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Integrated Climate forcing and Air pollution Reduction in Urban Systems

D4.1 Report on the methodology for estimating individual exposure

WP4 Population exposure and health impact assessment

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1 Introduction

This report describes the ICARUS methodology for estimating individual exposure using AQ sensor technologies, personal activity and GPS sensors, as well as modelling approaches such Agent Based Modelling (ABM) for assessing exposure at the individual and community level of a city population. This document contains the outcome of the work done under Tasks 4.1 and 4.2 of the ICARUS WP4 and it is based on:

- the methodological aspects of population exposure as defined in the D1.2, deliverable on the conceptual framework of ICARUS,
- the conclusions of the D1.3, deliverable on the use of sensor technologies in defining external exposure at individual level,
- the conclusive part of the work reported under milestone MS9, focused on the protocol of the sensor-based exposure monitoring, that describes the proposed study elements, i.e. design, considerations, aspects, methods,
- the inhouse ABM platform latest developments and its adaptations to the ICARUS exposure modelling concept.

The report describes the methodology that leads to the exposure data to be used in Task 4.4 and deliverables D4.3 and D4.4.

1.1 Overall approach

In D1.2, deliverable on the conceptual framework of ICARUS, the overall exposure approach of ICARUS is defined. The aim of the ICARUS approach is to overcome the oversimplification of existing approaches that use ambient concentrations and apply concentration-response functions (CRFs) to estimate exposure, by taking into account the actual individual exposure to chemical stressors, which depends on time-activity profiles of individuals (e.g. time spent in traffic vs. indoors) as well as on the inhalation rate due to the intensity of every activity.

Exposure to environmental stressors varies depending on sociodemographic characteristics as well as in space and time. Thus, there is the need for a methodology that accounts for this complex nexus of interactive exposure determinants, rather than potentially misclassifying exposures by ignoring or improperly accounting for differences.

As personal “smart” technologies became more prevalent, portable, lower cost sensor systems enable monitoring of either personal exposure or external exposures close to the personal level, thus providing a more reliable “time–geography of exposure”. Wearable multi-sensor technologies can provide data relevant to a person's exposure to air pollutants accounting for the various microenvironments where one moves and the carried-out activities he/she undertakes.

Sensors are distinguished between two types: air quality sensors (AQ), and physical activity (PA) including location (GPS) tracking sensors. Within the first group we consider sensors measuring presence/concentrations of gases, particulate matter as well as specific environmental (e.g., meteorological) parameters. Second group comprise various physical activity sensors: accelerometers (also included in smartphone devices), respiration, heart rate, R-R interval, breathing rate, etc.

The **sensors to be used in the ICARUS project, measuring dynamically in time personal exposure, location, intensity of activity as well as some key meteorological parameters**, include: a) GPS, personal movement/activity and intensity of activity detection sensors (e.g. Fitbit, Moves app) and b) sensors that track environmental factors, such as temperature and relative humidity. In addition, we will explore the possibilities of using portable air quality monitors for air pollutants such as PM and NOX, as well as for toxic organic compounds such as PAHs, dioxins, furans, using and adapting smartphone technology, commercial off the shelf sensors and academic technological developments. Study participants will also be asked to fill in a questionnaire, providing useful information regarding their sociodemographic background.

A multi-platform data collection tool will store, manage and analyse all data coming from different devices, providing interpretation of the data using statistical advances, sophisticated data mining techniques, computing power as well as a careful sharing of data sources while also maintaining privacy protections for personal data.

Acknowledging the technical and financial hurdles involved in collecting real individual data for whole populations - especially when you want to capture exposure profiles of the entire sociodemographic spectrum of a region – , a decision has been made to also use simulation techniques to model human movement and interaction behaviour, informed by the sensor campaigns captured data.

The ICARUS modelling approach is based on Agent Based Modelling (ABM), a modelling technique that simulates the actions and interactions of autonomous software objects, the "agents", enabling a better understanding of the behaviour of individuals and populations in social and evolutionary settings. The agents (which can be people, vehicles, roads, cities, animals, products, etc.) are programmed to react and act in their environment and to have goals that they aim to satisfy. By modelling agents individually, the full effects of the diversity that exists among agents in their attributes and behaviours can be observed as it gives rise to the behaviour of the system as a whole.

By storing data in a Geographic Information System (GIS) and using geographically explicit ABM architecture, the trajectory of virtual people, "human agents", is modelled and projected on a single layer, superposed onto urban air quality modelled maps of major pollutants. Therefore the ICARUS ABM model, thoroughly explained below, captures individual spatio-temporal behaviours and makes it possible to assess exposure at the individual level. ABM can fill the data gaps regarding real individual space-time movement data for whole populations, or for subgroups for which no available information exist. Grouping individual exposure profiles based on criteria such as age, gender, area of residence/work/study, SES and behavioural patterns, leads to the extraction of representative exposure profiles for subgroups of population.

The central difference between ABM and more traditional, aggregate methods, is that ABM simulates the behaviour of the *individual* components whose activities ultimately define the behaviour of the overall system. In effect, this approach allows a model to **capture certain system behaviours that would be difficult to represent using aggregate methods that disregard the importance of individual heterogeneity and interactions.** ABM allows researchers to design a model according to their theoretical understanding of the dynamics of a system. They can then run the model to see whether these fundamental rules lead to model outcomes that are comparable to real world conditions. The ICARUS ABM exposure profile calculation process will be validated against real exposure data retrieved by the ICARUS personal sensor campaigns.

