemodelling.html>

92 population exposed to *Lden* values that exceed 65 dB is first presented. Then the average influence
93 of each variable or parameter on the sound level at receivers is analyzed. Finally, receivers with a
94 similar sensitivity to the model input parameters are grouped and a spatial analysis is carried out.
95 The results are discussed in Section 4, and conclusions are drawn in Section 5.

96 2 METHOD

97 2.1 Morris Method

98 The Morris method is widely used for global sensitivity analysis, since it is adapted to models
99 with quantitative inputs (i.e. physical or configurational parameters) and outputs [17]. It is part of
100 the OAT (One At a Time) methods, meaning that the process of exploring the definition domain
101 makes the inputs vary one at a time. It can be considered as a statistical analysis of empirical
102 estimates of changes in the output of the model with respect to each parameter. In the case of a time-
103 consuming model, or a model with many inputs, the method is a simple way to make a first selection
104 among the inputs according to their influence on the outputs. Enough repetitions are still required to
105 ensure confidence in the results obtained and consequently to allow a reliable sensitivity analysis.

106 The principle of the Morris method is as follows (adapted from [18]). The method begins by
107 sampling a set of initial values within the defined range of possible values for all inputs, and next by
108 calculating the subsequent model outcome. The second step modifies the value for one parameter
109 (all other inputs remaining at their initial values) and calculates the resulting change in model
110 outcome compared to the first run, called elementary effect. Next, the value of another parameter is
111 changed (the previous variable is kept at its first-step value and all other ones remain at their initial
112 values) and the resulting change in model outcome compared to the second run is calculated. This
113 process goes on until all inputs have been changed once. This procedure is repeated r times, each
114 time with a different set of initial values, which leads to a number of $r(k + 1)$ runs, where k is the
115 number of inputs. Such number of runs is very efficient compared to more demanding methods for
116 sensitivity analysis, such as exhaustive research among each range values, Monte Carlo, etc.

117 For the sensitivity analysis presented in this paper, the total procedure is repeated 50 times
118 ($r=50$) for a group of 15 inputs ($k=15$), resulting in 800 simulations. To ensure that the space of
119 exploration does not favor any area, 500 trajectories are drawn and only the fifty trajectories that
120 maximize exploration are retained (in terms of Euclidean distance), as described in [19].

121 The Morris method allows to access to three indicators:

- 122 - μ is the arithmetic mean of the effect associated with the k -th parameter. In case of an
123 independent linear dependency, μ is the change in the output when the k -th parameter
124 changes by one step (as defined by its range of variation in Table 1);
- 125 - μ^* is the mean of the absolute effect associated with the k -th parameter. It is similar to μ but
126 it is the average of the absolute differences caused by a change in the k -th parameter. This
127 value is interesting to avoid cancelation effects in the average (as it can be the case for a non-
128 monotonic function);
- 129 - σ is the standard deviation of the effect associated with the k -th parameter. It tells how much
130 the effect of the k -th parameter changes with the value of this k -th parameter and the values
131 of the other inputs. It gives an indication of the presence of nonlinearities or interactions
132 between the k -th parameter and other inputs.

133 Classically, the results of the sensitivity analysis performed with the Morris method are
134 presented on a two-dimensional graph: The x-axis shows the absolute mean of the elementary
135 effects μ^* for each parameter and the y-axis shows the standard deviation σ . On one hand, if the
136 ratio σ/μ^* is close to 0.1, the effects of the parameter are considered linear and between 0.1 and 0.5
137 the effects are probably monotonic. On the other hand, if the ratio is close to or greater than 1, the
138 effects are strongly non-linear or non-monotonic.

139 2.2 Noise Computation method

140 For this study, the sensitivity analysis is performed on the CNOSSOS-EU noise emission and
141 propagation model for road traffic. This model was proposed as a contribution to the harmonization
142 of European calculation methods and is now mandatory for use by the Member States [3]. This

143 model can be divided into two independent parts. The first part concerns the modelling of the noise
144 emission of each road section. The second part models the propagation of the sound wave between
145 each road section and the receivers. To assess the population exposed to sound levels that exceed a
146 given threshold, the method also gives recommendations for positioning receivers around buildings
147 in the study area which is described in Section 2.6. The reader can refer to the documentation
148 related to the method for in-depth interpretation of the presented results [3].

149 A background noise of 35 dB(A) is added at each receiver to the calculated sound levels, to
150 mimic urban background noise. This value has been set to ensure that realistic noise levels exist for
151 all receivers regardless of the parameters (even if reflections and diffractions are not considered).
152 Even if a receiver is reached by no sound path, this background noise value will be applied. Thus,
153 the sensitivity analysis can be performed on all receivers. This value of 35 dB(A) is discussed in
154 Section 4.

