



HAL
open science

Individual-level activity-based modeling and indicators for assessing construction sites noise exposure in urban areas

Pierre Hankach, Valentin Le Bescond, Pascal Gastineau, Pierre-Olivier Vandanjon, Arnaud Can, Pierre Aumond

► To cite this version:

Pierre Hankach, Valentin Le Bescond, Pascal Gastineau, Pierre-Olivier Vandanjon, Arnaud Can, et al.. Individual-level activity-based modeling and indicators for assessing construction sites noise exposure in urban areas. *Sustainable Cities and Society*, 2024, 101, pp.105188. 10.1016/j.scs.2024.105188 . hal-04411562

HAL Id: hal-04411562

<https://hal.science/hal-04411562>

Submitted on 29 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Individual-Level Activity-Based Modeling and Indicators for Assessing Construction Sites Noise Exposure in Urban Areas

Pierre Hankach^{a,d,*}, Valentin Le Bescond^{b,d}, Pascal Gastineau^{b,d},
Pierre-Olivier Vandanjon^{b,d}, Arnaud Can^{c,d} and Pierre Aumond^{c,d}

^a*Univ Gustave Eiffel, MAST-LAMES, F-44344 Bouguenais, France*

^b*Univ Gustave Eiffel, AME-SPLOTT, F-44344 Bouguenais, France*

^c*Univ Gustave Eiffel, UMRAE, F-44344 Bouguenais, France*

^d*Institut de Recherche des Sciences et Techniques de la Ville (IRSTV), F-44321 Nantes, France*

ABSTRACT

Abstract removed from title page

*Corresponding author

✉ pierre.hankach@univ-eiffel.fr, Tel: +33 2 40 84 58 31 (P. Hankach)

ORCID(s):

ABSTRACT

Construction site noise significantly contributes to urban noise pollution. To accurately assess the noise exposure from urban construction sites, it is essential to consider the variability and dynamic nature of the urban context. This paper proposes an innovative approach using individual-level activity-based modeling to tackle the given challenge. The methodology introduced encompasses: the modeling of construction site noise emission sources, individual-level activity-based modeling zones of influence, a modeling chain for assessing individual noise exposure levels, and a novel dedicated exposure indicator. To illustrate the relevance of our methodology, a case study is conducted in Champigny-sur-Marne, France; this study involves the generation of a synthetic population of 1,344,394 individuals distributed among 591,153 households, with 4,854,597 associated activities, using the Eqasim simulation framework. A traffic model is then established using the multi-agent transport simulation software MATSim. NoiseModelling software is employed to compute noise maps both with and without the construction site. Subsequently, the noise exposure for each individual is assessed throughout the day for both configurations. Thanks to this complete modeling chain, the proposed indicator quantifying the cumulative amount of time of exposure above a given threshold can be compute, with the case study result being estimated at more than 3,300 person.quarter-hours above 65 dB(A).

KEYWORDS

urban construction sites; individual noise exposure; activity-based models; synthetic population; noise maps; noise exposure indicators

1. Introduction

Construction site noise is one of the main sources of noise pollution inside urban dwellings (Dervaux et al., 2022). Numerous studies have shown that exposure to noise has detrimental effects on human health and well-being. In addition to general annoyance, serious health problems can arise from such exposure (Jung et al., 2020; Mir et al., 2023). For example, during prolonged exposure, noise can cause sleep disturbance (Pirrera et al., 2010) and cardiovascular disease (Münzel et al., 2014; Wang et al., 2023). Since construction activities carried out in heavily urbanized areas are essential for the development and maintenance of infrastructure and the built environment, mitigating the exposure to construction site noise has become a major concern for project managers and policymakers. The most efficient way to mitigate the noise impacts of construction site operations entails careful site planning, whereby noise reduction goals are explicitly incorporated as a decision variable during the pre-construction stage.

To minimize population exposure to construction site noise through effective construction site planning, it is essential to conduct an adequate and informative assessment of population exposure to such noise during the pre-construction stage. This study aims to develop and demonstrate a novel methodology for assessments of this kind. The goal herein is to provide a reliable assessment framework, capable of facilitating the management of construction operations, while involving sustainability and noise reduction considerations at the planning stage. For example, this assessment must adequately reflect the noise impacts of construction operations, in enabling a comparison between multiple scenarios of operational planning. In addition to a global evaluation of population exposure within the zone of influence, it is sought to evaluate the exposure of different population categories in order to ensure social and environmental justice.

Many challenges arise as part of the process to achieve a reliable and detailed assessment of exposure to construction site noise, that is also suitable for decision-making. For such an assessment protocol, it is imperative to employ a methodology that takes into account the variability of construction site configurations and the site environment. It is in fact impossible to rely on any

preestablished values of typical representations when deriving a reliable assessment (Dervaux et al., 2022). Rather, specific details of each construction site configuration and the population within its zone of influence are to be considered. Therefore, a bottom-up assessment methodology, starting from these specific details, is needed. Such a methodology requires adequate modeling, simulation tools and processing. More specifically, it requires achieving reliable representations, at the pre-construction stage, of two layers of information: population within the construction site zone of influence and noise levels with the presence and absence of the construction site. Furthermore, adequate assessment indicators must be defined.

For zone of influence representation, a detailed spatiotemporal representation of the population is of paramount importance; any exposure assessment that fails to take into account individuals' precise locations, as this location changes during the day with respect to personal activities, is incomplete. For example, a proportion of residents near a construction site may be at their workplace during the day, and therefore may not be concerned by daytime worksite noise exposure. Moreover, a comprehensive assessment of exposure necessitates an understanding of the demographic characteristics of the exposed population, thus enabling a targeted evaluation of the exposure of distinct demographic categories. For noise level information, the temporal variation of noise maps throughout the day, in taking into account both noise emissions from the construction site and city background noise, is important to consider. This information is essential to account for the impacts of a particular site layout. Starting from this comprehensive source of information on noise levels and population, the assessment methodology should be able to compute a carefully designed metric that quantitatively measures population noise exposure.

Previous studies investigating noise exposure from urban construction sites have not fully addressed the challenges inherent in a reliable and detailed assessment at the pre-construction stage. Instead, they have mainly relied on a brief description of the construction site's zone of influence (Hong et al., 2021; Choi et al., 2022), for the most part limited to the number of persons residing in the zone, without any further details about precise location, socio-demographic characteristics, activities or effective presence during the day. Such a limited representation restricts

the adequacy of results and poses challenges in achieving social and environmental justice as regards construction site noise exposure. Furthermore, the majority of these studies do not take into account city background noise in their analyses. When urban background noise is included, its representation often involves a static noise map that fails to account for variations. This limitation greatly hinders a realistic evaluation of the true impact of construction site activities on the overall noise environment, thereby undermining the ability to adapt construction site planning for noise reduction.

This paper proposes an individual-centric approach to evaluate construction site noise impacts. According to this approach, a temporally-detailed exposure assessment of each individual of the population is performed, wherein a realistic exposure evaluation of an individual is computed for successive time periods of the day. Such a granular bottom-up approach, is essential to achieve an accurate and detailed assessment of the population's exposure. This individual level assessment approach is enabled by data availability in recent years as well as recent innovations in synthetic data generation methods and activity-based multi-agent simulation tools. Moreover, in this paper, the accuracy of noise levels at an individual's location is enhanced by computing noise maps every 15 minutes, notably, by taking into account the temporal variation of city background noise, i.e. traffic noise. The use of such a detailed spatiotemporal representation of the population and noise levels in a construction site impact evaluation is unprecedented; it enables investigating individuals' exposure to construction or traffic noise throughout the day, whether at home, at work or engaged in any other modeled activity. This paper presents, for the first time, both global and category-specific assessments of population exposure, as obtained by aggregating these temporally-detailed individual exposure values.

To implement our methodology, a novel modeling chain paired with specific indicators is being introduced. The construction site's zone of influence is modeled using an activity-based approach: an attribute-rich synthetic population is created, and activity plans with spatiotemporal details are associated with each individual of the population. Moreover, to obtain accurate noise levels at individual locations, we propose modeling and processing methods that are appropriate for

computing noise maps for consecutive time periods throughout the day, both with and without the construction site. With these two layers of information, the exposure to construction site noise can be computed for each individual throughout the day. Lastly, an indicator is formulated to aggregate these individual exposures into a global assessment, or category-specific assessment, of the population noise exposure.

The contributions of this paper include:

1. Formulating a suitable model and applying convenient methods of synthetic data generation to represent the construction site zone of influence with rich spatiotemporal and demographic details of the population ;
2. Producing a suitable model of construction site emission sources at the pre-construction stage ;
3. Creating noise maps for consecutive time periods throughout the day using appropriate simulation tools ;
4. Establishing a complete modeling chain for computing individual noise exposure for successive time periods throughout the day ;
5. Developing a novel indicator tailored to the generated methodological framework.

This framework will subsequently be illustrated by means of an application assessing noise exposure to a construction site in Champigny-sur-Marne (France).

The approach outlined in this paper is highly valuable for both practitioners and researchers, particularly those dedicated to achieving sustainable urban environments. Our framework can assist construction project managers by integrating sustainability criteria into the planning phase: designers can schedule construction activities in a way that minimizes noise disruptions; civil engineers can select machinery and equipment best suited to the construction site environment; and local authorities can improve communication and engagement with the community. For the research community, this individual-level activity-based modeling approach provides a framework for

dissecting and understanding the intricate socioeconomic and health ramifications of construction site noise exposure.

The remainder of this paper, will describe our approach in further detail. Section 2 presents a literature review summarizing existing research in the field. The methodology section (Section 3) then outlines the approach adopted herein. Section 4 focuses on the case study, dedicated to examining a specific construction site, while Section 5 discusses our findings. Lastly, the final section provides a conclusion.

2. Literature review

In recent years, a number of studies have been conducted on the assessment and management of construction noise. In general, three categories of studies can be distinguished: noise measurement, noise level prediction and noise control measures (Mir et al., 2022). The main objective of the first category, i.e. noise measurement, is to quantify the noise level generated by different construction activities and equipment. Various devices and procedures are employed for this evaluation. For example, noise measurement devices are placed at a certain distance from the source to record the noise level (Rempel et al., 2019). These measurements could be utilized for forecasting noise emissions in future projects during their planning phase. The second category of study, i.e. noise prediction, estimates noise level during the pre-construction stage at various locations in the vicinity of the site based on the noise emission level of construction activities. In their systematic review, Mir et al. (Mir et al., 2022) classified noise prediction methods into two categories, depending on whether they apply noise propagation formulae (either directly or through software (e.g. CadnaA (Computer Aided Noise Abatement) (Hong et al., 2021)), or use historical data from previous projects along with methods such as Monte Carlo simulation (Haron and Yahya, 2009) or case-based reasoning (Kwon et al., 2019). The third category of study, i.e. noise control measures, aims to select the most suitable noise control strategy to manage noise emissions from the construction site from a noise management perspective (Lee et al., 2008; Mir et al., 2022). Mitigation measures should be proposed whenever necessary and may consist of: time

of construction machine operations (e.g. when impact is minimal), emission source power control (e.g. devices with low noise emissions), path control (e.g. noise barriers), and receiver control (e.g. hearing protection devices) (Gilchrist et al., 2003; Mir et al., 2023).

These studies do not address many key challenges when investigating exposure to noise from urban construction sites at the pre-construction stage. The assessments conducted for the benefit of pre-construction planning are mainly focused on evaluating construction activity noise levels; they are concerned with either construction equipment emission levels or the prediction of levels at different locations in the vicinity of the construction site. Studies that attempt an exposure evaluation rely mainly on a brief description of the site's zone of influence which tends to be limited to the buildings in the zone (Hong et al., 2021) or the number of residents (Choi et al., 2022). Generally, such studies do not consider the effective presence of people found in the site's impact area and, as a result, are even less likely to identify the socioeconomic characteristics of the affected populations or activities disturbed by site noise. In addition, background noise (usually road traffic noise) is not considered or, if accounted for, frequently derived from static noise maps external to the modeling framework used, with less fine-grained temporal variability than the simulation of site-specific noise. In light of these limitations, the methods commonly employed may not be entirely adequate for predicting and mitigating individual exposure to construction site noise. It is necessary therefore to more carefully consider the dynamic nature of the urban environment, especially human movement throughout the day in relation to their activities.

The integration of activity-based models with environmental models provides a promising method for extensively examining the interconnected concerns regarding the effects of noise sources (e.g. road traffic, air traffic, construction site activities) on personal exposure (Gastineau et al., 2023). By incorporating the source of the emission and receivers of a nuisance within the same framework, this integrated modeling chain offers a robust means to assess scenarios and address issues related to environmental exposure at fine spatial and temporal scales. Disaggregated activity-based models have thus been gaining increased attention in recent years for use with planning and evaluations in the urban context. Activity-based modeling, coupled with agent-based

simulation, has been adopted in various studies including health-related evaluations (Tomintz et al., 2008; Edwards and Clarke, 2013), transport planning (Kickhöfer and Kern, 2015; Hörl et al., 2018), economic studies (Avram et al., 2013; Sutherland and Figari, 2013), geographic information science (O’Sullivan, 2008) and air pollution exposure (Beckx et al., 2009; Hatzopoulou and Miller, 2010; Vallamsundar et al., 2016; Cucurachi et al., 2018). A handful of studies have relied upon activity-based multi-agent models to evaluate noise exposure. Kaddoura et al. (Kaddoura et al., 2017) proposed a framework for road traffic noise evaluation. Cucurachi et al. (Cucurachi et al., 2018) evaluated noise footprints from personal land-based mobility within a life cycle analysis framework. Gerike et al. (Gerike et al., 2012) mapped external noise costs to transport system users. Le Bescond et al. (Le Bescond et al., 2021) performed a dynamic assessment of road traffic noise exposure. Zwick et al. (Zwick et al., 2021) assessed the impact on traffic noise from city-wide autonomous ride-pooling. Lastly, Ganic et al. (Ganić et al., 2023) generated dynamic aircraft noise maps for Heathrow Airport. To the best of our knowledge, no study using a disaggregated activity-based approach has specifically focused on construction site noise.