The following sections describe a) the structure of the ICARUS personal exposure campaigns and b) the ABM approach that - being informed and validated against the real data captured during the campaigns - estimates exposure profiles at the individual and community levels of a city's population.

2 Objectives

- Collect data on external environmental exposure and exposure determinants by combining location and activity data, and data on air pollution in different microenvironments
- Demonstrate feasibility of using new sensor and mobile technologies in collecting exposure data.
- Analyse and compare exposure data in several different European cities.
- Use data to parameterize and/or validate simulation models – ABM modelling

3 ICARUS exposure assessment campaigns

3.1 Study design

This study will require participation of individuals living in the respective participating city. The study aims to characterize urban population exposure to air pollutants by measuring personal exposure through a combination of measured data related to (a) personal sensors and (b) the outdoor and indoor place(s) air pollution levels that they spend the most time in.

Each participating city will recruit 100 individuals. Volunteers from all ages and all sociodemographic groups will be recruited, with a focus on including people living in hot spot areas (e.g. near roads and in other locations with high pollution concentrations and vulnerable groups of population (e.g. asthmatics, children and elderly).

The study will include both at home and personal monitoring for 7 days, including a weekend. The process will be executed in the same way in both summer and winter periods, in order to capture seasonal variation. The types of information to be collected include exposure monitoring devices, smart phone apps, questionnaires and time activity diaries. During the monitoring period volunteers, can contact fieldworkers, if needed.

Some of the data collected will be viewable by the subject during the monitoring period, as they will be measured using do-it-yourself devices. Some of the data will need to be sent to a laboratory for analysis.

Subjects will be given a subject information leaflet, explaining the study's aims and objectives. The test procedures will be explained to each subject and each will be given an opportunity to ask questions prior to them providing consent for themselves, their household, and child to participate on the study by means of a signed Subject Consent Form.

3.2 Inclusion criteria

These are the criteria for a household to participate in our study.

- Subjects must give voluntary informed consent for themselves, the household, and child(ren)
- Subjects and other household members must be willing and able to have sampling equipment in home and accept fieldworkers to survey their home, and place data collection devices in the home.
- Subjects must be willing to carry around personal monitors and perform any functions required to maintain or record data from them
- Subjects must be willing to use the ICARUS electronic portal for data gathering and answer any questionnaires requested of them
- Subjects must be willing to share anonymised data with external parties and with the ICARUS portal.
- Subjects must be willing to accept use of all anonymised data, including publication, and the confidential use and storage of all data by study.
- Subjects should own a Smartphone with Bluetooth that runs either iOS 7 or Android 4.0 and up.

- Subjects must have a desktop or laptop with internet access and wireless connection at home and allow use of this connection for study devices

3.3 Exclusion criteria

If potential subjects meet any of the following criteria they will be excluded from the study.

- Restrictions on ability to have study devices at home or other locations (such as work)
- Live outside the study area
- If the study researcher or field worker deems that the subject is not functionally capable of giving informed consent.

3.4 Sample size

For each study centre (participating city) 100 hundred individuals will be recruited.

3.5 Treatment of subjects

3.5.1 Investigational treatment

In this study, volunteers will be asked to allow fieldworkers to place indoor air quality sensors in the home, and use do-it-yourself monitoring devices during a period of 7 days (for each campaign). The exposure assessment monitoring devices and questionnaires are described in more detail below. Each volunteer and household will be given a non-identifying username, email address, and password for the study. These will be used to set up accounts on the devices listed below. For any apps where information can be shared with other users in the community, privacy settings will be set to the most restricted viewing.

3.5.2 Personal data collection devices

Based on D1.3, deliverable on the use of sensor technologies in defining external exposure at individual level, the following is suggested to be considered for collection of multi-sensor data for personal exposure monitoring foreseen within ICARUS:

- Ideally, multi-sensor setup should comprise environmental, location and personal movement/activity data, combined in user friendly, easy to use “package”. In general, off-the-self commercially available devices with proven applicability should be used. Location tracking is essential component in exposure assessment.

- Suggested environmental parameter is particulate matter, as it is a widely recognized pollutant of concern in urban environments, commercial availability of such sensors and mainly due to the fact that use of such devices was efficiently tested and demonstrated in many studies. Regardless of the device used, it should be pre-calibrated, preferably using the co-location approach under same environmental conditions as during the deployment.

- A multi-platform data collection tool should be developed in order to store, manage and process all data coming from different devices.

The following sections give details on the campaigns equipment, as well as treatment of data captured.

3.5.2.1 Physical Activity Sensors

Fitbit Surge *or* Garmin Vivoactive HR

Physical activity sensors such as the Fitbit Surge or the Garmin Vivoactive HR track steps, sleep, 24/7 heart rate data including resting HR and active time. There's also GPS built in that tracks coordinates. These wristband sensors also include an altimeter to track elevation. Based on these data and using a person's height, weight, and age, these sensors also estimate energy expenditure.

Figure 1. Fitbit Surge and Garmin Vivoactive HR

These monitors use Bluetooth connection protocols to sync data with a smartphone or computer. Data will be also synced to the ICARUS portal.

The wristband should be worn at all times by the participants, unless there is a reason it needs to be removed (e.g. charging, need to go through security).

3.5.2.2 Air Quality personal sensors

3.5.2.2.1 Do it Yourself (DIY) monitors

Custom made monitoring devices will be used for measuring PM, based on Arduino microcontrollers connected to small sensors that track PM2.5 and PM10 based on laser particle counters (such as the SEN0177 PM2.5 laser dust sensor – Figure 2).
For gaseous pollutants, custom modified gaseous sensors for CO, NO2 and O3 will be combined based on Alphasense 4-electrode sensors, integrated at an Arduino setting, able to transmit data wirelessly.