155 **2.3 Noise Computation software**

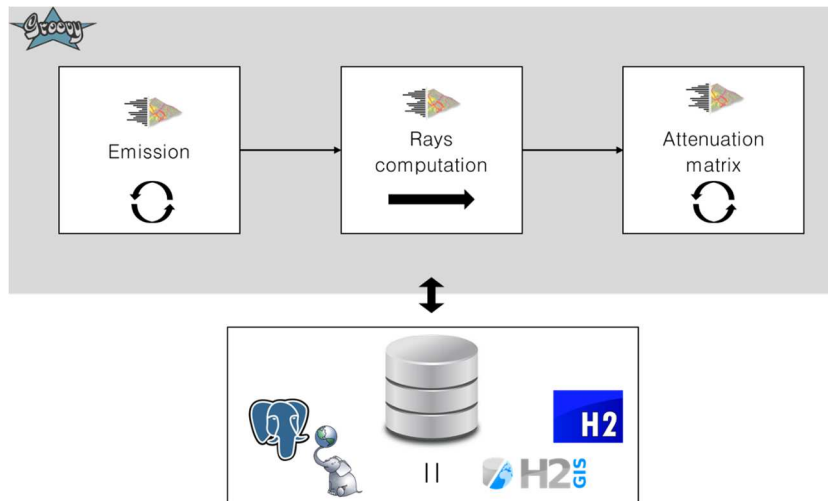
156 Noise Modelling is a free and open-source software designed to produce environmental noise
157 maps on wide urban area and more generally on large-scale outdoor spaces. It can be used as a Java
158 library or be controlled through a web interface [16]. The CNOSSOS-EU model is implemented for
159 the estimation of road traffic emissions, as well as for the calculation of its attenuation along
160 propagation paths. Noise Modelling allows information to be stored at three levels: the noise sources
161 and their sound levels, the geometry of the propagation paths and finally the transfer matrix for each
162 of the source/receiver pairs. This choice was made because the computation time of such a software
163 is essentially concentrated into the pathfinding algorithm. The calculation costs of the CNOSSOS
164 model for emission and for propagation are considerably lower once the geometry is known and the
165 paths are calculated. To launch many replications of the model, the idea is then to store the
166 geometry of every paths. Then it is possible to recalculate several possible emission levels for the
167 sound sources, and several possible attenuations for the source/receiver couples, according to the
168 varying parameters. We can also calculate all possible paths between sources and receivers and then
169 adapt the attenuation for each of the paths depending of input parameters. For example, if we do not
170 want to consider the reflected paths, we associate an infinite attenuation to them. A path that would
171 change geometry by a change in the study area, such as the height of buildings for example, cannot
172 be considered by our methodology.

173 Figure 1 presents the technical framework behind the global sensitivity analysis using Noise
174 Modelling: a groovy script allows to manage interaction between Noise Modelling libraries and a
175 spatial database (PostGIS⁴ or H2GIS⁵). From a configuration file containing the values on the input
176 varying parameters, many simulations are performed. Paths and results are stored in dedicated
177 compressed folders. All the framework is open-source and available on github⁶ to ensure the
178 research is reproducible and adaptable to other case studies.

⁴ www.postgis.net

⁵ www.h2gis.org

⁶ <https://github.com/Ifsttar/NoiseModelling>



179

180 Figure 1 – Sensitivity analysis framework using NoiseModelling. The NoiseModelling JAVA libraries

181 directly interact with Postgre/PostGIS or H2/H2Gis databases.

182 2.4 Study parameters

183 More than 40 input parameters (either physical or configurational) can be identified when
 184 calculating a noise map using CNOSSOS-EU [4]. Only some of them are prone to generate
 185 significant uncertainty in the output depending on the period of the map considered (hourly, daily,
 186 monthly, etc.), the study area, the receiver’s locations, etc. For this sensitivity analysis, we study the
 187 case for which an operator wants to know the sensitivity of the CNOSSOS model outputs when
 188 making monthly day-evening-night maps of road traffic noise. The proposed sensitivity analysis
 189 focuses on 15 input parameters, among which 4 concern the model configuration and 9 are related to
 190 physical inputs. The ranges of variation on the physical inputs were defined using information on
 191 their monthly range of variation over one year for the studied area and the uncertainty around each
 192 input parameter. Parameters such as “proportion of studded tires” or “average speed” were for
 193 instance not including in the analysis, respectively because they are not appropriate to this case
 194 study (studded tires are not used in this area), or because of their known poor influence on
 195 calculated sound levels (the monthly variation in the average speed of traffic is negligible).

196 Table 1 shows the chosen parameters, their related topic reference codes, steps, and ranges
 197 values of variation. Road-related input parameters are considered to vary homogeneously between
 198 three categories of roads depending on their flow rate. For example, if the vehicle flow rate
 199 increases by 10% for medium axes, this is the case for all road segments of the road network, which
 200 have a flow rate included in [300;1000] vehicles per hour. Also, we have chosen a range of variation
 201 between 0 and 1 order of reflection even if reflection 0 is not in agreement with the CNOSSOS-EU
 202 method. However, the cost of the calculation would have increased significantly for higher orders of
 203 reflection. We considered that this cost was too high for results dependent on our case study. A
 204 study applied to the annual standardized noise mapping should, for example, prefer higher orders.
 205 Vertical diffraction has been included as a parameter, although it is not required for road noise maps
 206 according to CNOSSOS-EU. More generally, all ranges of variation and parameters chosen are
 207 specific to this study and should be adapted to any other case study. Above all, our aim is to propose
 208 a methodology that can be replicated, including long-distance sound propagation for peri-urban
 209 applications for example.

210 Table 1 – Sensitivity analysis parameters, related topic reference codes, ranges of variation and step types
 211 (multiplicative * or additive +).