3. Methodology

This paper proposes a bottom-up approach assessing the noise exposure due to urban construction sites; it consists of four steps:

1. **Modeling the noise emission sources of an urban construction site:** By relying on both construction site spatiotemporal planning and construction machine characteristics, the site noise emission sources can be identified and described in terms of their emission power as well as their spatial and temporal attributes. The modeling approach aims to achieve adequate spatial and temporal resolutions individually, with the highest spatiotemporal resolution, yet remaining convenient for representing site information at the pre-construction stage. The temporal information on emission sources is given by a daily schedule broken down into time periods, while the spatial information is given as a precise or approximate location.

2. **Generating an individual-level, activity-based model of the construction site zone of influence:** A synthetic population, representative of the actual one and constituted of synthetic individuals grouped into households is generated using appropriate methods. This generation step is performed based on available public databases and population surveys. In addition, spatially-detailed activity plans are assigned to synthetic individuals according to travel surveys. As a result of this process, households and individuals are precisely located in the territory throughout the day, and their demographic and economic attributes are recorded.
3. **Assessing individual noise exposure levels for successive time periods (e.g. quarter-hour time periods) over the day, with and without the construction site:** This third step evaluates individuals' noise exposure levels within a construction site's zone of influence for successive time periods during the day. This assessment is carried out for two configurations: the first encompasses exposure to the cumulative power of both the background noise and construction site noise; while the second configuration is limited to just the exposure to background noise. The specific exposure due to site noise is then determined by comparing these two configurations. The ability to conduct this individual exposure assessment, for successive time periods throughout the day, is facilitated by the detailed spatiotemporal information regarding emission sources and personal activities obtained from previous steps. To execute this step, we have employed simulation software, including traffic simulation tools to evaluate traffic conditions both with and without the construction site. We have also utilized noise simulation software to measure the noise levels in both configurations. Furthermore, this step incorporates a dedicated module for individual exposure assessments covering the day's successive time periods.
4. **Computing construction site noise exposure indicators:** Novel indicators are being proposed to facilitate this assessment. These indicators are based on the cumulative amount of time of exposure above a given threshold (e.g. 65 dB), as expressed in a person.time-period (e.g. person.quarter-hour) unit. A global indicator quantifying the additional noise exposure imposed on the entire population resulting from the construction site is calculated as the

difference between the total number of person.time-periods above the threshold with the site and the total number identified without it. This indicator therefore considers the influence of existing noise levels in the area, in recognizing that construction site noise emitted in a noisy environment has a lower impact on annoyance modification than noise emitted in a quiet area. More refined indicators, targeting specific categories of the population (e.g. different socio-demographic groups), can also be computed by considering just those individuals in a given social, demographic or economic category.

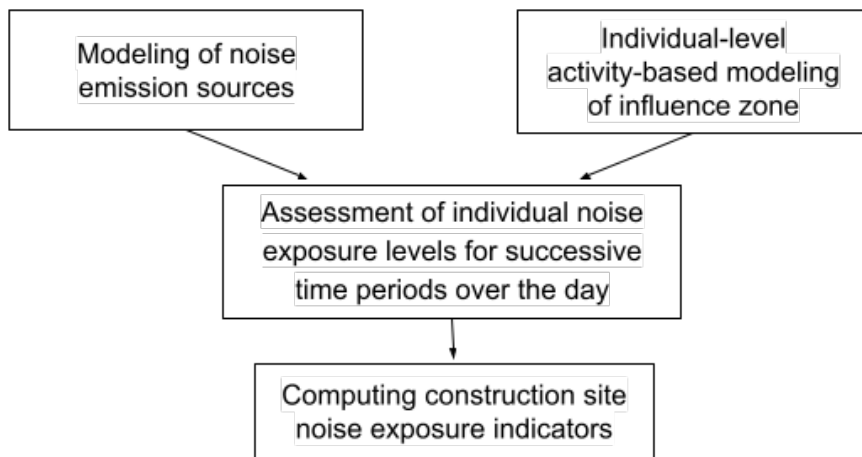


Figure 1: The four-step process for assessing exposure to urban construction site noise.

3.1. Step 1: Modeling the noise emission sources of an urban construction site

A construction site can be viewed as an assembly of major works operations, such as earthworks, foundation, concrete, masonry, metals and finishes. Each of these operations is referred to as a construction phase, and each phase may be further broken down into sub-phases according to the spatial, temporal and technical requirements specified in the construction project plans. In relying on these spatiotemporal plans of the construction project (e.g. GANTT diagrams and maps), various aspects of emission sources can be distinctly identified and characterized. By utilizing the information provided in the project plans, the types, characteristics and spatiotemporal details of emission sources are established during the pre-construction stage.

3.1.1. Types and characteristics of emission sources

Two types of noise emission sources relative to urban construction sites can be distinguished: 1) direct sources relative to site operations, e.g., construction machinery; and 2) indirect sources, e.g. additional emissions resulting from reduced speeds, congestion and vehicle queuing due to the presence of the construction site.

Site equipment constitutes the main emission sources for any given construction phase (Elanchelian, 2013; Fang et al., 2009). Such equipment includes rollers, scrapers and excavators for earthworks, cranes for material hoisting, hammers for pile driving, etc. These sources are characterized by their power of emission. A temporary infrastructure alteration causing a modification in traffic patterns is also associated with additional emissions from the site. To quantify the power of these emissions, a mandatory first step entails assessing the change in traffic. It is important to precisely establish the revised infrastructure (e.g. line closure, capacity drop) to assess the resultant change in traffic.

The sound power levels attributed to construction machines can be obtained from either the machine label or its technical specifications (Directive, 2000). These values can also be found in technical construction guides, e.g. (Cahen et al., 2019; , 2009, BS). However, the emission level may vary depending on the age of the machine (Haron et al., 2012; Vardhan et al., 2006), operating conditions such as load and speed (, BS), and maintenance status (Vardhan et al., 2006). To account for these parameters, a correction factor can be applied based on the findings of studies devoted to recording the noise emission levels of machines operating at construction sites. For example, Haron et al. (Haron et al., 2012) measured the noise emission level generated by excavators and compactors at construction sites and drew a comparison with emission values found in a technical guide (, BS). Their study found that older machines had higher emission levels, with a linear relationship derived between noise emission level and machine age.

3.1.2. Spatiotemporal details of emission sources

Since our approach is intended to provide evaluations at the pre-construction phase, an adequate model is necessary for this purpose. Such a model should strike a balance between the accuracy of representation and the uncertainties associated with pre-construction plans. As such, temporal information is represented as discrete time steps, referred to as time periods. These time periods are characterized by their duration, e.g. one hour. During a given period, an emission source is associated with a given emission power. The advantage of a time period format is its flexibility, since the time period length can be adjusted according to the precision of available information.

Spatial information is given for each emission source over each time period. Two cases can be distinguished:

1. A precise position is available and the emission source is fixed: the position is provided as point coordinates for a construction engine or line coordinates for a road segment;
2. The emission source is mobile or a precise position is not available: the coordinates of an area of presence are defined. Adequate methods should be applied to take into account the locational uncertainty of the emission source. Possible methods include: considering the geometric center of the defined area as the emission source position, considering the surface of the area as the emission source, etc.

The case study presented in Section 4 features a typical construction site (Dervaux et al., 2022). Figure 6 portrays the location of construction site machinery responsible for emitting noise throughout a typical day in Champigny-sur-Marne during the earthworks-foundations phase. Furthermore, Figure 7 provides the temporal details of these emission sources, while Table 1 lists the emission power of the equipment. Together, these figures and table offer a comprehensive understanding of the site's noise emissions and their spatiotemporal characteristics.

3.2. Step 2: Generating an individual-level activity-based model of the construction site zone of influence

A detailed and accurate representation of the population and activities in the construction site's zone of influence is necessary to properly assess the exposure to urban construction noise. In recent years, several methods have been developed to reproduce a realistic representation of populations and activities; these methods enable the representation of individuals with detailed socio-demographic attributes and their activity plans, along with precise locations throughout the day. Generating synthetic populations and activity plans relies on the availability of adequate data sources, which have tremendously expanded in recent years. These sources include: census data with population samples, aggregated data for administrative areas, data surveys on mobility.

3.2.1. Synthetic population generation

A synthetic population is generated with the aim of representing the actual population. During the generation process, a number of attributes for individuals (e.g. sex, age) and/or households (e.g. income, dwelling surface area) are reproduced. The individual and household levels can be represented simultaneously, whereby individuals are grouped into households. The synthetic population is usually generated for administrative jurisdictions, with available aggregate and sample data. Yaméogo et al. (Fabrice Yaméogo et al., 2021) summarized the methods available for the synthetic population generation process. These methods include both Synthetic Reconstruction algorithms that produce synthetic populations by replicating individuals (Müller, 2017; Hermes and Poulsen, 2012) and Statistical Learning algorithms that draw a population following a joint probability estimation (Farooq et al., 2013; Sun and Erath, 2015; Borysov et al., 2019). Some of these methods have been implemented as commercial or open-source software. An additional step entails assigning households to a specific dwelling on the map (Sallard et al., 2020; Chapuis et al., 2018). After generating and spatializing the synthetic population, a detailed description of the static aspect of the territory is output. Figure 2 illustrates the result of this process, showing spatialized individuals and households along with their attributes.

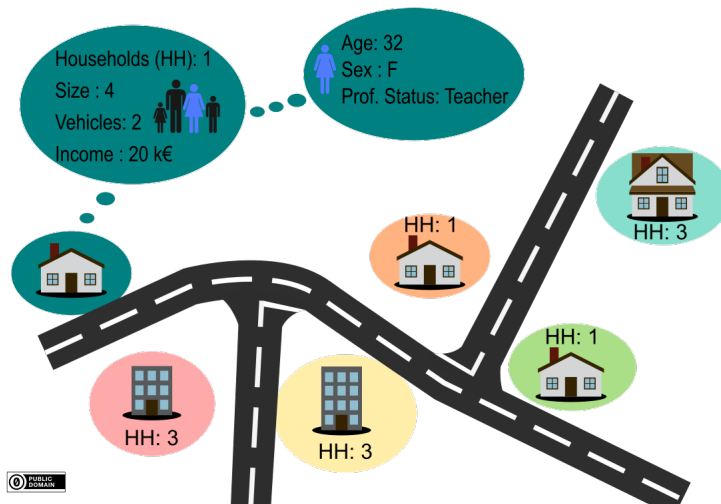


Figure 2: Spatialized individuals and households with their attributes after completion of the synthetic population generation process.

3.2.2. Activity plan generation

In order to yield a description of the dynamic aspect of the territory, individuals' activity plans are also generated. Activity plans describe the activity chain of each individual, consisting of types of activities, timetables, location, and modes of transport. By virtue of describing all daily activities of the individual, an activity plan depends on both the individual's attributes (obtained during the synthetic population generation) and the dwelling location. The methods for assigning activity plans to the synthetic population agents generated previously, include statistical matching (Namazi-Rad et al., 2017), rule-based methods (Roorda et al., 2008), sequence alignment methods (Shoval and Isaacson, 2007), and profile hidden Markov methods (Saadi et al., 2016). Figure 3 shows an example of the activity plan of an individual once the generation process has been performed.

3.2.3. Eqasim synthetic population and activity plan generator

This article uses the Eqasim version 1.5.1 (Hörl and Balac, 2021b), an open-source software tool designed to generate synthetic populations and activity plans for urban and transportation modeling. Eqasim can create synthetic populations and activity plans for different regions and at different scales, ranging from small neighborhoods to entire cities. Eqasim implements a pipeline consisting of several steps. First, a synthetic population is generated using a direct sampling method based on

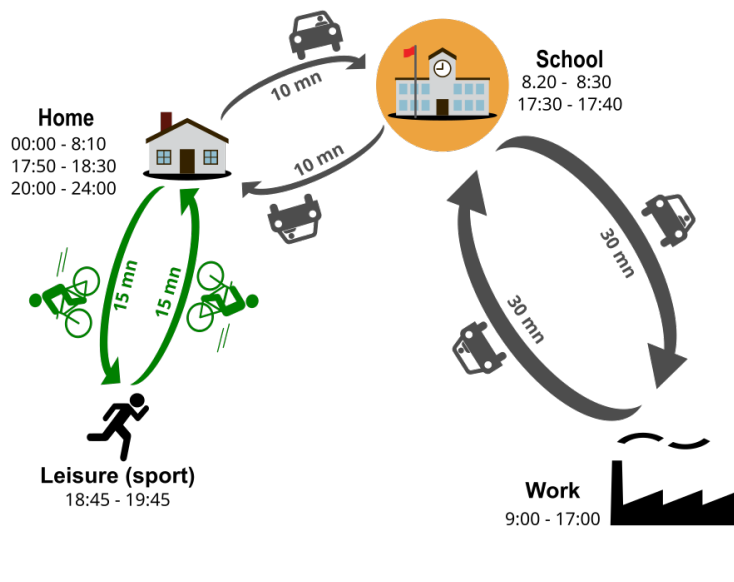


Figure 3: An example of an activity plan of an individual after the generation process is performed.

the household weights given in the census sample. Afterwards, activity chains are generated by means of matching algorithms to attach Household Travel Survey (HTS) observations to synthetic individuals based on their attributes (age, sex, income, etc.). Lastly, the location of activities is assigned using commuting patterns and by sampling addresses from the locations available within each municipality. A detailed description of Eqasim is given in (Hörl and Balac, 2021b) and (Hörl and Balac, 2021a).

3.3. Step 3: Assessing of individual noise exposure levels, for successive time periods over the day, with and without the construction site

To assess the contribution of construction site noise exposure, it is important to evaluate two distinct configurations of temporally-detailed individual noise exposure. First, the individual exposure to background noise in the absence of the construction site must be assessed. In this study, the background noise consists primarily of traffic-related sounds since traffic is the primary source of acoustic disturbances in the city (Aletta et al., 2018). Next, individual exposure to overall noise, which encompasses both background noise and the construction site noise, needs to be evaluated.