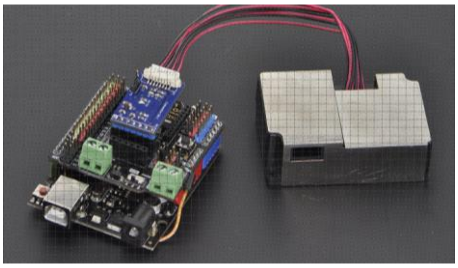


Figure 2. SEN0177 PM2.5 laser dust sensor

In addition, custom made silicon wristbands will be provided for the assessment of several chemical compounds, including PAHs, pesticides, and flame retardants. While they are being worn, the bands passively absorb a wide range of organic chemicals from the participants' surroundings, trapping them within the silicone polymer matrix. After participants return the bracelets, researchers extract chemicals from them using various solvents or thermal desorption methods.

Figure 3. silicon wristbands as passive samplers

Figure 4. Silicone wristbands absorb organic chemicals from the environment.

3.5.2.2.2 Commercially available air quality monitors

Flow

Flow, is a portable air-quality monitor that works both inside and outside the home. It can be attached to a belt or a bag and its battery lasts 12 hours on a single charge. You can track pollution levels either through 12 coloured LEDs on the front of the device, or through a companion app. Flow measures small particulate matter through optical sensing, ozone, and volatile organic compound levels, alongside temperature and humidity.

Figure 5. Flow air quality sensor

3.5.2.3 Air quality static sensors

Netatmo

The Netatmo is a home environment sensing device with two modules. Each Netatmo module measures temperature, humidity, and carbon dioxide, with one module also measuring noise (dB). The Netatmo needs to be connected to the household's Wi-Fi network. The data collected by the Netatmo modules are synced to the online account, which will be set up for each household, using an anonymous username and email address that the study assigns. Volunteers can see their household measurements data by downloading the Netatmo app on their smartphone. Netatmo data will be also synced to the ICARUS portal.

Figure 6. Netatmo weather station and smartphone application

Air Quality Egg

The Air Quality Egg (AQE) is an Open source hardware Internet of Things platform and a device for crowdsourced citizen monitoring of airborne pollutants. The device is consisted of two identical-looking plastic enclosures vaguely resembling white eggs. One unit, the base unit, is connected to the user's ethernet LAN connection. The second unit, based on the module used, monitors NO2, CO, VOC or PM levels and reports these readings every few minutes back to the base unit via a custom wireless protocol. The Egg detects particles from 0.5 microns to 10 microns.

Figure 7. The Air Quality Egg sensor

Figure 8. The GlobalSat LS-113E PM2.5 sensor

GlobalSat LS-113E PM2.5 LoRaWAN

This monitoring device includes a calibrated PM2.5 sensor module together with Temperature/ Humidity sensors. It is a smart device that can transmit and sync data through a long-range distance using a low-power wireless connectivity protocol (LoRaWAN).

3.5.2.4 Smartphone apps

Moves

The Moves app can be downloaded to a person's smartphone. This app tracks a person's location, activity (as steps), and can estimate the mode of transportation being used. Volunteers will be asked to label locations, not already/automatically labelled by the app, such as "home," "work," etc. The app can be run in a battery saving mode if smartphone's battery drain is a concern. Moves will be synced to the ICARUS portal. Volunteers will be asked to carry their phone with them at all times, except when it is not feasible (e.g. while sleeping, in the shower).

Figure 9. Moves app User Interface

3.6 Questionnaires & Time Activity Diaries

Study subjects will be asked a set of questions by the fieldworkers, including information about their household characteristics (observations on the exterior and interior of the dwelling; e.g.: potential sources of pollution, proximity to major roads, presence of mould, house ventilation frequency and occupants' activities such as smoking), as well as personal demographics (age, gender) and socio-economic status (such as level of education, employment status, marital status).

Questions administered by the fieldworkers will be recorded preferably by tablet, for later upload into a database. The subjects will also be asked to answer a questionnaire about their experience with the study at the end.

Volunteers will also be asked to fill in a time activity diary (TAD), a paper log that gives information on how study objects use their time; their activities and type of microenvironment in time, during the days of the campaign. This information will be used to confirm the validity of the physical activity sensor measurements. Activity pattern information for different sociodemographic groups will be also useful for the ICARUS modelling approach, thoroughly explained below.

3.7 Data collection portal

The ICARUS portal is an online 'personal data portal' on which data from multiple devices can be uploaded or synchronized. Participants have the opportunity to see all the data in one portal while it allows researchers to collect the encoded data for data analysis. Data from wireless devices and apps will be uploaded to the ICARUS portal automatically. Subjects are free to check their data as often as they wish

3.8 Methods

3.8.1 Study procedures

3.8.1.1 Subject contact

If a person has expressed interest in this study during the recruitment process, a research staff member will contact the person by phone and/or e-mail and provide an explanation of the study. If the person agrees to participate, the staff member will set up an appointment for the first visit and reserve a date and time for the second visit. Names of subjects will not be stored with their phone numbers on mobile or other phones. A participant information sheet and consent form might be sent to the participant in advance of the first visit, so that they will have time to read it and think about it in advance.