Parameter	Code	Variation	Step	Parameter	Code	Variation	Step
Total Vehicle Flow Rate on major axes (>1000 veh./hour)	Q _{maj}	[0.7;1.3]	0.2 (*)	Buildings absorption coefficient	wallAlpha	[0.5;1.5]	0.33 (*)
Total Vehicle Flow	Q _{med}	[0.7;1.3]	0.2 (*)	Temperature	Temp	[6;18]	4 (+)

Rate on medium axes (300-1000 veh./hour)				(°C)			
Total Vehicle Flow Rate on small axes (<300 veh./hour)	Q _{sma}	[0.7;1.3]	0.2 (*)	Humidity (%)	Hum	[20;80]	20(+)
Heavy Vehicle Ratio	HV	[0.5;1.5]	0.33 (*)	Order of Reflection	Refl	[0;1]	1 (+)
Medium Vehicle Ratio	MV	[2;8]	2 (+)	Horizontal diffraction	Dif_hor	[true/false]	-
2 Wheels Vehicle Ratio	WV	[2.7;3.3]	0.2 (+)	Vertical diffraction	Dif_ver	[true/false]	-
Favorable meteorological conditions	MeteoFav	[0.7;1.3]	0.2 (*)	Maximum Propagation Distance (m)	DistProp	[300;750]	150(+)
Wind direction (°)	WindDir	[-60;60]	30 (+)				

212

213 2.5 Model outputs

214 As an output of the analysis, sensitivity to the model's input parameters is observed on 3
215 indicators:

- 216 - The sound pressure level for day/evening/night periods (L_{den}) at each receiver, expressed in
217 dB(A). The L_{den} value is computed as defined in [20]. The traffic flow rate are annual average
218 daily flows for the three-corresponding periods (day, evening and night);
- 219 - The L_{den} value averaged over all receivers on the whole area of the noise map;
- 220 - The population ratio exposed to a L_{den} value that exceeds 65 dB(A) on the same area/map;

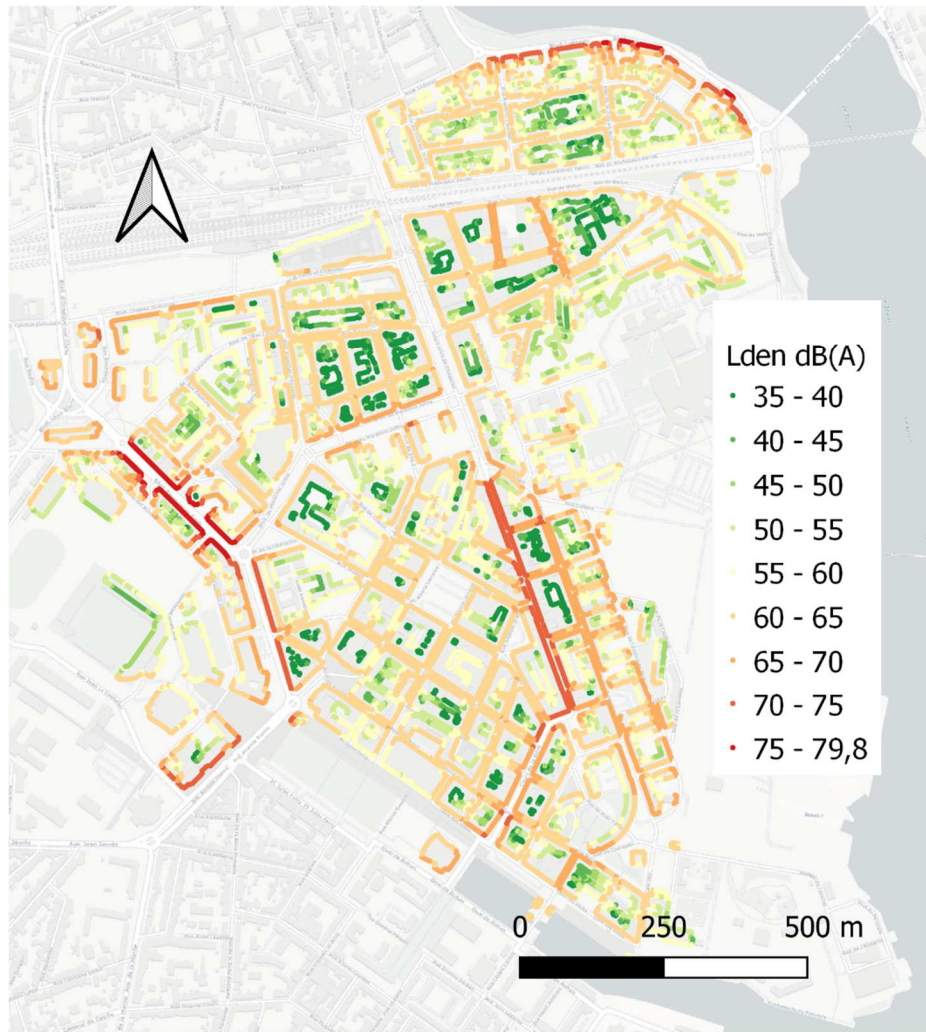
221 The result of the analysis therefore includes 3 sensitivity parameters (μ , μ^* and σ), for each of
222 the 15 input parameters, and on 3 observed outputs.