To assess individual exposure for each configuration, substantial processing is required, which involves several steps: after generating the synthetic population and activity plans described above, a multi-agent activity-based traffic simulation is run to simulate traffic patterns. Afterwards, a dedicated software simulates the propagation of noise emitted by sources such as traffic or construction site machinery, between the source and receiver positions. An individual noise exposure assessment module is introduced to accurately assess individual exposure, for each configuration, for successive time periods over the day. Subsequently, this dual evaluation serves to calculate exposure indicators relative to construction site noise.

3.3.1. Modeling chain for a temporally-detailed evaluation of individual exposure

The workflow of the process to evaluate individual exposure is depicted in Figure 4, illustrating the individual assessment of noise exposure for the two configurations, one with a construction site the other without. Let's note that this process requires significant time and effort in order to properly calibrate the models involved.

For the first configuration, i.e. intended to evaluate individual exposure to traffic noise without the construction site, the following steps are required:

1. The Eqasim pipeline is utilized to generate synthetic population and activity plans. This step involves inputs such as census and travel survey datasets;
2. A traffic model is built using the MATSim multi-agent transport simulator (Horni et al., 2016). Inputs to MATSim include the generated activity plans and transport network data;
3. NoiseModelling (Bocher et al., 2019) is then employed to generate traffic noise maps for consecutive time periods throughout the day. This step entails utilizing the building layers obtained from Open Street Map, as well as traffic data obtained from MATSim;
4. Lastly, a dedicated individual exposure assessment module is used to assess individual exposure to traffic noise by overlapping the noise maps for consecutive time periods throughout the day with the spatialized synthetic population. This individual exposure is

derived for successive time periods over the day, taking into account individuals changing their location.

In the second configuration, the evaluation of individual exposure to traffic noise in the presence of the construction site follows a process similar to that of the first configuration, but with a number of specific adjustments, namely: a) the traffic model is built using a modified network graph that accounts for the effects of the construction site operations; and b) noise maps for consecutive time periods throughout the day are generated by incorporating the modified traffic model and direct emission sources from the construction site, such as site machinery. By implementing these adjustments, a temporally-detailed assessment of individual noise exposure resulting from both traffic and construction site activities can be obtained for the second configuration. The remainder of this section will provide a more detailed description of MATSim, NoiseModelling and the individual exposure assessment module.

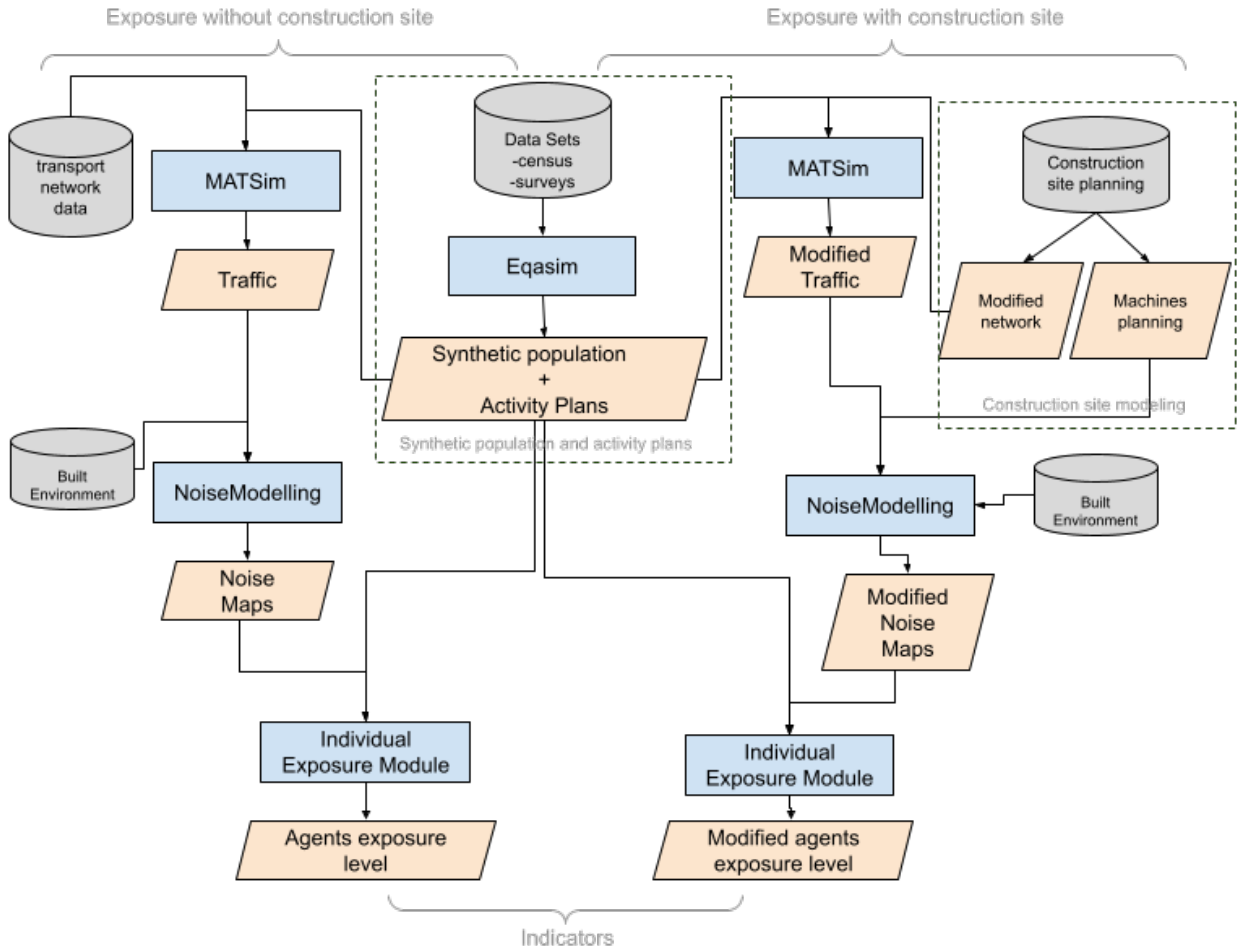


Figure 4: Workflow for assessing individual noise exposure to emission sources for both configurations: with the construction site and without it.

3.3.2. MATSim - Traffic simulation

MATSim (Horni et al., 2016), an open-source software, is an example of a multi-agent activity-based transport simulation system (version 15.0 is run in this paper). For our purposes herein, the choice of a multi-agent activity-based transport simulation model is a natural one given that the synthetic population and activity plans generated in Step 2 constitute the required input for such a model. MATSim achieves an equilibrium between mobility demand and supply, which will serve to characterize travel and congestion over the territory. MATSim input includes the network graph, and the initial transport demand, as represented by the activity plans of each individual. In cases where the construction site causes alterations to the original network graph, it becomes necessary

to conduct two separate simulations using each of the two graphs. This approach allows for an evaluation of traffic noise exposure considering both scenarios: with and without the presence of the construction site. The simulation output provides a precise monitoring, in both time and space, of each individual's set of trips.

MATSim enables simulating complex urban mobility patterns and behaviors. Unlike traditional four-step transport models (McNally, 2007), MATSim can capture the mobility dynamic at a disaggregated individual level. However, MATSim displays some drawbacks compared to these other systems. For one thing, to ensure accurate simulations, MATSim relies on the availability of detailed data sources to derive disaggregated travel demand, as opposed to traditional four-step models' reliance on aggregated data, in the form of origin-destination matrices. For another, users with limited computational capacity may face a challenge when running simulations with MATSim, given that the software processes individual travel plans and moreover demands substantial computational resources, particularly for larger scale scenarios (Zhuge et al., 2021). Lastly, building a transport model with MATSim requires programming skills, notably Java and XML, to set up and modify the simulation scenarios, parameters and algorithms.

3.3.3. NoiseModelling - Noise propagation and emission models

NoiseModelling (Bocher et al., 2019) is an open-source software for environmental noise mapping (version 4 is being run here) based on the standard European method CNOSSOS-EU (Kephalopoulos et al., 2012) for environmental noise assessment and management. The NoiseModelling software includes two principal models. The first one is dedicated to estimating the sound power level of traffic (rail or road), as based primarily on flow rates and speeds. The second model employs a path-finding algorithm to determine the paths between sources and receivers; it computes the attenuation value along each propagation path for a selected range of octave (or third-octave) bands, in relying on key physical phenomena such as meteorology, ground absorption, and diffraction on building edges. The noise model integrated into NoiseModelling is identical to that incorporated in commercial software. Except for unintentional deviations or potential development

errors on either side, the results provided by NoiseModelling and its commercial counterparts are actually equivalent.

3.3.4. Individual noise exposure assessment for successive time periods over the day

In the individual exposure assessment process, an exposure level is assigned to each individual for successive time periods over the course of day. A typical time period considered for exposure assessment is fifteen minutes. The individual exposure assessment module uses information from both the noise map and spatialized synthetic population data at a given time period to compute individual exposure during this period. This temporally-detailed exposure of individuals has been computed for both configurations: with and without the presence of a construction site. As a result, exposure is determined by considering the specific times when individuals are present in their homes, workplaces, or activity locations.

Noise maps are computed for successive time periods over the day by placing noise sensors on building facades during noise propagation simulation. Noise emission sources for each time period are obtained from both construction site emission modeling and the traffic model derived from MATSim. Furthermore, the spatiotemporal representation of the population and activities is adjusted, in transforming time from a second-based scale to a time period scale. In fact, the generation process, using Eqasim, yields a representation of the construction site's zone of influence with a high space-time resolution. Synthetic population individuals are assigned a precise location every single second. By decreasing this temporal resolution, for each individual, a single location is assigned for each time period (e.g. quarter-hour), thus corresponding to the spatial position (associated with the location of an activity) where the individual has spent the majority of their time during that period. It is important to note that the reduction of time resolution in population representation is only applied to the input of the exposure assessment module and not to the MATSim transport simulation software. By taking into account the aforementioned considerations, the module then calculates the exposure level of each individual for each time period.

3.4. Step 4: Computing construction site noise exposure indicators

The final stage of the analysis calculates a newly developed indicator, which allows for an accurate and detailed evaluation of the impact of the construction site on noise exposure. This indicator is expressed in the unit "person.time-period". Typically, quarter-hours are used as the time intervals for assessing noise exposure, hence the metric can be represented as a "person.quarter-hour". Choosing a 15-minute duration (quarter of an hour) is motivated both by the fact that sound environments are homogeneous at this time scale (Brocolini et al., 2013), and by its correspondence to the usual outputs of the MATSim model (Le Bescond et al., 2021). The advantage of such an indicator compared with conventional sound level indicators like LAeq, is that in describing impacts, it is key to consider the sound level preceding the noise source being assessed (referred to here as background noise), because an additional noise source has a greater impact if the original noise is low. The method is illustrated here with a threshold of 65 dB(A), but the assessment could be extended by considering other thresholds, whether higher or lower.

In order to compute the indicators, we first need to compute for every individual i whether the equivalent sound level of exposure (in dB(A)) at time period j is greater than the defined threshold value:

$$IsExposedThresh_{ij} = \begin{cases} 0 & \text{if } LAeq_{ij} \leq Thresh \\ 1 & \text{if } LAeq_{ij} > Thresh \end{cases} \quad (1)$$

where:

- $IsExposedThresh_{ij}$ indicates whether the equivalent sound level of exposure of individual i during time-period j is greater than a defined threshold value;

- $Thresh$ is the exposure level threshold, as expressed in decibels (dB(A)). For example, such a threshold can be set at 65 dB(A);
- i is the individual identifier;
- j is the time period of the day, with $1 \leq j \leq T$; T being the total number of time-periods throughout the day;
- $LAeq_{ij}$ is the equivalent sound level of exposure of an individual i during a time-period j , expressed in dB(A). This exposure level is fixed for the entire duration of the time-period as discussed above.

This indicator aims to capture the disparity in the total duration of exposure above a specified noise threshold between the two distinct scenarios, with and without the construction site. It can be calculated for different groups, such as the entire population or specific categories of individuals (e.g. different socio-demographic groups). The indicator is calculated as follows for a group G of individuals. First, a count is performed of the number of time periods during which individuals of the group are exposed to a sound level above the threshold for the configuration with the construction site. Second, a count is made of the number of time periods during which individuals' exposure exceeds this same threshold for the configuration without the site. Then the difference between these two counts is calculated. Here is our indicator:

$$nThresh_{G,day} = \left(\sum_{1 \leq j \leq T} \sum_{i \in G} IsExposedThresh_{ij} \right)_{CS+B} - \left(\sum_{1 \leq j \leq T} \sum_{i \in G} IsExposedThresh_{ij} \right)_B \quad (2)$$

Where:

- $nThresh_{G,day}$ is the difference in the count of time periods, between the configurations with and without the construction site, for group G of individuals when the exposure level lies above the defined threshold;

- G is the group of considered individuals: In the context where a global indicator is calculated to reflect the exposure of the entire population to noise from the site, G includes the total number of individuals in the zone of influence. On the contrary, if a specific indicator is calculated for a particular category (e.g. by age group), then G includes the number of individuals within that category;
- i is the individual identifier, where $i \in G$;
- j is the time period of the day, where $1 \leq j \leq T$;
- T is the total number of time periods throughout the day. If the duration of a time-period is fixed to be a quarter-hour, then $T = 96$ throughout the day;
- $IsExposedThresh_{ij}$ indicates whether the level of exposure of individual i during time period j is greater than the defined threshold value;
- $\left(\sum_{1 \leq j \leq T} \sum_{i \in G} IsExposedThresh_{ij}\right)_{CS+B}$ is the count of time periods where individuals of group G are exposed to a sound level above the threshold for the configuration with both construction site and background noise emissions;
- $\left(\sum_{1 \leq j \leq T} \sum_{i \in G} IsExposedThresh_{ij}\right)_B$ is the count of time periods where individuals of group G are exposed to a sound level above the threshold for the configuration with background noise emissions only.

4. Case study

To illustrate our methodology, we have conducted a case study aimed at evaluating the impact of a construction site. Specifically, this case study focuses on the earthworks-foundations phase of the Grand Paris Express station construction site in Champigny-sur-Marne, France. The geographic location of Champigny-sur-Marne is depicted in Figure 5. This urban locale is situated within the administrative boundaries of the Val-de-Marne department in France. Covering an approximate

area of 11.3 square kilometers, Champigny-sur-Marne is home to a population of around 77,439 residents. In this case study, we assess the noise exposure experienced during a typical day of earthworks-foundations phase. The focus is on evaluating exposure to direct emission sources of the construction site, therefore no infrastructure change is considered.