3.8.1.2 First visit

Volunteers will be provided with another copy of the information sheet and the research staff will explain each part of the sheet to volunteers, who will then be given an opportunity to review the sheet and ask questions. Volunteers will have to consent for themselves to be in the study. Once they have signed the consent checklist, the fieldworkers will administer questionnaires to the adult subject, set up measurement equipment in the home, and set up and provide instructions to the adult subject about using the personal measurement devices and apps. The fieldworkers will set up all devices and will ask the subject for permission to link to their home wireless internet connection. They will also help the subject set up the apps on the subject's smartphone. The fieldworkers will go through all the procedures for use of the do-it-yourself devices, apps, and websites with the adult. The subject will receive a folder with instructions, their anonymized study username, email, and password, and who to contact in case of questions or an emergency. All subject data will be aggregated in an encoded manner in the ICARUS portal. Volunteers together with the fieldworkers will also confirm the date and time of the next visit. This visit is expected to take approximately 2 hours.

3.8.1.3 During the study

Volunteers will be provided with a phone number to call in case of questions or problems with the equipment. The fieldworkers will call the adult subject mid-way through the sampling period to see if the subject has any questions, to remind them to use their devices, and to confirm the date/time of the second visit. The subject will also receive notifications on their phone periodically (not more often than once a day) to remind them to use their devices. Any data that is linked to the ICARUS portal will be monitored by the fieldworkers and research staff, and if there are any questions regarding this information, the subject will either be contacted during the study or will be asked during the second visit, depending on the nature of the issue. We estimate that each day the participant would take 15 minutes on activities, such as syncing their Fitbit. It will vary by participant and day but we do not anticipate more than 15-30 minutes/day.

3.8.1.4 Second / Final visit

During the second visit, which will be scheduled for 7 days later, the fieldworkers will log and remove all in-home measurement devices and take back the personal monitoring devices. The fieldworkers will ask if the subject had any problems and go over any issues that may have arisen during the study, including questions about the data from the ICARUS portal that the research staff may have. Additionally, the fieldworkers will administer a questionnaire to the subject about their experience with the study and use of the devices. This visit will take about 1.5 hours.

3.9 Ethical considerations

3.9.1 Regulation statement

The study will be conducted in compliance with the protocol and all amendments to the protocol. The protocol and any changes to the protocol effecting the design, rationale or objectives of the study, or the burden of or health risks for the volunteers will only be implemented after written approval of the ethics committee of the School of Life Sciences of Heriot-Watt University.

The study will be conducted according to:

- The current revision of the World Medical Association
- Declaration of Helsinki.
- 64th WMA General Assembly, Fortaleza, Brazil, October 2013.
- Note of clarification on paragraph 29 added by the WMA General Assembly, Washington, 2002.
- Note of clarification on paragraph 30 added by the WMA General Assembly, Tokyo 2004;
- The current national regulations.

3.10 Recruitment of subjects

Each participating city will develop its own recruitment plan based on previous experience. Some common approaches include:

- Information desks will be organised, where ICARUS research teams can further inform people at social events during days like the World Health Day (7th of April) or European Immunization Week (last week of April).
- NGOS, nurseries and groups that sponsor activities for parents, children and/or elderly will be approached, by posting informational posters and providing information. Advertisements through online sites, social networks, local magazines and via word-of-mouth will also help.

Campaign's printed or online leaflets will always link (QR code in printed version / direct link in online version) to an online form so that potentially interested volunteers could fill in their details. In all cases, the recruitment materials will include a telephone number and email for people to contact with.

Researchers will contact the potential subject via telephone and/or email. If a person has expressed interest in this study during the recruitment process, a research staff member will contact the person by phone and/or e-mail and provide an explanation of the study. If the person agrees to participate, the staff member will set up an appointment for the first visit and reserve a date and time for the second visit.

Subjects will be given a subject information leaflet, explaining the study's aims and objectives. The test procedures will be explained to each subject and each will be given an opportunity to ask questions prior to them providing consent for themselves, their household, and child to participate on the study by means of a signed Subject Consent Form.

Names of subjects will not be stored with their phone numbers on mobile or other phones. A copy of the participant information sheet and consent form will be sent to the participant in advance of the first visit, so that they will have time to read it and think about it in advance.

3.11 Risks to participants

The devices used pose low risk of harm. The fieldworkers will need to take precautions that any devices placed in the home or worn by the adult caretaker will pose minimal threat of harm to the household members and children. This includes instructing the adult subject to be watchful of the devices, especially in the presence of children, so that they are not accidentally misused. The fieldworker will place measurement devices, with consultation from the adult subject, in areas where a child cannot easily access the devices.

All equipment will be checked upon return from the field and prior to use in the field. If any problems are noted in the field, the fieldworkers are instructed to not use the device and use either a backup or to bring another functional device later, if possible.

The subjects will be instructed to report any incidents involving study equipment or procedures as soon as possible to study staff. If a study device is accidentally broken by the subject, they will not be required to make any payment or replace the device. Any other incidents that may adversely affect the subject during the study or the subject's ability to comply with study procedures should also be reported.

3.12 Administrative aspects, Monitoring and Publications

3.12.1 Data Management and Security

All researchers will be trained in the ethics of human subject research and in the appropriate information governance. Subject names and contact information will be kept in a separate file, linked with the person's ID code for the study. This will be kept encrypted on a password protected computer. Only personnel authorized by the study will have access to this and any other files containing private information. Any paper documents with subject information will be kept in a locked cabinet, and only study personnel will have access to the keys.

A data management system will be used to securely store and share data via the internet, ensuring that only authorized ICARUS personnel have access. The stored data will be encrypted. Any data to ultimately be made public will be adequately de-identified. No potentially identifying data will be revealed in any public data or data publication.