223 2.6 Study Area

224 The sensitivity analysis presented in this article is part of the CENSE project (Characterization of
225 urban sound environments using a comprehensive approach combining open data, measurements and
226 modeling), which includes a noise mapping case study based on both modelling and sensors
227 deployment, in the city of Lorient, France⁷ [21], [22]. As shown in Figure 2, it covers an area of
228 about 2 km², in which 14343 receivers (around 1772 buildings of which 1204 are occupied) were
229 selected to serve as a support for this sensitivity analysis. The influent input parameters (*e.g.* built-
230 up characteristics, ground topology, road traffic data, ground characteristics, etc.) are a compilation
231 of data collected from CEREMA, IGN and the city council. Figure 2 shows an example of results
232 through the median L_{den} value of the 800 simulations in dB(A) representing 9672 inhabitants.
233 Approximately 24% of them are exposed to road traffic L_{den} values above 65 dB(A).

7

<http://cense.ifsttar.fr/en>



234

235 Figure 2 – Study area of the analysis. 14343 receivers are represented on the map. The color represents the
 236 median L_{den} value at each receiver over the 800 simulations.

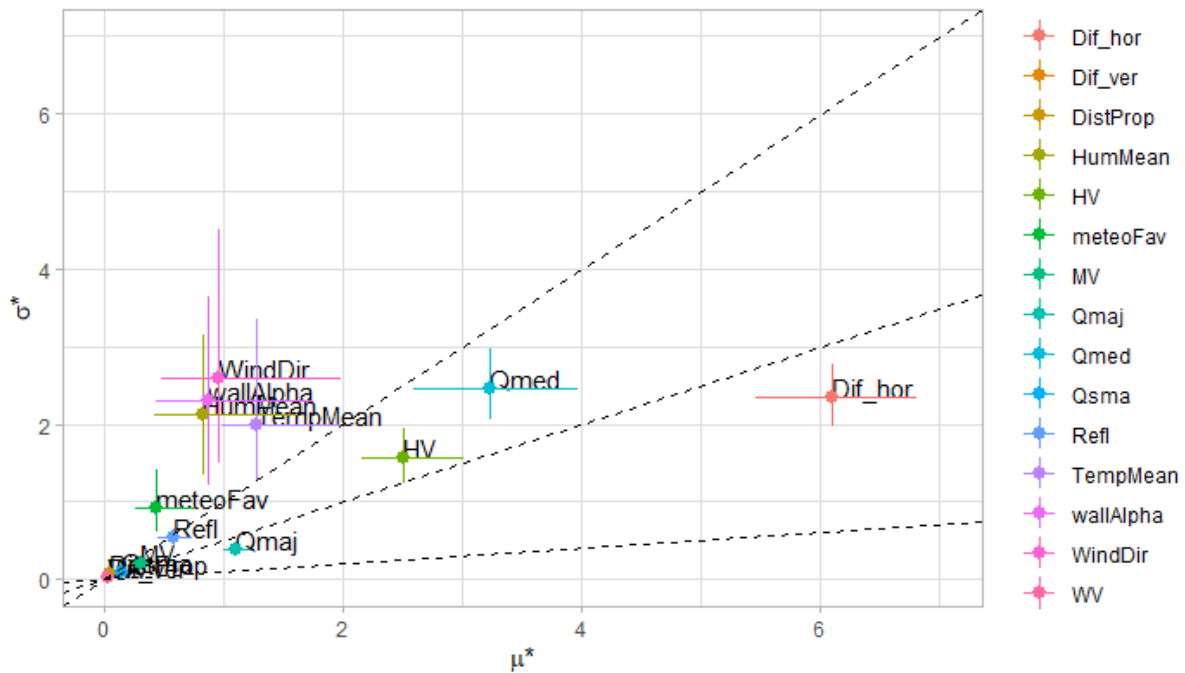
237 **3 RESULTS**

238 **3.1 Software performance**

239 During this study, 35 million of paths had to be stored, which represents a compressed file size
 240 of 19.8 GB. The computation time on a latest-generation desktop computer with SSD (solid-state
 241 drive) to calculate and store all the paths was 8 hours and 49 minutes. An additional computation
 242 time of 8 hours and a half was necessary to carry out the 800 simulations once the paths were stored.
 243 This computation time is short enough to consider an additional number of simulations, but $r = 50$
 244 was sufficient to cover enough of the exploration space of the set of parameters (see Section 2.1).

245 **3.2 Sensitivity analysis regarding the population ratio exposed to more than 65 dB(A)**

246 Figure 3 shows the results of the sensitivity analysis regarding the ratio of inhabitants exposed to
 247 L_{den} values of more than 65 dB(A) for the 15 varying input parameters of the model (Table 1). The
 248 x-axis represents the μ^* values, which is the mean of the absolute effect. So the figure reads as this:
 249 a μ^* of 1% means that 1% of more or 1% less of the population is exposed to a level of more than
 250 65 dB(A), compared to the reference value of 24%, that is 23% or 25% (not 1% of 24%, what would
 251 mean 23.76% or 24.24%). The bars around each pair (μ^*, σ) represent 66% of the variability over the
 252 50 trajectories. Also, parameters cannot be sorted exactly based on their μ^* value, which
 253 corresponds to a step in the variation scheme, as all parameters have not the same number of steps
 254 of variation.