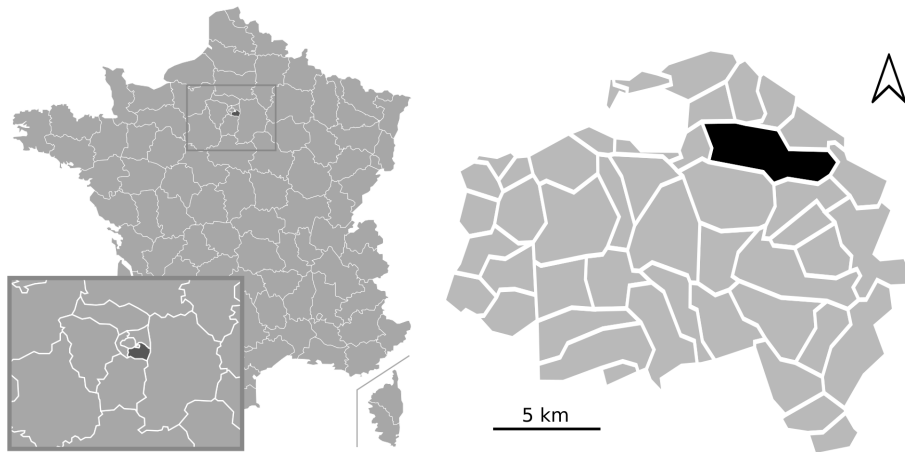


Figure 5: Geographic location of Val-de-Marne (left) and Champigny-sur-Marne (right), France.

4.1. Describing the construction site

Figure 6 provides the geographical location of the construction site in Champigny-sur-Marne. All emission sources are assigned to the geometric center of the construction site due to the inaccessibility of precise location information.

Figure 7 displays the temporal details of the emission sources during the earthworks-foundations construction phase throughout a typical day, as outlined in the construction site description by Dervaux and Rochaix [Dervaux and Rochaix \(2022\)](#). The temporal scheduling of machine operations is provided on an hourly basis. Construction activities begin at 7 a.m. and conclude at 5 p.m., with different machines operating during distinct time periods.

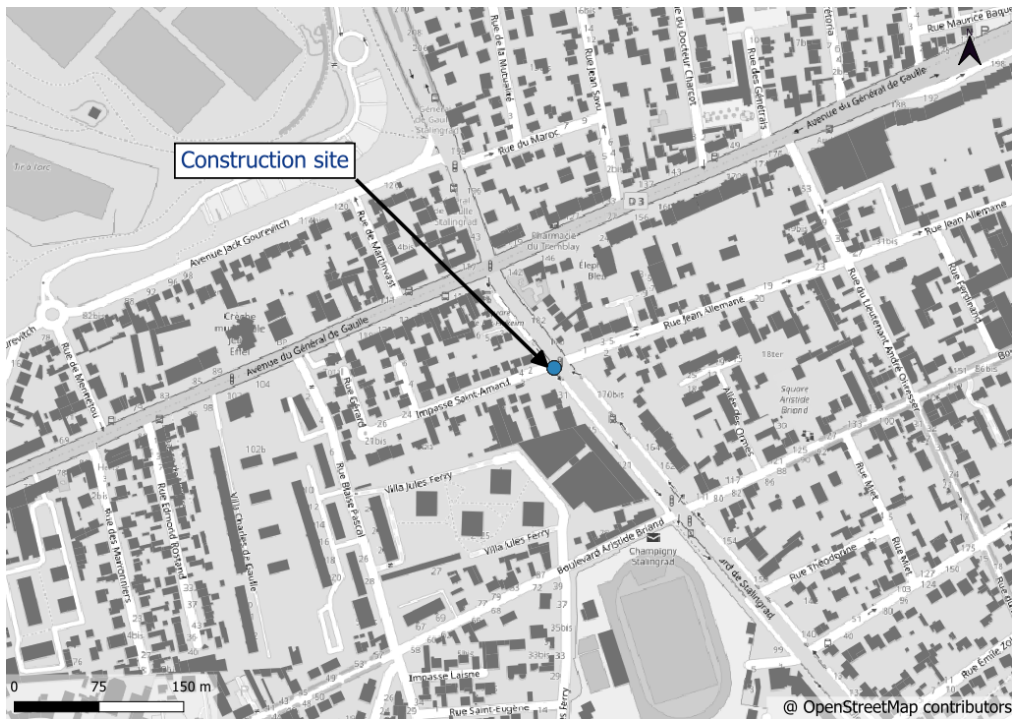


Figure 6: Location of noise emission sources of the construction site during earthworks-foundations construction phase in Champigny-sur-Marne.

Machinery	7am-8am	8am-9am	9am - 10am	10am-11am	11am-12pm	12pm-1pm	1pm-2pm	2pm-3pm	3pm-4pm	4pm-5pm
dump truck 1										
dump truck 2										
cable-operated skip										
cutter										
concrete mixer truck										
concrete mixer										
hydraulic breaker										
excavator										
mini excavators										
network cleaning equipment										

Figure 7: Temporal details of equipment use for a typical day of earthworks-foundations phase of the construction site (Dervaux and Rochaix, 2022).

The sound power level of the equipment is illustrated in Table 1, inspired by a technical guide on construction sites (Cahen et al., 2019). These values are rough estimates using a pink noise signal and can be replaced by more precise values if detailed technical descriptions for each equipment

are available. It can be observed that certain equipment, such as the hydraulic breaker, exhibits remarkably high emission power.

Table 1

Sound power of construction site equipment(Cahen et al., 2019).

Machine	Sound Power Level (dB(A))
concrete mixer truck, concrete mixer, dump truck, cable-operated skip	91
hydraulic breaker	109
excavator, mini excavator	96
network cleaning equipment, cutter	101

4.2. Synthetic population and activity plans generation

In this study, a synthetic population of individuals residing in the Val-de-Marne department and the corresponding activity plans with spatial details were generated. Using this generated dataset, it is straightforward to obtain synthetic population and activity plans specifically for the Champigny-sur-Marne municipality. The generation process involved utilizes a diverse range of data sources, including:

- A data sample containing socio-demographic information on residents in the Val-de-Marne department from INSEE, the National Institute of Statistics and Economic Studies (INSEE, 2023c);
- Aggregated population totals in the Val-de-Marne department from INSEE (INSEE, 2023c);
- Origin-destination data from INSEE (INSEE, 2023c);
- Income tax data from INSEE and the ministry of finance (INSEE and the ministry of finance, 2023);
- Service and facility census from INSEE (INSEE, 2023b);

- National household travel survey from the Ministry of Ecology (Ministry of Ecology, 2023);
- Enterprise census from INSEE (INSEE, 2023a);
- Buildings database from IGN, the National Institute of Geographic and Forest Information in France (IGN, 2023).

The generation process resulted in the production of 1,344,394 individuals distributed among 591,153 households. Table 2, Table 3 and Figure 17 in appendix A present the attributes and some statistics of the generated synthetic population. Each individual was assigned a set of localized activities with specific start and end times throughout the day. In total, 4,854,597 activities were generated for the 1,344,394 individuals.

Figure 8 shows two maps representing the generated synthetic population at different points in time. It depicts the number of individuals present in different 100x100 m. grid areas in Champigny-sur-Marne at 10 a.m. and 3:15 p.m., respectively. Slight fluctuations can be observed in terms of the presence of individuals across various regions of Champigny-sur-Marne. Note that we selected 10 a.m. and 3:15 p.m. as the two time points for analysis, as they exhibited a significant contrast in the noise emission levels from the construction site, as evident from Figure 10. Therefore, the difference in noise exposure at these two time points can be illustrated (Figure 14).



Figure 8: Count of persons across different 100x100 m. grid areas in Champigny-sur-Marne at 10 a.m. and 3:15 p.m. respectively.

4.3. Traffic simulation and corresponding noise maps

A MATSim (version 15.0) simulation was established for the extended area of Val-de-Marne, rather than focusing solely on Champigny-sur-Marne, to incorporate the traffic incoming from

outside Champigny-sur-Marne. The synthetic population and the corresponding activity plans generated earlier serve as the input for this simulation. The simulation output provides the traffic patterns throughout the day. The generated traffic was analyzed in discrete quarter-hour time periods. The NoiseModelling propagation was performed with specific parameters, including a maximum source distance of 750 meters, a maximum reflection distance of 50 meters, a reflection order of 1, and the inclusion of both vertical and horizontal diffraction. Figure 9 depicts traffic noise maps of Champigny-sur-Marne for the quarter-hours starting at 10 a.m. and 3:15 p.m. respectively, computed using the MATSim Val-de-Marne traffic model. It can be noticed that at 3:15 p.m., certain road segments display an increase in noise emissions compared to 10 a.m. However, as projected, our simulation indicates that traffic noise emissions are lower for both time intervals compared to peak hours at the start and at the end of the day.

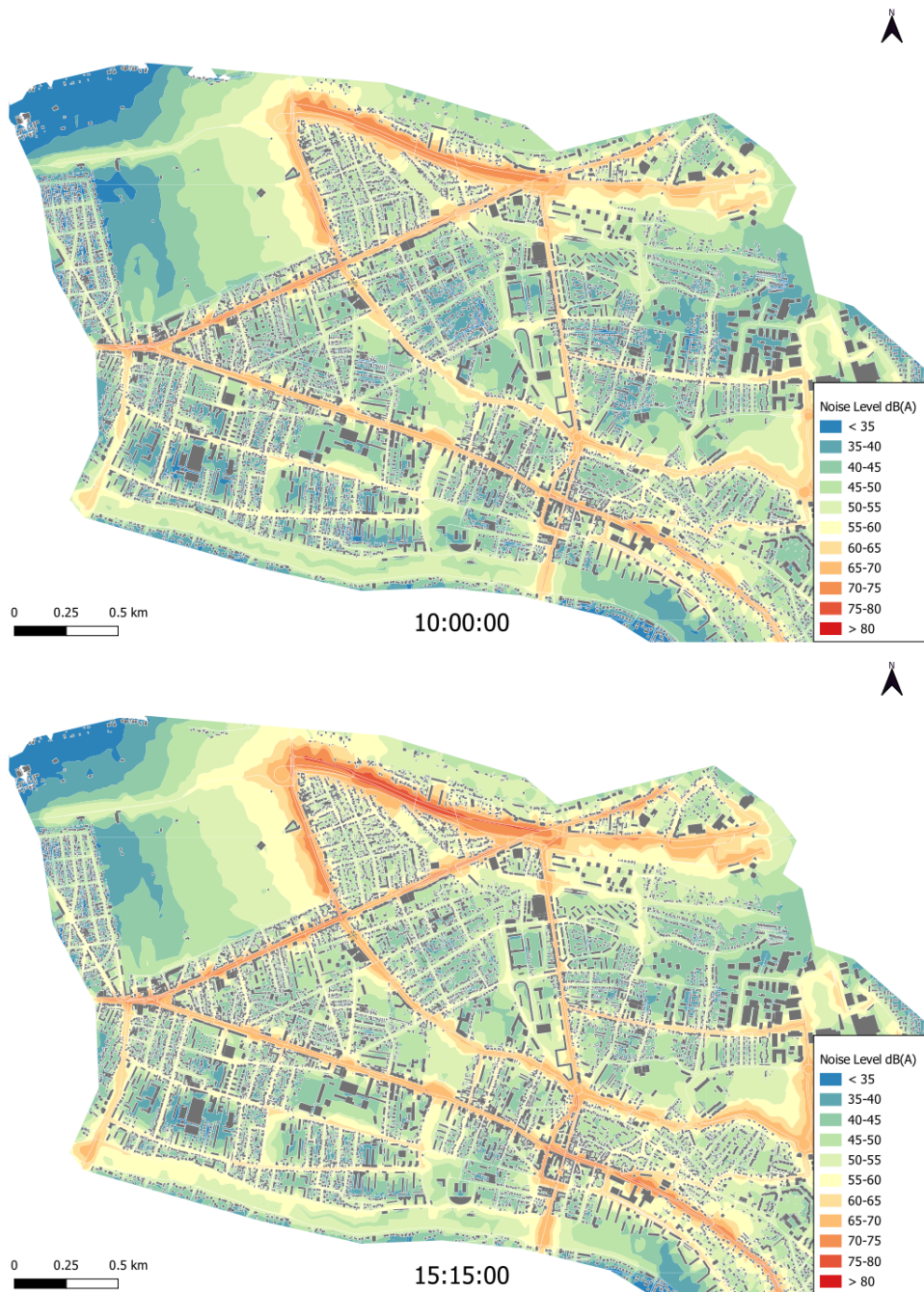


Figure 9: Traffic noise map of Champigny-sur-Marne for the quarter-hours starting at 10 a.m. and 3:15 p.m. respectively.

4.4. Construction site noise maps

As previously stated, it is important to consider construction site noise levels in relation to background noise. Nonetheless, to illustrate the noise emissions from construction site machines,

Figure 10 presents noise maps that show the emission of these sources independently, respectively, for the quarter-hours starting at 10 a.m. and 3:15 p.m. It can be seen that there is a notable surge in noise emission attributed to construction activities at 3:15 p.m. This aligns with the operation of the hydraulic breaker, known for its substantial emission power.