Data collected using do-it-yourself devices will be uploaded to an online portal using an anonymous account. After a subject is included in the study, he/she will be provided with an envelope including a login for an email account (which is linked to the subject number) and a password. Prior to the start of the study, for each subject number an account is created for Fitbit (activity monitor), Moves (Smartphone app), Netatmo, and the ICARUS portal. The email account will be linked to these accounts. Data from these applications will be synchronized to the ICARUS portal via an Application Protocol Interface (API). The portal is hosted on a server, constantly monitored and maintained by UPCOM. For authorisation we use the Spring Security framework, which is responsible for the control of passwords (encrypted and decrypted) and the relevant different users (e.g. subject, fieldworker, administrator etc.) Furthermore, the subject data and personal information will be stored in two different and separate databases. All links implemented into the portal work with the OAuth authentication, which is a part of Spring Security. Spring Security is a long-established framework with a large support. All providers (Netatmo, Fitbit, Moves) will be linked to the ICARUS portal work with this platform.

Only anonymized data can be downloaded from the ICARUS portal for subsequent tabulation and statistical analysis. Subjects and households will be assigned a unique identification code that does not include any identifying information. Information such as address and phone number will be kept in a separate, encrypted database and will not be linked to subject data in analyses.

3.12.2 Device and sample management

Electronic and do-it-yourself devices will be re-used throughout the study. In all cases, data will be downloaded and removed from the device before re-use in another household and for another subject. Do-it-yourself devices will be reset for use with a new user and password, and the past user's information will not be available to the next user. Each device will be assigned a unique ID, which will be linked with any identifiers, such as a serial number, for the device, and will not be changed during the study. This will allow researchers to track any issues that may come up with certain devices. The device ID used for each household/subject will be recorded and entered into a database.

3.12.3 Monitoring and quality assurance

Audits of the data collection and processing procedures will be taken throughout the project. For example:

- An audit of the data collection process employed by the fieldworkers will be carried out at regular project meetings, between study centres.
- Most of the data collected will not be manually entered. Research staff will be responsible for checking that data is uploaded to the ICARUS portal during the collection period for each household and to the database during and after the collection period.
- Any manually entered data will be checked for completeness of entry and compared to the paper questionnaire and data logs by someone who did not enter the data.
- All devices will be tested before use in the field. Tests will include co-location, reliability for the sampling time, and comparison with a reference instrument, if available.

3.13 Report back to study subjects

The study subjects will be able to view their data on the do-it-yourself devices. Within 6 months of data collection the study participants will receive an overview of their results that are available at that time.

4 Exposure assessment using Agent Based Modelling

4.1 Background

Complex phenomena are best understood through consideration of the behaviour of all interacting parts since macroscopic events emerge through microscopic actions and interactions. Agent-Based Modelling (ABM) helps to understand and explore this kind of phenomena where typically independent and autonomous entities interact together to form a new emergent whole. While direct representation of the behaviours of individuals is organisationally difficult, ABM simplifies this process by managing information at the individual level.

An example of such a system is the flocking behaviour of birds (Levy 1993). Although each bird is independent, somehow, they interact together to form a flock, and seemingly without any leading entity, manage to stay in tight formations. With this in mind, simulations using ABM attempt to discover the rules embedded in these individual entities that could lead to the emergent behaviour and eventually attempt to make interpretations about future states of these systems. It is, therefore, a simulation technique, capable of representing the kinds of systems where one level of abstraction (individual agents) can generate a new level of abstraction through the interactions that occur in the system, such as how individual birds form a flock.

By simulating the actions and interactions of autonomous software objects, the "agents", at an individual level, the full effects of the diversity that exists among agents in their attributes and behaviours can be observed as rise is given to the behaviour of the system as a whole. Patterns, structures, and behaviours that were not explicitly programmed into the model, arise through the agent interactions enabling therefore the prediction and examination of expected and unexpected emerged behaviours.

The agents (which can be people, vehicles, roads, cities, animals, products, etc.) are programmed as autonomous decision-makers to react and act in their environment and to have goals that they aim to satisfy, according to a set of rules. In practice, agent actions in models revolve around exercising choice among available options in order to achieve defined goals. The outcome of an agent making a particular choice is translated as a difference in either the location of the agent (i.e. the agent moves) or in the environment. Depending on the model context, this may involve: (a) the agent exploiting resources at its current location (there will be therefore a shift regarding the supply of those resources at that location), (b) altering the state of the location (e.g. changing the land use), (c) acquiring the land at its present location; or, perhaps simply updating its current 'map' of the environment. In each case, there may be an accompanying change in the state of the agent itself, such as when resource exploitation increases the agent's wealth or energy resources.

During the last years, of particular interest is the integration of functionality from geographic information systems (GIS) software libraries (e.g. ESRI's ArcGIS), which provide ABM toolkits with greater data management and spatial analytical capabilities required for geospatial modelling. Agents may be mobile and they may change their spatial relationship with the environment over time. Moreover, agents are able to evaluate spatial configurations. This ability may be as simple as determining that the availability of some resource at the current location is sufficient for some purpose, or is greater than at neighbouring locations. Generally, mobile agents (whether human or some other animal) will be making decisions at time scales dictated by their mobility on the one hand and their perception of the nature of the spatial distribution of resources on the other. The decision-making timeframe combined with the speed of movement of the agents then effectively frames a sensible spatial grain for a model of this type.

It should be noted that an ABM requires many simulations to evaluate any particular situation as it is based upon an underlying stochastic model. Randomness is applied to many involved processes; accordingly, two model runs will not result in exactly the same result.