255
 256 Figure 3 – Sensitivity of the ratio of inhabitants exposed to more than 65 dB(A) for the 15 input parameters.
 257 The dashed lines represent the σ/μ^* values equal to 0.1, 0.5 and 1.
 258

259 Figure 3 shows that parameters likely to impact the ratio of inhabitants exposed to levels above
 260 65 dB(A) are especially those influencing the calculation for receivers at levels close to 65 dB(A).
 261 Hence the low importance, for example, of a parameter such as the mean flowrate at small-axis,
 262 which impacts receivers subject to levels much lower than 65 dB(A). As a result, the most
 263 influential parameters/variables in this study are the horizontal diffraction (*Dif_hor*), the vehicles
 264 flow rate on medium axes (*Q_med*) and the ratio of heavy vehicles (*HV*).

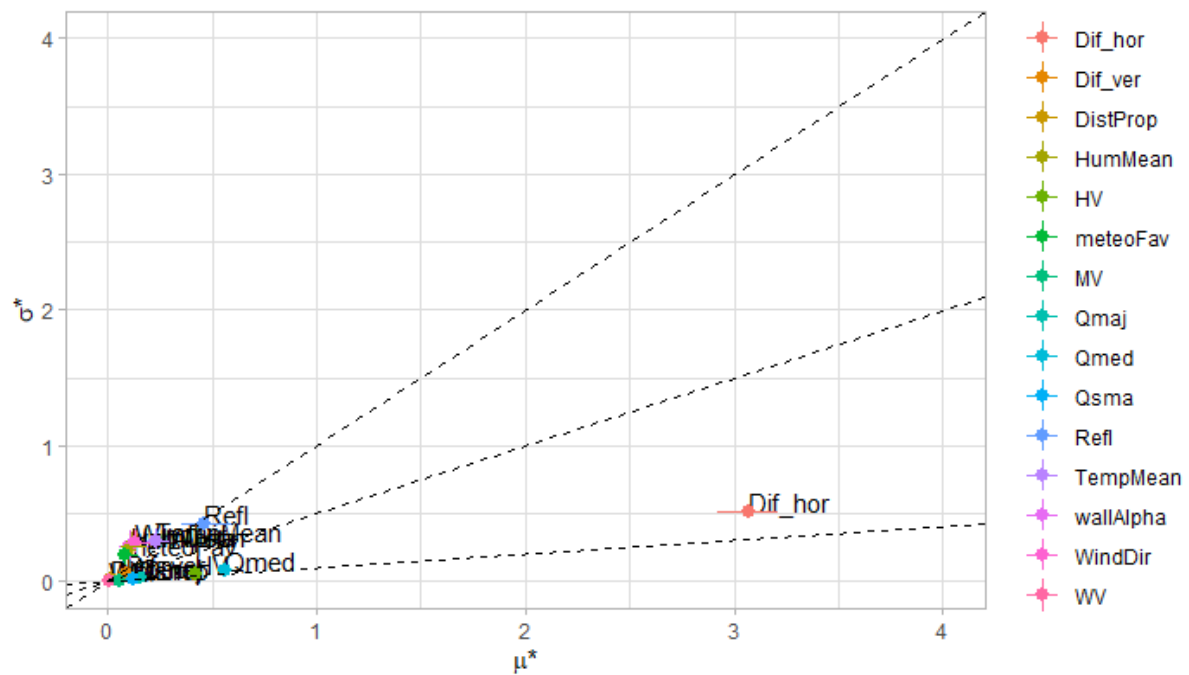
265 *Q_med* and *HV* are two parameters that influence the calculation of noise emissions, which are
 266 therefore particularly influential on noise levels around 65 dB(A) often observed at the edge of the
 267 roads, with short propagation distances. A variation of 20% in *Q_med* leads on average to a variation
 268 of 3.2% in the ratio of inhabitants exposed to levels above 65 dB(A). A variation of 30% in the ratio
 269 of heavy vehicles leads on average to a variation of 2.5 % in the ratio of inhabitants exposed to
 270 levels above 65 dB(A). *Q_med* and *HV* have a monotonic behavior, as tells the σ/μ^* values. Finally,
 271 the μ value reveals that the exposed population increases with these two parameters ($\mu = \mu^*$). In the
 272 appendix A, the values of μ , μ^* and σ are presented for each of the parameters.

273 The influence of introducing or not the horizontal diffraction in the calculation is also very high,
 274 reaching 6.1% of the affected population. This physically means that 6.1% of the receivers have a
 275 level that rises above 65 dB(A) if horizontal diffraction is included in the calculation. In addition,
 276 the low σ/μ^* value ($\sigma/\mu^* = 0.39$) tells that this is relatively independent of the other parameter
 277 values. The spatial analysis proposed in section 3.4.1 will help to understand which the receivers are
 278 concerned.

279 Finally, one distinguishes a group of four parameters with μ^* values around 1 dB(A) but high
 280 σ/μ^* values, namely the mean humidity ($\sigma/\mu^* = 2.56$) and temperature ($\sigma/\mu^* = 1.57$), the wind
 281 direction and ($\sigma/\mu^* = 2.74$) the α_{wall} ($\sigma/\mu^* = 2.64$). The influence of these parameters is directly
 282 driven by the other parameter values.

283 3.3 Sensitivity analysis regarding the mean L_{den} value

284 Figure 4 shows the results of the sensitivity analysis for the mean L_{den} values on all the receivers
 285 of the whole studied area (cf Figure 2), and for the 15 varying input parameters/variables of the
 286 model.