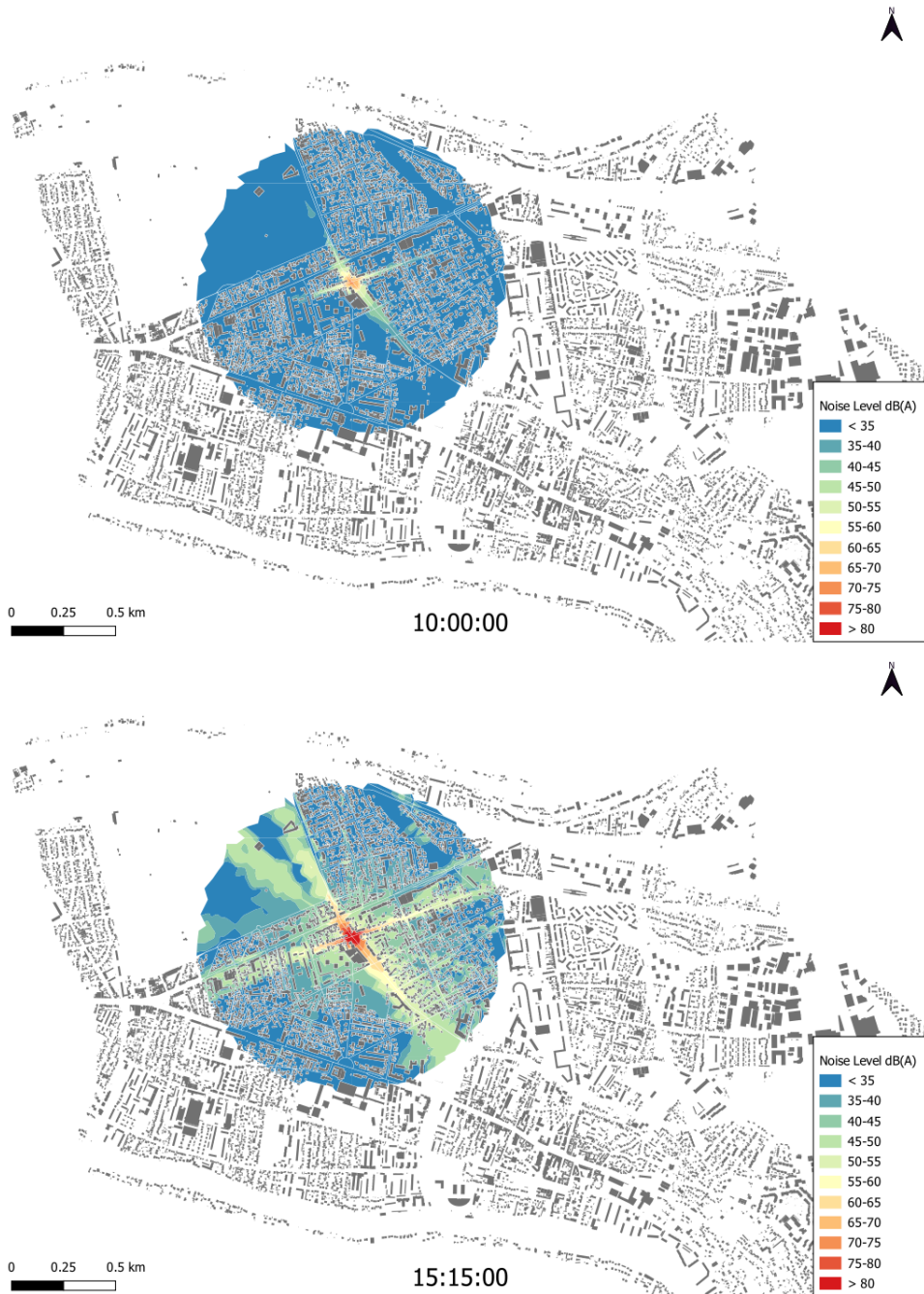


Figure 10: Noise map of construction site machines for the quarter-hours starting at 10 a.m. and 3:15 p.m. respectively.

4.5. Individual exposure assessment

In this study, the individual exposure module computes the exposure level for each individual in the synthetic population for quarter-hour time periods throughout the day. Figures 11 and 12

illustrate the noise exposure levels of two persons, chosen among the individuals impacted by the construction site. In both figures, activities of each individual are represented at the bottom. The blue curve represents the traffic noise level at each individual locality, the red curve represents the construction site noise level, and the green curve represents the logarithmic sum of the two levels.

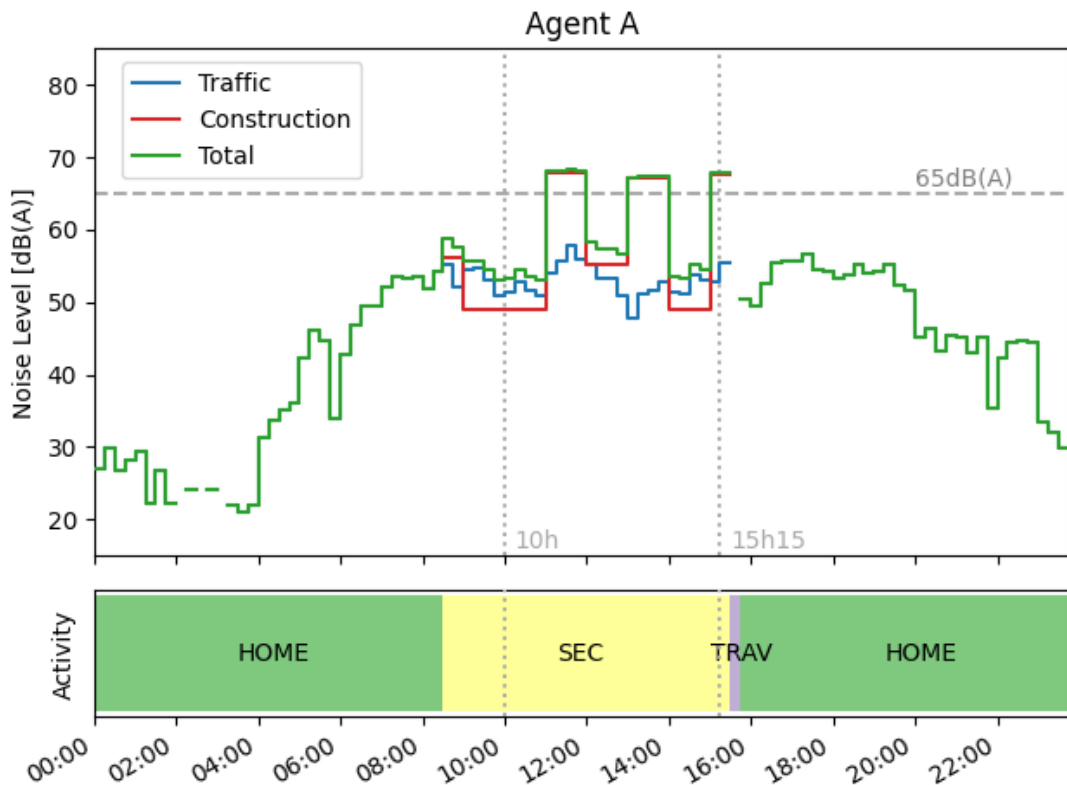


Figure 11: Noise exposure of individual A at different points in time and during various activities throughout the day.

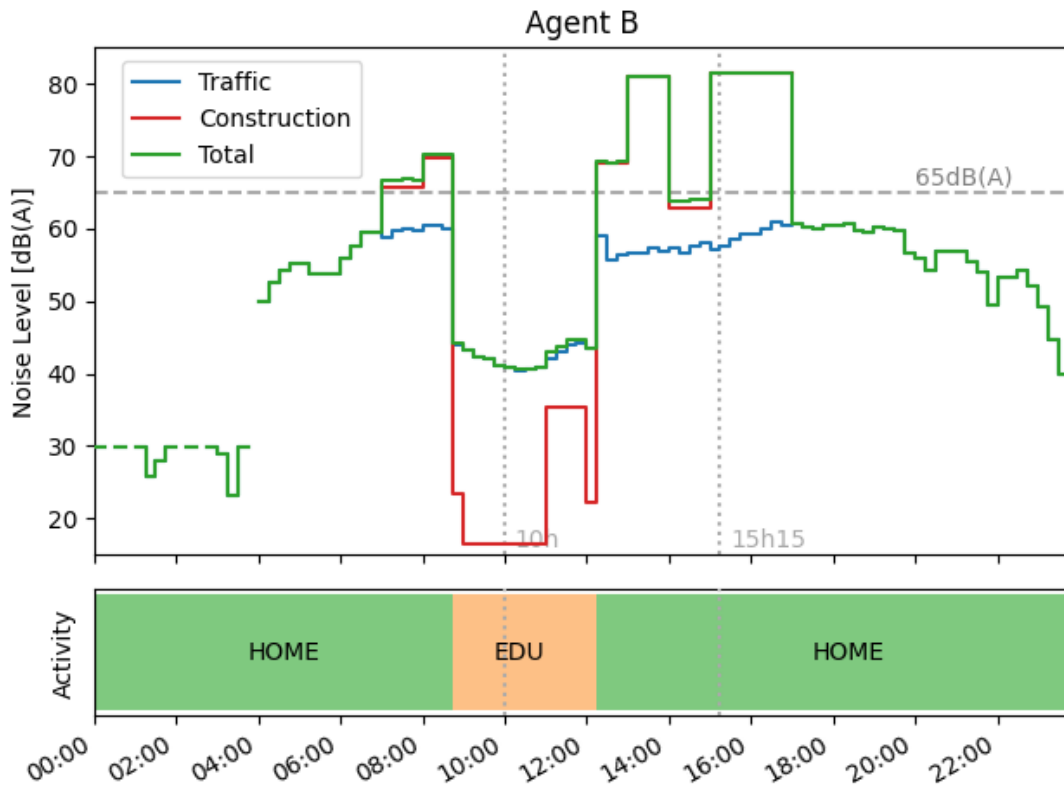


Figure 12: Noise exposure of individual B at different points in time and during various activities throughout the day.

Figure 11 illustrates the noise exposure of individual A at different points in time and activities throughout the day. Noise exposure is exclusively due to the traffic noise when individual A is at home (“HOME” activity), as there is no contribution from the construction site. When individual A engages in a secondary activity (“SEC” activity), the construction site contributes to his or her exposure level, with this contribution fluctuating depending on the construction site schedule. It should be noted that the noise level is zero when the individual is in transit (“TRAV” activity), as we do not take into account the exposure during travel. Figure 12 shows the noise exposure of individual B. Individual B is impacted by construction site noise during both his “HOME” and “EDU” (for education) activities. However, the “EDU” activity is located farther away from the construction site and the buildings provide some noise attenuation. As a result, the noise level during the “EDU” activity is almost the same as the traffic noise. On the contrary, while at home,

the agent is severely impacted by the construction site. A key aspect shown in these figures, used to compute our assessment indicator of construction site noise exposure, is when the construction site's contribution leads to an individual's "Total" noise level exposure surpassing a specified threshold for particular time periods of the day. Herein, we use the 65dB(A) threshold to illustrate this phenomenon.

The individual exposure assessment throughout the day can be used to compute various statistics. For example, Figure 13 depicts maps of the number of individuals exposed to a "Total" noise level exceeding 65 dB(A) across 100x100 m. grid areas for the quarter-hour starting at 10 a.m. and the quarter-hour starting at 3:15 p.m. respectively, taking into account both background noise, stemming from the traffic computed by MATSim, and construction site noise emissions. The analysis reveals a clear pattern: the grid areas with the highest concentration of individuals exposed to noise levels exceeding 65 dB (A) are located close to major road segments or the construction site. For grid areas near the construction site, this observation holds particularly true for the quarter-hour starting at 15:15 p.m., coinciding with the operation of the hydraulic breaker at the construction site.

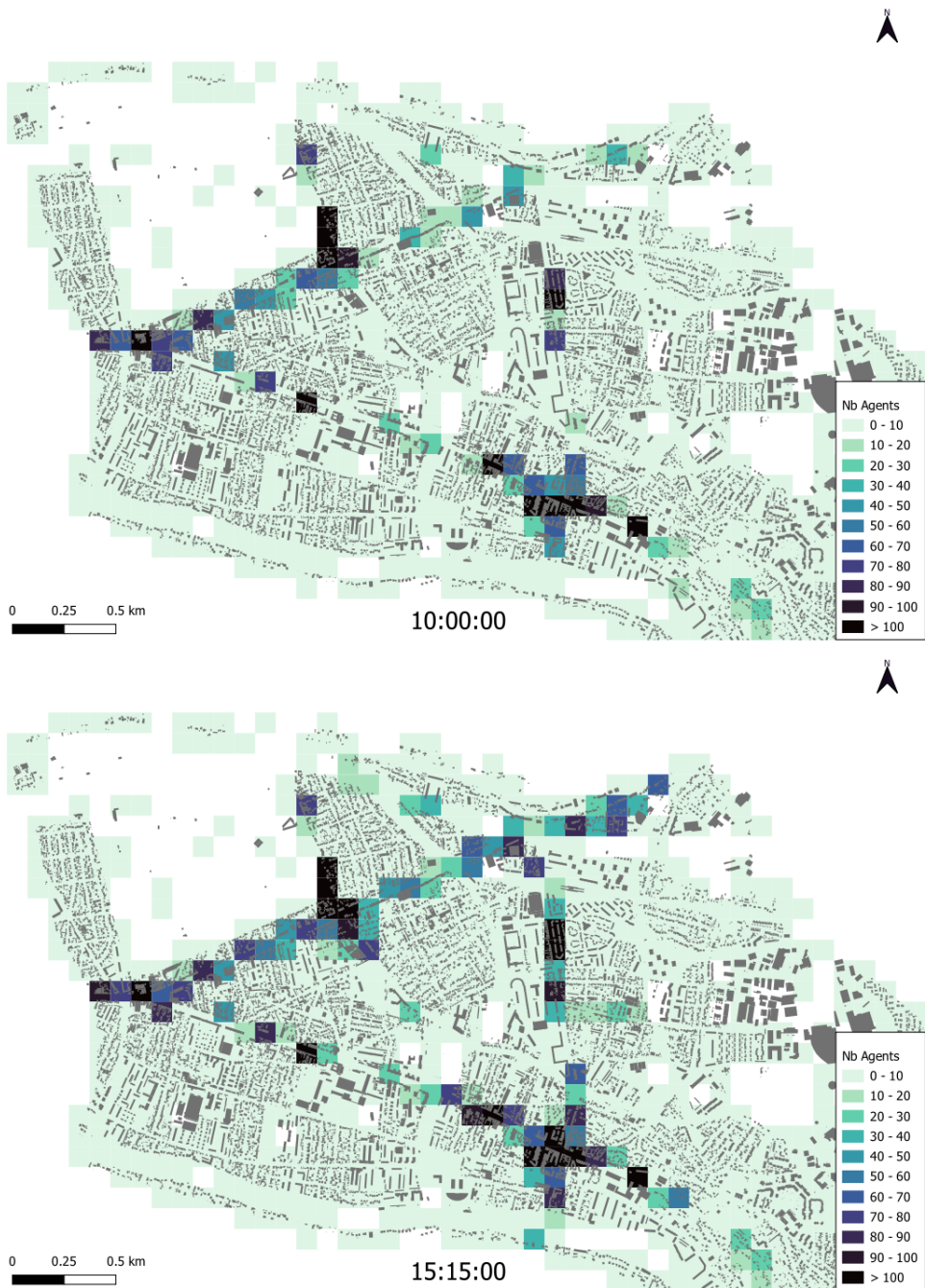


Figure 13: Count of individuals exposed to a noise level exceeding 65 dB(A) across 100x100 m. grid areas for the quarter-hours starting at 10 a.m. and 3:15 p.m. respectively, taking into account both background noise (i.e. traffic noise) and construction site noise emissions.