It is also worth noting that the resulting model is often one where a full explanation of the model behaviour calls for a chronological interpretation of the events in the model. Describing and understanding the model specific agent-agent interactions will matter, and a detailed account of the model "history" may be necessary for a complete understanding of any particular model run. The difference from the real world target system we seek to understand, is that a model allows repeated runs and enables a probabilistic or general account of the system behaviours and tendencies to be developed.

The ability of ABMs to describe the behaviour and interactions of a system allows for system dynamics to be directly incorporated into the model. This represents a movement away from the static nature of earlier styles of urban and regional modelling. In most cases ABMs are a relatively late arrival in a field where there is considerable previous experience with styles of model that adopt a more aggregated approach. The increasing ease with which ABMs can be developed, coupled with their representational agent based approach, is the main reason why this modelling approach became more popular during the recent years. The appeal lies on the fact that individual-level decision making is the fundamental driver of social systems.

ABM techniques have already been established in the fields of finance, gaming but mostly in social sciences, aiming to study human social phenomena. Such studies focus on modelling flows, transmission of culture, propagation of disease as well as interpreting group formation and population dynamics. Notable examples in which ABM was applied, include stock market behaviours (LeBaron 2002), predicting the spread of epidemics (Huang, Sun et al. 2004), modelling human immune system (Folcik, Broderick et al. 2011), simulations of migration urban evacuation (Chen and Zhan 2008) as well as urban transport systems (Dia 2002). ABM has also been successfully applied to pedestrian and traffic modelling (Helbing and Balietti 2013). There are only few ABM models nowadays that have attempted to model entire cities. For example, the model of (Haase, Lautenbach et al. 2010) explores urban growth along the West Yellow River Corridor of China.

Overall, there are three model features that support a good case for exploring the usefulness of an ABM approach: (a) the *heterogeneity* of the decision-making context of agents, (b) the importance of *interaction effects*, and (c) the overall *size* and *organization* of the system (Bankes S. C. 2002). All these criteria favouring the adoption of ABM, call for considerable prior knowledge and insight about the characteristics of the under examination system.

4.2 The use of ABM in ICARUS

To understand variations in exposure across all groups of a society, large population samples are needed representing both different time periods (weekends, weekdays, and seasons) as well as different subgroups of population (Freijer, Bloemen et al. 1998, Burke, Zufall et al. 2001, Gulliver and Briggs 2005). Innovative sensor technologies can indeed facilitate wider-scale and longer-term monitoring of exposure for population surveys. Measuring, though, personal exposure directly, especially when you want to capture exposure profiles of the entire sociodemographic spectrum of a region, requires a large number of people. Considering the substantial technical and ethical hurdles involved in collecting real individual space-time-activity data for whole populations, a decision has been made to simulate human movement and interaction behaviour using Agent Based Modelling (ABM), validated against sensor data captured from local campaigns.

We will now provide details of a modelling framework that can be used in exposure assessment to take account of sociodemographic characteristics at the individual and population level.

4.2.1 ABM methodology

For the purposes of this project, the GAMA agent-based simulation platform (Grignard, Taillandier et al. 2013) is being used. This platform offers a complete modelling and simulation development environment for building spatially explicit multi-agent simulations. GAMA provides a rich modelling language based on Java, GAML, which allows to define complex models integrating at the same time, entities of different scales and geographical vector data. It provides a true geometry to all situated agents. This geometry, which is based on vector representation, can be simple (point, polyline or polygon) or complex (composed of several sub-geometries). The agents' geometry can be defined by the modeller (a list of points) or directly loaded from a shapefile. In the context of simulation, the advantage of geographical data agentification is to give the possibility to manage geographical objects (buildings, roads) exactly like other agents (people) in the simulation: you can give them an internal state and a behaviour. It is possible to initialize the virtual work to a present arrangement and then let the model run and observe its behaviour. Agent states of various sub-populations can be measured and aggregated across many simulation runs at each point in time in the simulation.

Aiming to develop a city scale model which is representative to real-world conditions, every entity taking part in the system is being agentified, it is therefore considered as an individual agent. The system is composed, among else, of road, building, vehicle and human agents.