287

288 Figure 4 – Sensitivity of the mean L_{den} for the 15 input parameters. The dashed lines represent the σ/μ^*
 289 values equal to 0.1, 0.5 and 1.
 290

291 The most influential parameter in terms of the mean L_{den} value is by far the horizontal diffraction,
 292 which leads to a variation of 3 dB(A) of the mean L_{den} value in this study. This is explained by the
 293 fact that certain receivers which are not in “direct” field with the sound sources (“line of sight” thus
 294 which cannot be linked via the side of the buildings, as receivers inside courtyard) are not reached
 295 by any propagation path if diffraction is not taken into account. Thus, the sound level at these
 296 receivers jumps from the background noise level of 35 dB(A) to a sound level that can be potentially
 297 high. This concerns a limited number of receivers but makes the mean of the absolute effect jump to
 298 a high value.

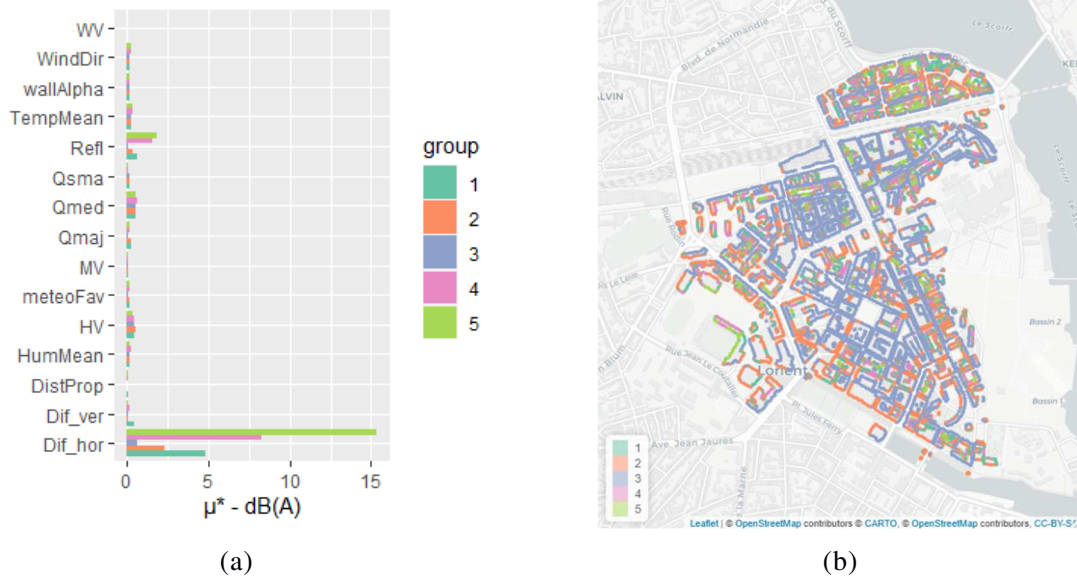
299 Any of the other parameters have a μ^* value inferior to 0.5 dB(A), even though their effect at
 300 some receivers can be high. A spatial analysis is presented in section 3.4 to illustrate this point.

301 3.4 Sensitivity analysis regarding the sound level by receivers

302 3.4.1 Sensitivity analysis on all the parameters

303

304 The previous analysis suggests that the sensitivity behavior to input parameters is not
 305 homogeneous over the receivers. Thus, a hierarchical descending classification was made on all
 306 receivers based on their Euclidean distance of the absolute mean of the elementary effects μ^*
 307 for each of the 15 parameters. The classification is done using the Ward algorithm [23] thanks to the
 308 function *hclust* of the package *R, stats v3.6.2*. Five main groups could be extracted from the analysis
 309 and are presented in Figure 5.



310 Figure 5 – Groups of receivers with similar sensitivity (following μ^* indicator) to varying input
 311 parameters. (a) the average μ^* value for each parameter and each receivers group. (b) The receiver’s
 312 location and their group membership.

313
 314 Figure 5 (a) confirms the high variations in L_{den} values according to the horizontal diffraction, to
 315 such an extent that this parameter concentrates most of the behavior of the receivers. The five
 316 categories summarize five types of receivers impacted to a greater or lesser extent by this only
 317 parameter. Group 3 corresponds to receivers in direct view with the sound source (i.e. in “line of
 318 sight”). It is the largest group with 53 % of the total number of receivers, which are barely impacted
 319 by horizontal diffractions. A comparison with Figure 1 shows that the other groups are mainly
 320 defined by their average sound level. Considering a background sound level of 35 dB(A), the
 321 receivers, once reached by the diffracted path, whose sound level increases to 50 dB(A) will be in
 322 category 5, then 40 dB(A) in category 4, and so on.