4.6. Computing construction site exposure indicators

In this section, we depict various representations of the indicator values assessing noise exposure to the construction site. We offer map-based and chart-based visualizations that provide a global assessment of population exposure. The same approach can be replicated and used to analyze noise impact on specific population categories. Figure 14 shows maps illustrating the difference in the number of individuals exposed to noise levels surpassing 65 dB(A) for different 100x100 m. grid areas, between the configuration with the construction site and the configuration without it. These maps specifically represent the quarter-hours starting at 10 a.m. and 3:15 p.m., respectively. Observations indicate that for the quarter-hour starting at 10 a.m., additional individuals exposed to levels above 65 dB(A) are localized within a single grid area positioned in immediate proximity to the construction site. This aligns with the operational period of construction machinery featuring lower emission power, such as the cable-operated skip and excavator. In contrast, during the quarter-hour starting at 3:15 p.m., additional exposed individuals are distributed across multiple grid areas surrounding the construction site. This trend corresponds to the utilization of construction site machinery characterized by higher emission power, particularly the hydraulic breaker.



Figure 14: Difference in the number of individuals exposed to noise levels exceeding 65 dB(A) across 100x100 m. grid areas, during the quarter-hours starting at 10 a.m. and 3:15 p.m. respectively, comparing the configuration with the construction site to the one without it.

Figure 15 shows a chart that visually represents the difference in the number of individuals exposed to noise levels surpassing 65 dB(A) across different time periods (i.e. quarter-hours)

throughout the day (Figure 20 in appendix C shows charts for 45 dB(A), 55 dB(A), and 75 dB(A) thresholds). In Figure 15, three distinct peaks are discernible, corresponding to time periods exhibiting a notable increase in the number of additional exposed individuals. These peaks exhibit a robust correlation with fluctuations in noise emissions from the construction site. This linkage becomes evident when scrutinizing Figure 7, revealing that these peaks coincide with the operation of machinery characterized by high emission power. It is worth noting that the number of additional individuals exposed to noise levels above 65 dB(A) is also influenced by two supplementary factors: the number of people present in the area and the background noise (i.e. the noise from road traffic, Figure 9). Nonetheless, the variations in these two factors remain minimal within the construction site's influence zone during the time periods when the peaks are observed.

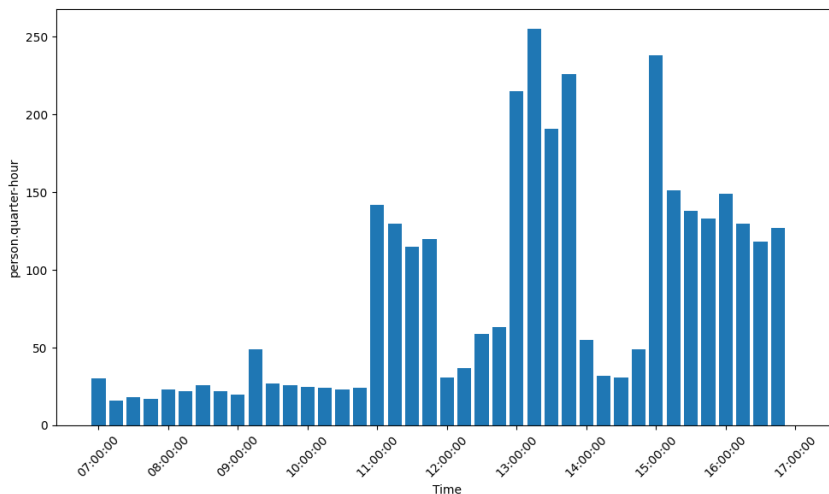


Figure 15: Difference in the number of individuals exposed to noise levels exceeding 65 dB(A) for different time periods throughout the day.

The granularity of the available data, facilitated by the individual-level activity-based modeling framework, enables us to analyze the characteristics of the additional individuals exposed to levels above 65 dB(A). This analysis allows for the identification of individual categories that are more susceptible than others to being exposed to noise from the construction site, along with additional insights into the specific zones of presence and the time periods that are most critical. Figure 18 in appendix B presents statistics regarding the sex, age, and income of the additional individuals

who have experienced noise levels exceeding 65 dB(A) because of the construction site activities on a typical day. Furthermore, Figure 19 in appendix B illustrates the activities undertaken by individuals during the quarter-hour period in which they were exposed to noise levels surpassing 65 dB(A) because of the construction site. For the sake of simplicity, we classify these activities into three types: 'home,' 'work,' and 'others', with the category 'others' encompassing leisure activities, shopping, and more.

Lastly, Figure 16 shows the difference in the number of person. quarter-hour exposed to noise levels surpassing specific thresholds during a typical day of the earthworks-foundations construction phase. For example, the total number of additional person. quarter-hour exposed above 65 dB(A) over a typical day is estimated at around 3,300. This value represents a good indicator to summarize the exposure to noise from the construction site for a typical day. It can be declined for specific population categories. It should be noted that this study focuses predominantly on exposure assessment using the 65 dB(A) threshold. However, the analysis can be extrapolated to different noise thresholds.

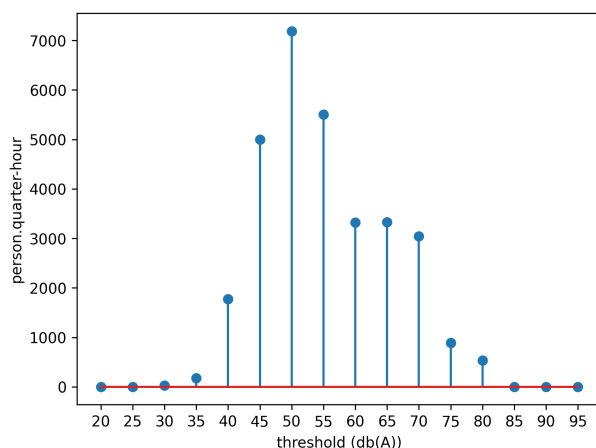


Figure 16: Difference in the number of person. quarter-hour exposed to noise levels exceeding various thresholds for a typical day during the earthworks-foundations construction phase.

5. Discussion

5.1. Benefits of the method

The novel individual-level activity-based method presented in this paper represents a significant advancement in the assessment of construction site noise exposure. By focusing on evaluating individual exposure for successive time periods over the day, this approach offers great potential by allowing for a finer, more reliable, and more detailed assessment of exposure to construction site noise. This enhanced accuracy sets our developed approach apart from previous methods. An in-depth explanation of the method's contributions and potential will be provided below.

5.1.1. Suitable assessment methodology for a noise mitigation managerial tool during pre-construction planning

A temporally-detailed individual-centric approach to evaluate construction site noise exposure enables realistic assessments that prove to be suitable for decision-making purposes. The method proposes indicators specifically tailored for such an individual-based evaluation. By offering appropriate and reliable metrics (see Equation 2, Section 3.4), it empowers decision-makers to make informed choices about construction site noise management and mitigation measures. This approach can also help decision-makers design more effective strategies to both reduce the noise impacts on surrounding communities and improve overall environmental quality. For example, during the pre-construction phase, different construction scenarios can be envisioned, with different starting times of the noisiest construction equipment. Using our methodology, each scenario can be evaluated and the one that minimizes the noise effects on nearby residents can be identified. In sum, all practitioners dedicated to achieving sustainable urban environments benefit from this research: design offices can better schedule construction operations, civil engineering companies can opt for equipment better suited to the site environment, and local authorities can better inform and engage with the local population about the construction project, thereby increasing public acceptance and reducing complaints.

5.1.2. An opportunity for further investigation

The method's ability to yield detailed socioeconomic evaluations of the population exposed to construction site noise expands its utility even further. Understanding the demographic characteristics and activity patterns of the exposed population can help identify vulnerable groups and tailor noise abatement measures to meet their specific needs. This approach promotes a more equitable and inclusive approach to noise exposure management, which in turn benefits both the construction industry and affected communities. In general, this novel individual-level, activity-based method opens new avenues for comprehensive and targeted noise exposure assessments, in offering the promise of a more sustainable and harmonious coexistence between construction activities and the surrounding environment. Additionally, this study has examined the noise pollution aspects of a construction site; however, similar methodologies could serve to evaluate the local impact of air pollution as well. Such an impact also varies with the population dynamics throughout the day, as would be expected. Lastly, the case study has illustrated the feasibility of a multi-agent simulation, especially as regards the computational resources required to address realistic scenarios.

5.1.3. Impact on regulations

Since current regulations depend on existing methodologies, this new method could pave the way for new regulations better adapted to the public's expectations and needs, thereby enhancing the social acceptance of construction projects.

5.2. Method limitations

Although the activity-based individual-level method offers significant advantages in assessing construction site noise exposure, it is crucial to recognize its limitations so as to gain a comprehensive understanding of its applicability as well as identify potential areas for further improvement. Some of the limitations inherent in the method and case study will be presented hereafter.

5.2.1. Limitations of the method

- Due to its application during the pre-construction phase, a degree of uncertainty is to be anticipated regarding the operations of construction site machinery. The positioning and

planning of this machinery may at times be imprecise, thus leading to potential inaccuracies in the noise exposure assessment.

- The representativeness of the synthetic population and activity plans depends on the available data used for their generation. Should the available datasets not be representative of the actual population, then considerable uncertainties would remain regarding individual descriptions, locations and activities, which in turn can affect the accuracy of the exposure assessment.
- For computational efficiency, a reduction in resolution was implemented when representing the time-space information of the population during the individual exposure assessment (this reduction is not applied to MATSim input). While this reduction does enhance computational efficiency, it may introduce inaccuracies into the evaluation of individuals' noise exposure.
- The use of complex simulators, such as traffic and noise simulators, introduces additional uncertainties, specific to, for example, the traffic model or the noise levels estimated by the propagation model.
- Assessing individuals' noise exposure levels inside buildings poses a challenge due to the lack of precise knowledge about their specific positions within the structure. As such, their exposure levels are considered to be equivalent to those measured at the building facade, thereby introducing uncertainties into the exposure assessment.

5.2.2. *Limitations of the case study*

- The exposure assessment focused on individuals who remain in fixed locations performing regular activities: individuals moving within the site's zone of influence, e.g. making trips, were not considered. The case study therefore neglects potential exposure while in movement.
- Due to incomplete information about the construction site, certain assumptions were necessary. For example, the scheduling of machinery activities was based on a typical day within the earthworks-foundations phase, in overlooking potential deviations. Also, due

to the unavailability of exact machine locations, emission sources were assigned to the geometric center of the construction site. Similarly, obtaining precise emission power data for construction equipment raised challenges, leading to the use of approximate values extracted from a technical manual. These limitations may have introduced a degree of uncertainty into the noise estimation process.

- During the noise simulation process, the positioning of receivers can exert a major impact on results. The receivers were randomly distributed on one facade of each building for this investigation, which may not accurately reflect true noise exposure. Although it would take longer to compute, a more complex strategy for positioning receivers throughout the building's facades would produce more accurate findings.
- The potential of the construction work to affect or modify the activities of people living or working near the site was not considered in this study. For example, due to the construction site, some places or services might become inaccessible or inconvenient, or else the noise level might become intolerable for some activities.
- The traffic model created for the case study contains several restrictions. The use of MATSim, which is not a framework for microscopic modeling, simplifies vehicle kinematics and might not adequately capture the impact of certain kinematic parameters on noise emissions. Furthermore, the absence of freight traffic data in the simulation limits its representation of real-world scenarios.

5.3. Perspectives as regards impact assessments

This article has presented a methodology for computing a variety of indicators beyond those reported. One key aspect of this methodology is the estimation of noise exposure for each individual for successive time periods over the day, both with and without the construction site being present. This feature enables computing of various indicators. Figure 16 displays, for example, the number of person-quarter-hour units of exposure to noise levels surpassing different thresholds. These

valuations can be employed to derive a comprehensive indicator using a suitable aggregation method. Such an indicator along with others can thus incorporate a broader calculation of noise costs; however, this step would necessitate deliberation on the aggregation of impacts at a 15-minute scale on a daily basis. In addition, indicators can potentially be weighted by time of day, so as to account for the varying noise sensitivity across different periods.

The present paper has introduced a case study that involves only direct emission sources from construction sites. In the case study, the noise emissions originated from construction site machinery, with no consideration given to the contribution from altered traffic patterns. These indirect effects can have two possible outcomes. In some areas, the direct effects of construction may be offset by the reduction in road traffic noise, which occurs when vehicles or activities are diverted or reduced. In other areas, a traffic shift leads to increased noise and travel times. A subsequent case study will examine and discuss these indirect costs as part of a more comprehensive assessment.

This same methodology could be used to evaluate noise exposure to indirect sources, in encompassing noise emissions related to traffic pattern adjustments. To achieve this goal, a revised transport network graph reflecting changes induced by the construction site would replace the assumption of an unaltered network graph when comparing configurations with and without the construction site. Integrating this modification would produce adjusted traffic noise emissions for the configuration with the construction site, in leaving all other procedural steps unaffected.