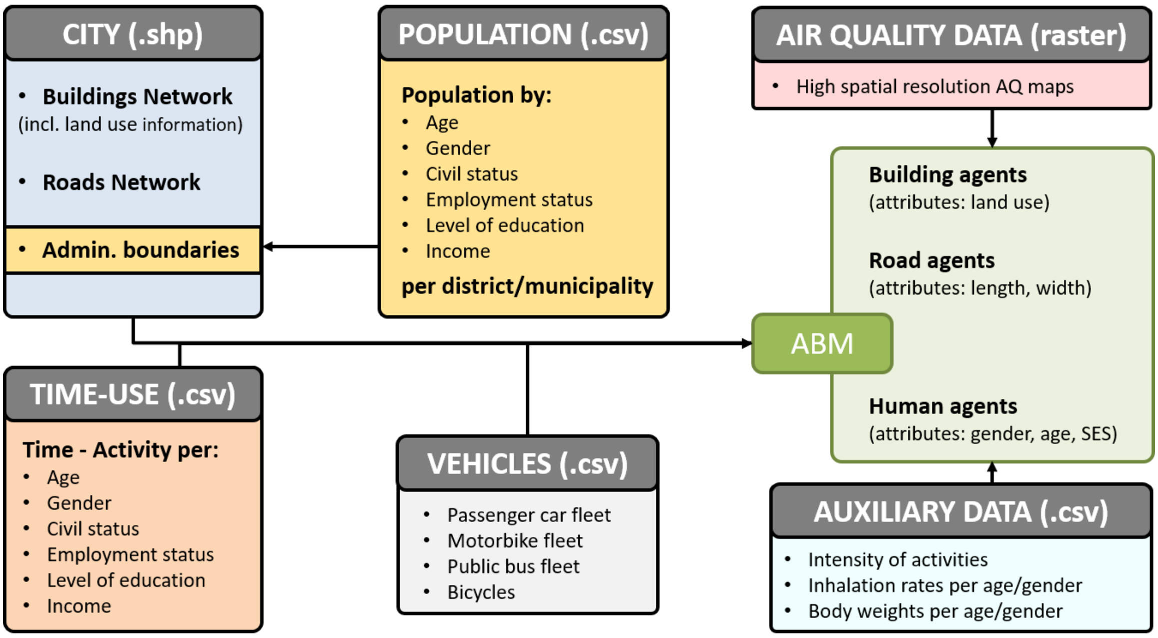


Figure 10. ABM model input data

4.2.1.1 City data

In order to define the system's environment, road and buildings networks of urban Thessaloniki, formed as high spatial resolution shapefiles, were included into the model and transformed to road and building agents respectively, carrying attributes such as the capacity of each street or land use information of a structure.

4.2.1.2 Population Data & incorporation of Socioeconomic status (SES) data

In order to extract information for the under-examination society, census population statistics are used, retrieved by local authorities at the municipality or even census block level. Based on the real population data of each municipality, the same number of human agents is being generated at the same region for which spatial information is available.

Particular emphasis is given in the case of in-model incorporation of sociodemographic data, since subgroups of population have different time activity patterns, travel by different modes, and spend different amounts of time doing activities within the microenvironments, such as physical activity or sleeping. The virtual population acquires attributes such as age, gender, level of education, employment status, civil status and income by following the official population statistics of their region where they were first conceptualised. That means, for example, that human agents a certain municipality will be generated based on the real population data, spatially allocated to the representative administrative region. They will, therefore, acquire personal attributes such as a certain age/gender, following the real age/gender distribution that corresponds to the same area.

4.2.1.3 Time – use data

Time-activity patterns of the under examination population can be retrieved from the Multinational Time Use Study (MTUS) that provides data for several European countries in the format of Harmonised simple file (HSF), Harmonised aggregate files (HAF) and Harmonised episode file (HEF). In this case, data is processed in a Harmonised simple file (HSF) format so that, at the end, every dataset row represents the time a diarist spends on 25 activity categories within 24 hours` observation time (diary). Additionally, it records respondents` demographic and socioeconomic information, including age, gender, household income, education level, civil status and employment status. For the ICARUS cities for which MTUS data is not available, similar information can be retrieved from the Harmonised European time use surveys (HETUS), data of which can be coded and processed under the same HSF format.

4.2.1.4 Human agents behaviour

When the model is initialized, human agents are randomly allocated to a residential place, within the municipality where they were first conceptualised, which will serve as their home for the entire simulation. They are also arbitrarily assigned to an office, university or school depending on their age, gender and occupational status. Moreover, human agents become part of family networks.

By following behavioural rules inside the ABM platform, a human agent's day is filled with activities not in a pre-scheduled/programmed way but rather in a dynamic one. Human agents' characteristics provide capabilities or constraints on the agents' behavioural rules. The reference point could be, for example, age or income that influence their preferences and decision-making (e.g. choosing a different activity based on personal background or choosing a different means of transportation to reach a destination). The duration of each activity is calculated using a gaussian distribution with known mean and standard deviation values, as captured by the MTUS or HETUS survey for a subgroup of population that shares common personal attributes with the under investigation human agent. Human agents have the added option of interacting with each other by evaluating invitations to participate in joint activities (e.g.: invitation to watch TV, eat etc.) within their family network.

Overall, based on their personal characteristics and of course based on the distance between point of departure and their targeted destination, different human agents will express different spatio-temporal behaviours. The very same human agent might follow a different sequence or even a different set of activities day by day.

An example of the input for the model can be understood easily if we look at means of transportation. The overall population will originally be initially distributed to use a certain transport mode; for example, 45% will use the car, 10% will walk, 5% cycle, and 40% will use public transport. However, this will change with each agent depending on sociodemographic attributes and distance to their target destination. This leads to 'rules' being applied and thus altering the distribution; so if for example, an agent is male, employed, and in a high-income group, the agent will have a higher probability of using the car to travel to work and be in the car for longer period of time, than a woman, who is a homemaker, with children. The output provides us with information regarding the distribution of transport mode choice throughout the day and we can pinpoint certain times within a day for more detail. This is an example where we can achieve a deeper and more precise understanding of existing phenomena.