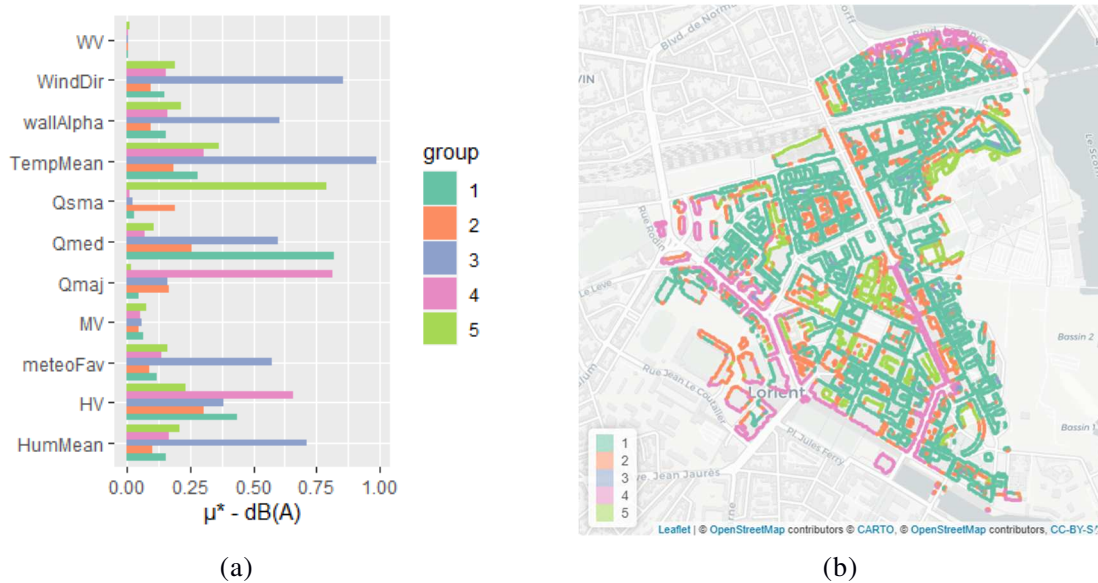
323 Figure 5 (b) shows that receivers located in building yards are highly affected by parameters such
 324 as diffraction variable. Again, this can be explained by the very high errors made when the number
 325 of paths in the simulation reaching certain isolated points, such as building yards, falls drastically
 326 when diffractions or reflections are not allowed in the simulation. It is even possible that for some
 327 simulations no paths reach the receiver. For these receivers, the variation on these propagation
 328 parameters (diffraction, reflection) can therefore induce very large variations on the observed sound
 329 levels. Also, increasing the range of variation of the reflection order to 3 or 4 would have certainly
 330 highlighted the impact of this specific parameter on this group of receivers. It is likely that if
 331 indicators of the type "number of persons exposed to less than 40 dB(A)" were considered, these
 332 indicators would be very sensitive to these calculation parameters, underlying the difficulty to
 333 characterize sound levels within quiet sides.

334 Although instructive, the distinction between these groups based on the μ^* is not very
 335 meaningful. In addition, this classification gives much weight to the groups 1, 4 and 5, which
 336 represent all together only 25% of the receivers, hiding the relative influence of other parameters,
 337 which potentially concern a higher number of receivers. To conclude, as the values at some
 338 receivers are very sensitive to configuration parameters (such as diffraction or reflection),
 339 depending to the output he is regarding, the operator can choose to set them at their maximum value
 340 regardless the increase in calculation times that this may induce. The uncertainty on the physical
 341 parameters would however remain.

343 3.4.2 Sensitivity analysis on physical parameters only

344
 345 In this section, a hierarchical descending classification is made on all receivers, based on the 9

346 parameters out of the 15 previously studied once the model configurational parameters are excluded.
 347 Five main groups could be extracted from the analysis and are presented in Figure 6.



348 Figure 6 – Groups of receivers with similar sensitivity (following μ^* indicator) to varying input physical
 349 parameters, without model configuration parameters. (a) the average μ^* value for each parameter and each
 350 receivers group. (b) The receiver’s location and their group membership.
 351

352 The five groups of receivers can be detailed as following:

- 353 • Group 1: 59.5 % of the receivers are mainly sensitive to the traffic flow on medium axes.
 354 Their location is close to these axes. The ratio of heavy vehicles is also influent at these
 355 receivers. The receivers mainly correspond to L_{den} values of about 65 dB(A) (see Figure
 356 1), hence confirming their impact on the ratio of inhabitants exposed to more than 65
 357 dB(A);
- 358 • Group 2: This is a mixed group that represents 18.4 % of the receivers. They are not very
 359 sensitive to a specific parameter, even if they show a relatively high contribution of flow
 360 rates parameters.
- 361 • Group 3: 1.6 % of the receivers are distinguished by their sensitivity to propagation-
 362 related parameters such as humidity, wind direction, etc. These receivers are those that
 363 are not in direct view of the roads (“line of sight”) and are the furthest away from traffic
 364 sound source. In this case, these parameters can have an impact on the propagation paths.
 365 Even if in this case study one may conclude on the poor sensitivity of calculations to
 366 these parameters, they could appear more important if one wanted to focus on low sound
 367 levels, with thresholds around 40 dB(A);
- 368 • Group 4: 11.5 % of the receivers are sensitive to the traffic flow on major axes. Their
 369 location is close to these axes. As the major roads are also those with the highest number
 370 of heavy vehicles, they are the most sensitive to the heavy vehicle ratio. These receivers
 371 correspond to locations with high sound levels of more than 65 dB(A), as depicted in
 372 Figure 1;
- 373 • Group 5: 8.9 % of the receivers are sensitive to the traffic flow on small axes. Their
 374 location is close to these axes and away from major axes.

375 To conclude, the most important parameters in this case study are those related to the road traffic
 376 flow on the sections close to the receivers. For each group and on average, the L_{den} variations stay
 377 lower than 1 dB(A) when an input parameter varies by one step. Concerning receivers mainly
 378 impacted by vehicle flow rates (groups 1, 4 and 5), this result directly echoes to the usual

379 logarithmic calculation: an increase of 20% in the flow rate corresponding to a sound level increase
380 of $10 * \log_{10}(1.2) = 0.8$ dB(A).