6. Conclusion

In this article, we have introduced a novel method along with a novel indicator for assessing construction site noise exposure. Our approach emphasizes achieving reliable and comprehensive pre-construction evaluations. Hence, it can be integrated into a pre-construction evaluation tool, empowering managers to inform the public and implement strategies for minimizing negative impacts. The paper introduces a four-step bottom-up approach, demonstrated through its application to analyze exposure to a construction site noise during the earthworks-foundations phase.

In the first step, noise emission sources are characterized in terms of their spatial, temporal, and emission power attributes. For our case study, we relied on the construction site machinery schedule during a standard day of the earthworks-foundations phase for spatio-temporal information. The emission power of the construction site machines was extracted from a technical guide. In the second step, an individual-level, activity-based modeling of the influence zone of the construction site is performed. For the case study, we used Eqasim to generate a synthetic population of 1,344,394 individuals grouped into 591,153 households, with social, demographic and economic attributes. Subsequently, a total of 4,854,597 activities during the course of a typical day, with precise locations, were assigned to individuals.

In the third step, individual exposure to noise is assessed for both configurations, with and without the construction site, throughout the day. To accomplish this, we use traffic and noise simulation software, along with a specially designed module for assessing individual exposure. For the case study, we used the MATSim simulation tool to establish a traffic model for the extended Val-de-Marne area. We utilized NoiseModelling software to calculate noise maps. The individual exposure module was then applied to assess the exposure of each person, at each time period, for both configurations. Maps were provided to illustrate noise levels and the distribution of individuals exposed to noise levels that exceeded defined thresholds throughout the day. In the final step, a novel indicator is computed, allowing a finer assessment of the contribution of the construction site to noise exposure. This indicator reflects the difference in the cumulative amount of exposure time above a given noise threshold between the two distinct configurations, with or without the construction site. This indicator can be computed for the global population or for specific categories. In the case study, a graph depicted the difference in the number of person.quarter-hour exposed to noise levels that exceeded various thresholds during a typical day of the earthworks-foundations construction phase. For instance, it highlighted a difference of over 3,300 person.quarter-hours above 65dB(A) between the two configurations. Furthermore, various statistics were provided for additional individuals exposed to noise levels above 65 dB(A).

Lastly, as a forward-looking perspective derived from this study, our intention is to incorporate our approach into the decision-making process for evaluating and selecting among various construction site's scenarios. This pertains to the assessment and comparison of diverse adjustments to construction site planning. Ultimately, this will empower decision-makers to make well-informed and suitable choices to minimize noise impacts.

A. Synthetic population data

Table 2

Generated attributes of synthetic individuals.

Attribute	Values	Stats
person_id	numerical	
household_affiliation	numerical	
age	numerical	mean: 39.8, std: 22.5
employed	True/False	True: 47%
sex	Female/Male	female: 50%, male: 50%
socio-professional_class	agriculture, independent, leading, intermediate, employee, worker, retired, other	respectively: 0%, 2%, 12%, 13%, 15%, 7%, 16%, 33%
has_driving_licence	True/False	True: 66%
has_public_transport_subscription	True/False	True: 23%

Table 3

Generated attributes of synthetic households.

Attribute	Values	Stats
household_id	numerical	
car_availability	True/False	True: 66%
income	numerical	mean: 3096, std: 2096

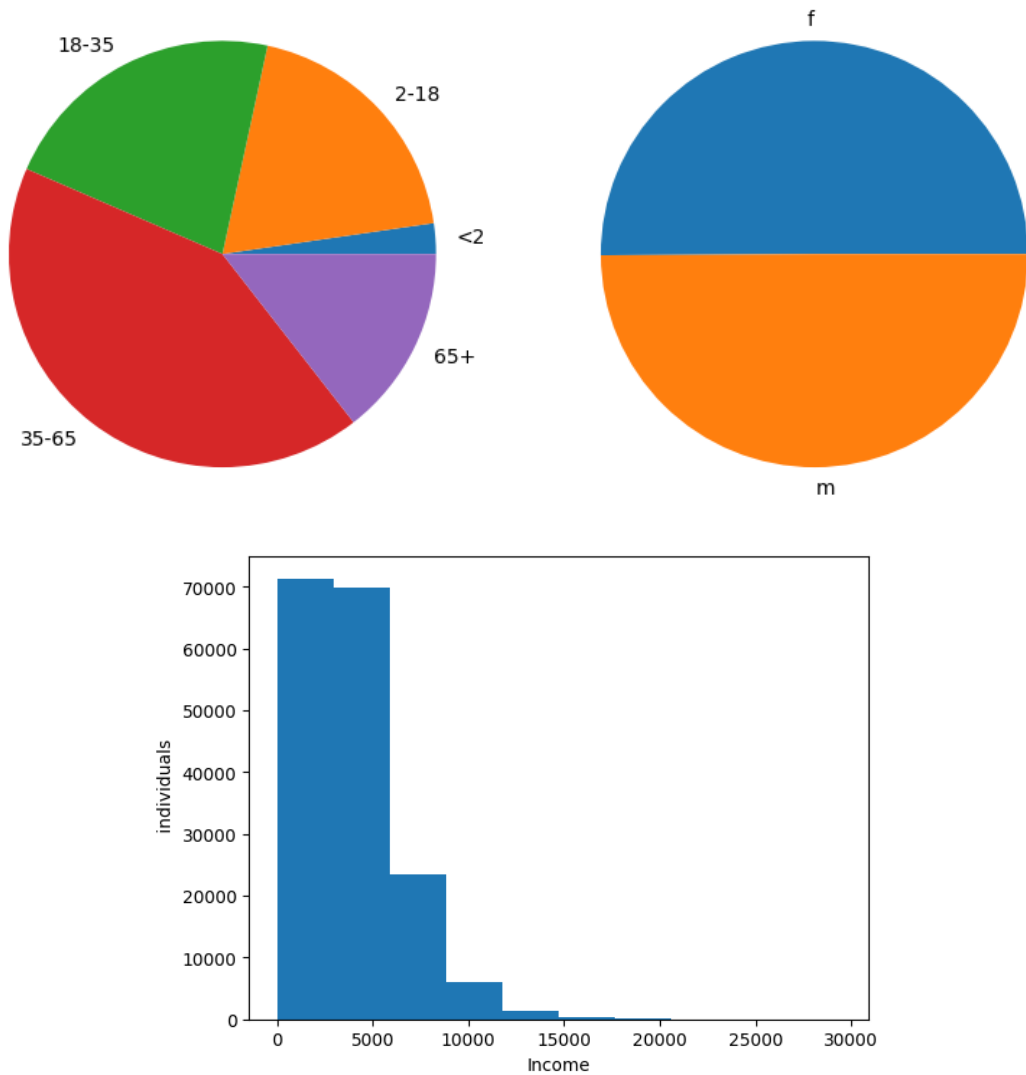


Figure 17: Statistical data depicting the characteristics (age, sex, and income) of the synthetic population. The top left chart illustrates the distribution of age groups, while the top right chart displays the distribution of sex groups. The bottom chart showcases the number of individuals (ordinate axis) per income range in euros per month.

B. Statistics of the population exposed to noise levels above 65 dB(A) due to the construction site

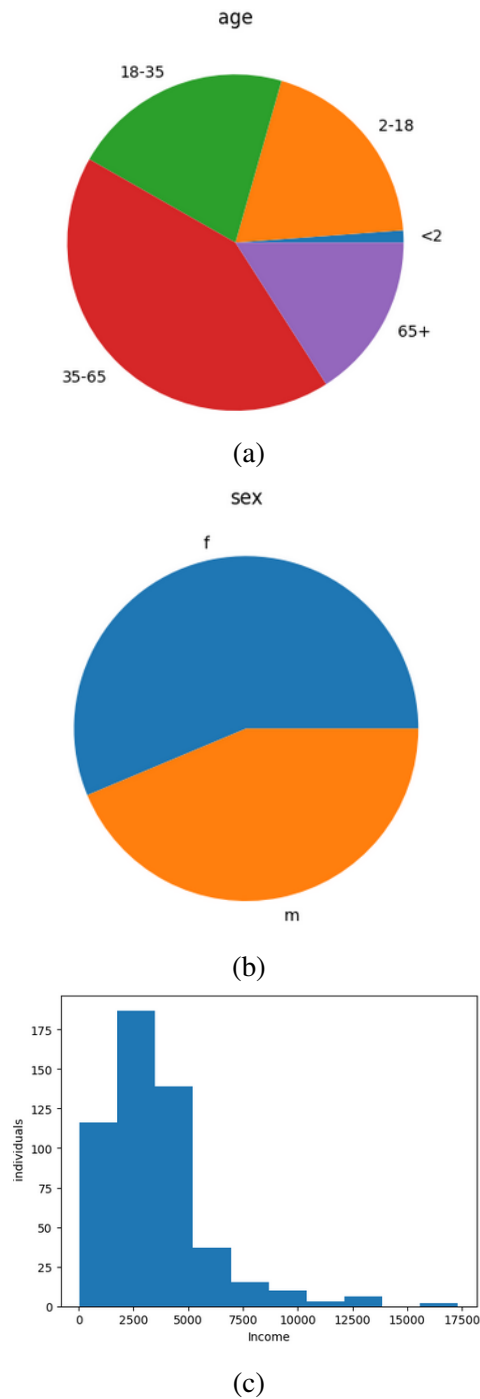


Figure 18: Statistical data depicting the characteristics of additional individuals exposed to noise levels above 65 dB due to the construction site. Chart (a) illustrates the distribution of age groups, while chart (b) displays the distribution of sex groups. The bottom chart (c) showcases the number of individuals (ordinate axis) per income range in euros per month.

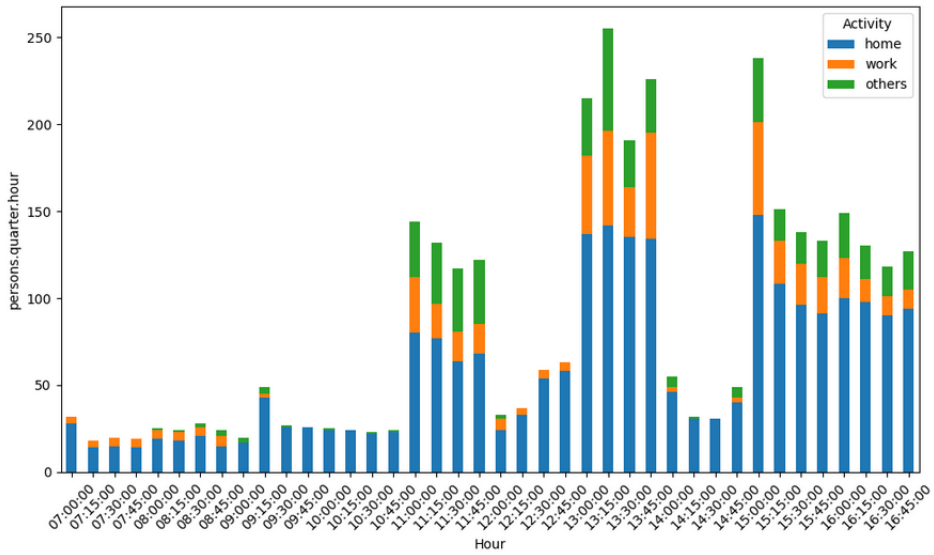


Figure 19: Activities carried out by individuals during the quarter-hour in which they were exposed to noise levels above 65 dB(A) due to the construction site.

C. Difference in the number of individuals exposed to noise levels exceeding 45 dB(A), 55 dB(A), and 75 dB(A) for different time periods throughout the day

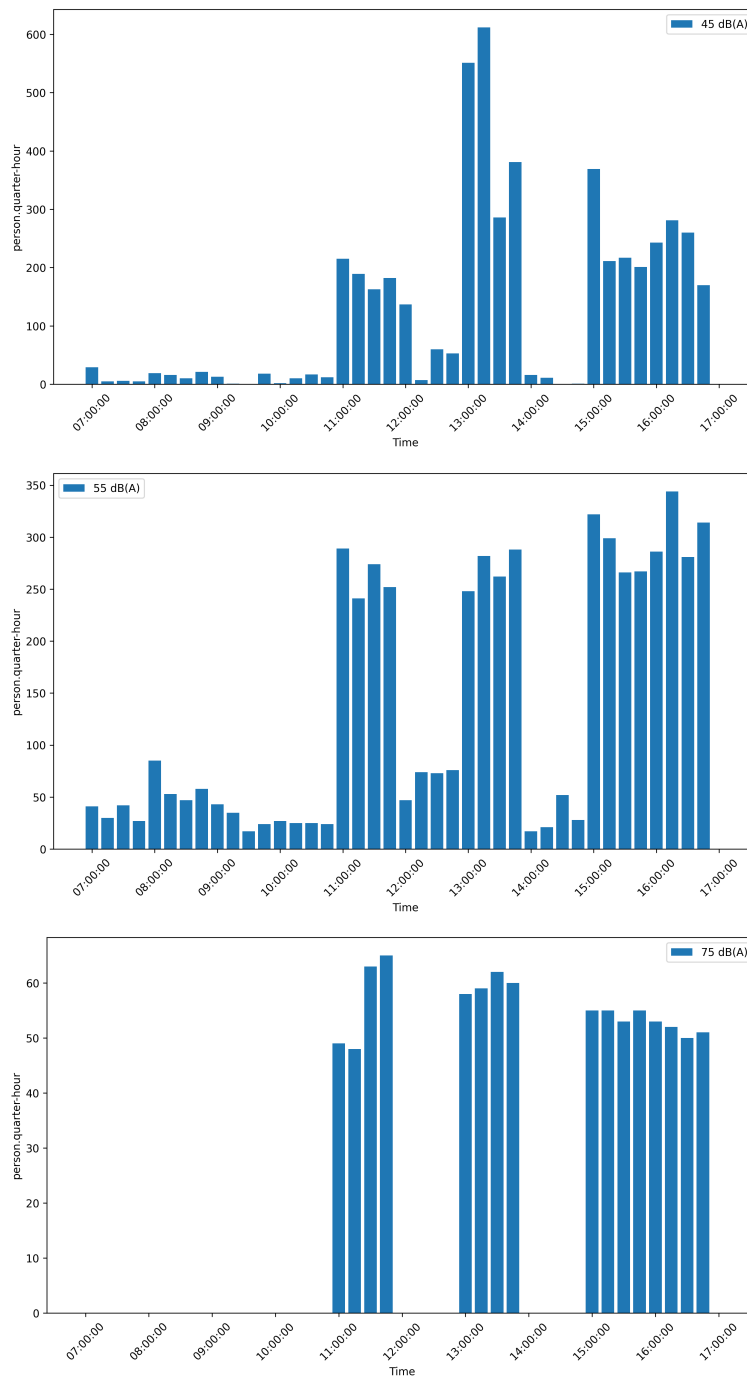


Figure 20: Difference in the number of individuals exposed to noise levels exceeding 45 dB(A), 55 dB(A), and 75 dB(A) for different time periods throughout the day.

References

- Aletta, F., Oberman, T., and Hatfield, J. (2018). Noise pollution in urban areas: An overview of its health effects, sources, and control strategies. *Frontiers in Psychology*, 9:1–18.
- Avram, S., Figari, F., Leventi, C., Levy, H., Navicke, J., Matsaganis, M., Militaru, E., Paulus, A., Rastringina, O., and Sutherland, H. (2013). The distributional effects of fiscal consolidation in nine eu countries. Technical report, Euromod working paper.
- Beckx, C., Panis, L. I., Arentze, T., Janssens, D., Torfs, R., Broekx, S., and Wets, G. (2009). A dynamic activity-based population modelling approach to evaluate exposure to air pollution: methods and application to a dutch urban area. *Environmental Impact Assessment Review*, 29(3):179–185.
- Bocher, E., Guillaume, G., Picaut, J., Petit, G., and Fortin, N. (2019). Noisemodelling: An open source gis based tool to produce environmental noise maps. *Isprs international journal of geo-information*, 8(3):130.
- Borysov, S. S., Rich, J., and Pereira, F. C. (2019). How to generate micro-agents? a deep generative modeling approach to population synthesis. *Transportation Research Part C: Emerging Technologies*, 106:73–97.
- Brocolini, L., Lavandier, C., Quoy, M., and Ribeiro, C. (2013). Measurements of acoustic environments for urban soundscapes: Choice of homogeneous periods, optimization of durations, and selection of indicators. *The Journal of the Acoustical Society of America*, 134(1):813–821.
- (BS), B. S. (2009). Bs5228:2009, code of practice for noise and vibration control on construction and open sites. part 1: Noise. Technical report, BSI, London.
- Cahen, R., Hiétin, G., and Masson, B. (2019). Livre blanc - silence chantier. Technical report, Société du Grand Paris.
- Chapuis, K., Taillandier, P., Renaud, M., and Drogoul, A. (2018). Gen*: a generic toolkit to generate spatially explicit synthetic populations. *International Journal of Geographical Information Science*, 32:1194–1210.
- Choi, J., Hong, J., Kang, H., Hong, T., Park, H. S., and Lee, D.-E. (2022). An automatic decision model for optimal noise barrier plan in terms of health impact, productivity, and cost aspects. *Building and Environment*, 216:109033.
- Cucurachi, S., Schiess, S., Froemelt, A., and Hellweg, S. (2018). Noise footprint from personal land-based mobility. *Journal of Industrial Ecology*, 23(5):1028–1038.
- Dervaux, B. and Rochaix, L. (2022). L'évaluation socioéconomique des effets de santé des projets d'investissement public. *Évaluation*.
- Dervaux, B., Rochaix, L., Meurisse, B., Robinet, A., Banoun, S., Domergue, S., Guéro, P., Hartmann, L., Meynard, C.-L., and Ni, J. (2022). Socio-economic evaluation of the health effects of public investment projects.
- Directive, E. (2000). 14/ec of the european parliament and of the council of 8 may 2000 on the approximation of the laws of the member states relating to the noise emission in the environment by equipment for use outdoors. *EU: Brusel, Belgium*, 2000.
- Edwards, K. L. and Clarke, G. (2013). Simobesity: combinatorial optimisation (deterministic) model. In *Spatial Microsimulation: A reference guide for users*, pages 69–85. Springer.
- Elancheliyan, S. (2013). Noise effects of generator sets at construction sites. *Int. J. Occup. Saf. Health*, 3(2):12–17.
- Fabrice Yaméogo, B., Gastineau, P., Hankach, P., and Vandanjon, P.-O. (2021). Comparing methods for generating a two-layered synthetic population. *Transportation research record*, 2675(1):136–147.
- Fang, J.-H., Zhou, Y.-Q., Hu, X.-D., and Wang, L. (2009). Measurement and analysis of exhaust noise from muffler on an excavator. *International journal of precision engineering and manufacturing*, 10:59–66.
- Farooq, B., Bierlaire, M., Hurtubia, R., and Flötteröd, G. (2013). Simulation based population synthesis. *Transportation Research Part B: Methodological*, 58:243–263.
- Ganić, E., Rajé, F., and van Oosten, N. (2023). New perspectives on spatial and temporal aspects of aircraft noise: Dynamic noise maps for heathrow airport. *Journal of Transport Geography*, 106:103527.

- Gastineau, P., Can, A., Yaméogo, B. F., Luquezi, L. G., Hankach, P., Vandanjon, P.-O., and Bescond, V. L. (2023). Modeling exposure to mobility-related pollution: Review and key challenges. *Transportation Research Record*, page 03611981231208907.
- Gerike, R., Becker, T., Friedemann, J., Hülsmann, F., and Heidegger, F. (2012). Mapping external noise costs to the transport users—conceptual issues and empirical results. In *Proceedings of the Euronoise 9th European conference on noise control, Prague*, pages 10–13.
- Gilchrist, A., Allouche, E., and Cowan, D. (2003). Prediction and mitigation of construction noise in an urban environment. *Canadian journal of civil engineering*, 30(4):659–672.
- Haron, Z., Noh, H. M., Yahya, K., Omar, W., and Majid, Z. (2012). Assessing noise emission levels from earthwork construction equipment. *Malaysian Journal of Civil Engineering*, 24(1):13–28.
- Haron, Z. and Yahya, K. (2009). Monte carlo analysis for prediction of noise from a construction site. *Journal of Construction in Developing Countries*, 14(1).
- Hatzopoulou, M. and Miller, E. J. (2010). Linking an activity-based travel demand model with traffic emission and dispersion models: Transport's contribution to air pollution in toronto. *Transportation Research Part D: Transport and Environment*, 15(6):315–325.
- Hermes, K. and Poulsen, M. (2012). A review of current methods to generate synthetic spatial microdata using reweighting and future directions. *Computers, Environment and Urban Systems*, 36(4):281–290.
- Hong, J., Kang, H., Hong, T., Park, H. S., and Lee, D.-E. (2021). Development of a prediction model for the proportion of buildings exposed to construction noise in excess of the construction noise regulation at urban construction sites. *Automation in Construction*, 125:103656.
- Hörl, S. and Balac, M. (2021a). Introducing the eqasim pipeline: From raw data to agent-based transport simulation. *Procedia Computer Science*, 184:712–719.
- Hörl, S. and Balac, M. (2021b). Synthetic population and travel demand for paris and île-de-france based on open and publicly available data. *Transportation Research Part C: Emerging Technologies*, 130:103291.
- Hörl, S., Balac, M., and Axhausen, K. W. (2018). A first look at bridging discrete choice modeling and agent-based microsimulation in matsim. *Procedia computer science*, 130:900–907.
- Horni, A., Nagel, K., and Axhausen, K. W. (2016). *The multi-agent transport simulation MATSim*. Ubiquity Press London.
- IGN (2023). BD TOPO. <https://geoservices.ign.fr/bdtopo>. Accessed: 2023-07-13.
- INSEE (2023a). Enterprise census. <https://www.sirene.fr/sirene/public/accueil>. Accessed: 2023-07-13.
- INSEE (2023b). Permanent database of facilities. <https://www.insee.fr/en/metadonnees/source/serie/s1161>. Accessed: 2023-07-13.
- INSEE (2023c). Population census. <https://www.insee.fr/en/metadonnees/source/serie/s1321>. Accessed: 2023-07-13.
- INSEE and the ministry of finance (2023). Mobilités professionnelles. <https://www.casd.eu/source/fichier-localise-social-et-fiscal/>. Accessed: 2023-07-13.
- Jung, S., Kang, H., Choi, J., Hong, T., Park, H. S., and Lee, D.-E. (2020). Quantitative health impact assessment of construction noise exposure on the nearby region for noise barrier optimization. *Building and Environment*, 176:106869.
- Kaddoura, I., Kröger, L., and Nagel, K. (2017). An activity-based and dynamic approach to calculate road traffic noise damages. *Transportation Research Part D: Transport and Environment*, 54:335–347.
- Kephalopoulos, S., Paviotti, M., and Anfosso-Lédée, F. (2012). Common noise assessment methods in europe (cnossos-eu).
- Kickhöfer, B. and Kern, J. (2015). Pricing local emission exposure of road traffic: An agent-based approach. *Transportation Research Part D: Transport and Environment*, 37:14–28.
- Kwon, N., Lee, J., Park, M., Yoon, I., and Ahn, Y. (2019). Performance evaluation of distance measurement methods for construction noise prediction using case-based reasoning. *Sustainability*, 11(3):871.

- Le Bescond, V., Can, A., Aumond, P., and Gastineau, P. (2021). Open-source modeling chain for the dynamic assessment of road traffic noise exposure. *Transportation Research Part D: Transport and Environment*, 94:102793.
- Lee, S.-W., Chang, S. I., and Park, Y.-M. (2008). Utilizing noise mapping for environmental impact assessment in a downtown redevelopment area of seoul, korea. *Applied Acoustics*, 69(8):704–714.
- McNally, M. G. (2007). The Four-Step Model. In A. Hensher, D. and J. Button, K., editors, *Handbook of Transport Modelling*, volume 1, pages 35–53. Emerald Group Publishing Limited.
- Ministry of Ecology (2023). National transport and travel survey. <https://www.insee.fr/en/metadonnees/source/serie/s1277>. Accessed: 2023-07-13.
- Mir, M., Nasirzadeh, F., Bereznicki, H., Enticott, P., Lee, S., and Mills, A. (2023). Construction noise effects on human health: Evidence from physiological measures. *Sustainable Cities and Society*, 91:104470.
- Mir, M., Nasirzadeh, F., Lee, S., Cabrera, D., and Mills, A. (2022). Construction noise management: A systematic review and directions for future research. *Applied Acoustics*, 197:108936.
- Müller, K. (2017). *A generalized approach to population synthesis*. PhD thesis, ETH Zurich.
- Münzel, T., Gori, T., Babisch, W., and Basner, M. (2014). Cardiovascular effects of environmental noise exposure. *European heart journal*, 35(13):829–836.
- Namazi-Rad, M.-R., Tanton, R., Steel, D., Mokhtarian, P., and Das, S. (2017). An unconstrained statistical matching algorithm for combining individual and household level geo-specific census and survey data. *Computers, Environment and Urban Systems*, 63:3–14.
- O’Sullivan, D. (2008). Geographical information science: agent-based models. *Progress in Human Geography*, 32(4):541–550.
- Pirrerá, S., De Valck, E., and Cluydts, R. (2010). Nocturnal road traffic noise: A review on its assessment and consequences on sleep and health. *Environment international*, 36(5):492–498.
- Rempel, D., Antonucci, A., Barr, A., Cooper, M. R., Martin, B., and Neitzel, R. L. (2019). Pneumatic rock drill vs. electric rotary hammer drill: Productivity, vibration, dust, and noise when drilling into concrete. *Applied ergonomics*, 74:31–36.
- Roorda, M. J., Miller, E. J., and Habib, K. M. (2008). Validation of tasha: A 24-h activity scheduling microsimulation model. *Transportation Research Part A: Policy and Practice*, 42(2):360–375.
- Saadi, I., Mustafa, A., Teller, J., and Cools, M. (2016). Forecasting travel behavior using markov chains-based approaches. *Transportation Research Part C: Emerging Technologies*, 69:402–417.
- Sallard, A., Balac, M., and Hörl, S. (2020). A synthetic population for the greater são paulo metropolitan region. *Arbeitsberichte Verkehrs-und Raumplanung*, 1545.
- Shoval, N. and Isaacson, M. (2007). Sequence alignment as a method for human activity analysis in space and time. *Annals of the Association of American geographers*, 97(2):282–297.
- Sun, L. and Erath, A. (2015). A bayesian network approach for population synthesis. *Transportation Research Part C: Emerging Technologies*, 61:49–62.
- Sutherland, H. and Figari, F. (2013). Euromod: the european union tax-benefit microsimulation model. *International Journal of Microsimulation*, 6(1):4–26.
- Tomintz, M. N., Clarke, G. P., and Rigby, J. E. (2008). The geography of smoking in leeds: estimating individual smoking rates and the implications for the location of stop smoking services. *Area*, 40(3):341–353.
- Vallamsundar, S., Lin, J., Konduri, K., Zhou, X., and Pendyala, R. M. (2016). A comprehensive modeling framework for transportation-induced population exposure assessment. *Transportation Research Part D: Transport and Environment*, 46:94–113.

- Vardhan, H., Karmakar, N., and Rao, Y. (2006). Assessment of heavy earth-moving machinery noise vis-à-vis routine maintenance. *Noise control engineering journal*, 54(2):64–78.
- Wang, P., Xiang, H., Guo, M., Shi, Y., Chong, K. C., Huang, J., and Ho, H. C. (2023). Indoor and roadside exposures to traffic noise and cardiovascular mortality and the role of urban environmental stressors across a high-rise, high-density environment: A case study in hong kong. *Building and Environment*, 229:109945.
- Zhuge, C., Bithell, M., Shao, C., Li, X., and Gao, J. (2021). An improvement in matsim computing time for large-scale travel behaviour microsimulation. *Transportation*, 48:193–214.
- Zwick, F., Kuehnel, N., Moeckel, R., and Axhausen, K. W. (2021). Agent-based simulation of city-wide autonomous ride-pooling and the impact on traffic noise. *Transportation Research Part D: Transport and Environment*, 90:102673.