381 **4 DISCUSSION**

382 The choice of input parameters (either physical or configurational) and ranges of variation of
383 their respective values is partly made on study area considerations and sometimes on arbitrary
384 choices which can be subject to discussion. Since sensitivity analysis is partly dependent on choice
385 and ranges of variation of those parameters, conclusions may differ.

386 The choice of background value can be questioned and may potentially influence some of the
387 conclusions of the analysis. It did not seem necessary to introduce more complex background
388 models as proposed in [24], but the operator who would like to reproduce the method could possibly
389 benefit from this choice.

390 One of the limitations of the proposed methodology is also the inability to incorporate changes in
391 geometry (*e.g.* building height). The pathfinding algorithm must be re-executed, which would
392 significantly increase the cost of the method by integrating such variation parameters.

393 More generally, all results presented are highly dependent on the selected site, which can be
394 summarized, in our case, as monthly traffic noise maps of L_{den} in a European city downtown.
395 Despite of this, since the whole framework of this study is based on open-source tools and available
396 to the acoustic community, the present methodology for sensitivity analysis can be easily developed
397 by any operator and adapted/applied to his own city/case study. For example, it would also be
398 interesting to analyze the sensitivity of standardized annual noise mapping to the quality of data
399 sources and the impact of using default data when data are missing.

400 Finally, as any model and software, CNOSSOS-EU and NoiseModelling have their own
401 limitations and approximations, thus the present study, as a sensitivity analysis based on those
402 models/tools, partially represents these models/tools.

403 **5 CONCLUSION**

404 A global sensitivity analysis of the CNOSSOS model concerning fifteen of its varying input
405 parameters is presented in this paper. The chosen case study is the production of monthly traffic
406 noise maps of L_{den} in a city downtown. The screening technique is based on Morris' method and
407 simulations were performed with the NoiseModelling v3.0 software.

408 The sensitivity analysis to the input parameters of the CNOSSOS model highly depends on the
409 location of the receivers. The most influential parameter is whether diffraction over horizontal edges
410 is considered or not, regardless of the observed indicator, namely the average sound level over the
411 area or the ratio of the population exposed to more than 65 dB(A). This can be easily explained by
412 the fact that some receivers may not be reached by a propagation path until this parameter is
413 introduced in the calculation. When model configuration parameters are excluded from the analysis,
414 it can be shown that for most receivers, the most influent parameters are linked with the emission
415 part of the CNOSSOS model, and concern the mean flow rates of the category of the closest road to
416 the receiver.

417 Many of the results presented are highly dependent on the choice of the case study, the
418 parameters chosen and their range of variation, but the experience and the method can easily be
419 replicated thanks to the development of open-source and freely available tools. We therefore
420 encourage practitioners and specialists to use these tools and methods, which are readily available,
421 to deepen their reflections on model uncertainties and propagation errors. For more general
422 conclusions about the influence of parameters on standardized noise mapping, the reader can also
423 refer to the “WG-AEN's Good Practice Guide and The Implications for Acoustic Accuracy”, which
424 fulfils this role in greater depth than our study [13].

425 Thanks to the sensitivity studies carried out by such methods, it becomes possible to select the
426 most influential parameters, in order to carry out a highly superior number of simulations that
427 enable to study the propagation of uncertainty through the acoustic model or to compute Sobol
428 indices.

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- 502

503 **APPENDIX A - Sensitivity analysis regarding the population ratio exposed to**
504 **more than 65 dB(A): μ , μ^* and σ for each of the parameters**

505

506 Table 1 Sensitivity analysis regarding the population ratio exposed to more than 65 dB(A): μ , μ^* and σ for each
 507 of the parameters

μ	μ^*	σ	parameter
-0.01	0.01	0.00	WV
0.01	0.01	0.02	DistProp
-0.06	0.06	0.01	MV
0.03	0.09	0.19	meteoFav
0.09	0.09	0.05	Dif_ver
0.01	0.11	0.25	wallAlpha
0.02	0.11	0.26	HumMean
0.12	0.12	0.02	Q_{sma}
0.03	0.13	0.28	WindDir
0.15	0.15	0.04	Q_{maj}
-0.04	0.23	0.30	TempMean
0.42	0.42	0.05	HV
0.46	0.46	0.43	Refl
0.56	0.56	0.08	Q_{med}
3.07	3.07	0.52	Dif_hor

508

509 **APPENDIX B - 3.3 Sensitivity analysis regarding the mean L_{den} value: μ , μ^* and**
 510 **σ for each of the parameters**

511 Table 2 Sensitivity analysis regarding the mean L_{den} value: μ , μ^* and σ for each of the parameters

μ	μ^*	σ	parameter
-0.02	0.02	0.03	WV
0.03	0.03	0.02	Dif_ver
0.04	0.04	0.08	DistProp
0.14	0.14	0.09	Q_{sma}
-0.31	0.31	0.22	MV
0.17	0.44	0.92	meteoFav
0.58	0.58	0.53	Refl
0.05	0.83	2.12	HumMean
0.38	0.87	2.30	wallAlpha
0.13	0.95	2.59	WindDir
1.10	1.10	0.39	Q_{maj}
-0.14	1.27	1.99	TempMean
2.50	2.50	1.58	HV
3.22	3.22	2.46	Q_{med}
6.09	6.09	2.36	Dif_hor

512