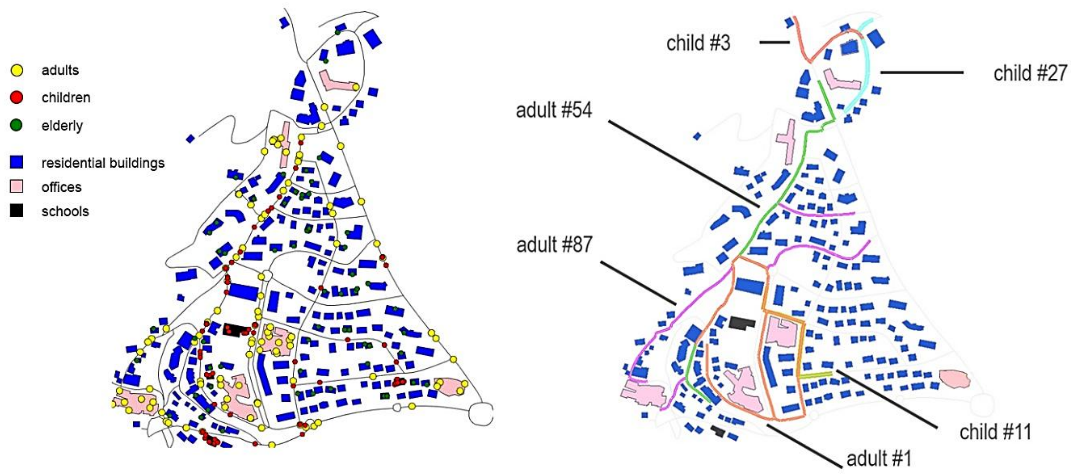


Figure 11. Right: ABM model running over a neighbourhood with building, roads and human agents. Left: At the end of an ABM run, trajectories of human agents can be exported.

At the end of a model run, activity patterns and space-time trajectories can be determined for every human agent, as an outcome of the prevalence of specific preferences and decision-making throughout the simulated time of experiment. Human agents' trajectories, derived by the coded routine, are captured as points (1 point captured per simulation step) and can be exported as a GIS shapefile together with a database that contains their coordinates and activities in time through different locations/microenvironments.

4.2.1.5 Air Quality Data - Outdoor concentration per human agent point

The ABM exported GIS layer can then be superposed onto high spatial resolution urban air quality maps of atmospheric pollutants. Urban outdoor air quality levels data will be retrieved from the high-resolution air quality maps produced in WP3, derived from data fusion of different origins (downscaled modelling results, satellite image processed data). Coupling position information with spatially resolved pollution levels allows us to assign pollutant outdoor concentrations to a virtual individual.

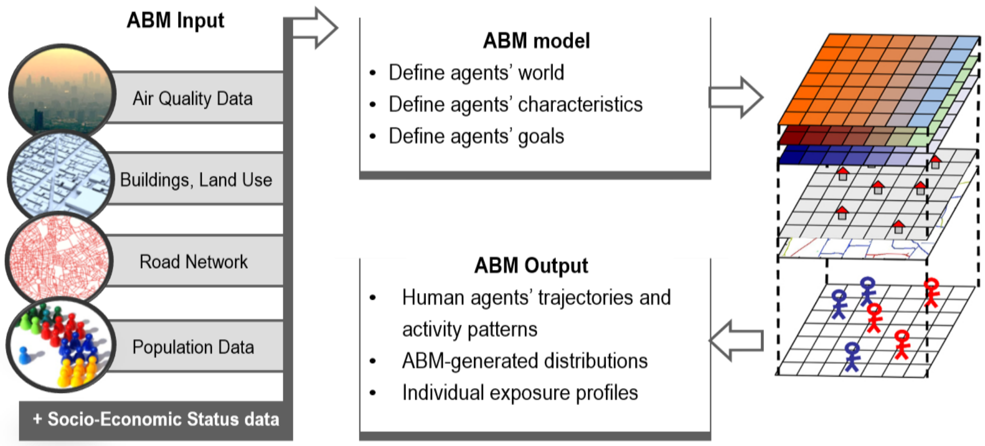


Figure 12. Overview of the personal exposure assessment ABM model

4.2.1.6 Indoor concentration per human agent point

The estimation of indoor concentrations for the cases where human agents are located in indoor environments, such as residential buildings, offices or schools. Indoor concentrations were estimated, using the INTERA computational platform (INTERA 2011). The estimation is based on a mass balance model, that takes into account the major processes governing particle concentration i.e. emissions, deposition, indoor/outdoor exchange rate, and outdoor infiltration. The mass balance is described by the following equation:

$$V \cdot \frac{dC}{dt} = Q \cdot (\inf \cdot C_{out} - C_{ind}) + E - k_{dep} \cdot C_{ind} \cdot V \qquad \textbf{Equation 1}$$

where *V* represents the volumes of the indoor location, *Q* the indoor-outdoor air exchange rate, *inf* is the infiltration rate, C_{out} is the outdoor concentration, C_{ind} the indoor concentration of the indoor location, *E* the strength of the emission sources (mass/time) and k_{dep} the deposition rate. Further details on the usage of the aforementioned equation can be found elsewhere (Sarigiannis, Karakitsios et al. 2014, Sarigiannis, Karakitsios et al. 2015).

4.2.1.7 Personal exposure, inhalation adjusted exposure and intake dose calculation

Based on the ABM derived time-activity pattern of a human agent, personal exposure over a given period of time, E_T, can be calculated (*equation 7)* knowing that he/she spent a fraction f_n of the time in *n* locations where the concentration of the pollutant under consideration was C_n.

$$E_T = \sum_n f_n \cdot C_n$$ **Equation 2**

An additional factor influencing the actual human intake is inhalation rate. Different types of activities demand different levels of effort that correspond to different inhalation rates. Inhalation-adjusted exposure, E_{inh}, can be calculated (*equation 8)*, taking into account an adjustment factor for each type of microenvironment encountered in the calculations, inh_{act}, related to the intensity of every activity the human agent follows during the simulated period. A detailed description of the activity based inhalation rates is given elsewhere (Sarigiannis, Karakitsios et al. 2012).

$$E_{inh} = \sum_n f_{loc} \cdot C_{loc} \cdot inh_{act}$$ **Equation 3**

Personal exposure assessment can then be extended to the calculation of daily intake dose (*equation 9)* by integrating daily exposure data, taking into account a representative weight and breathing rate.

$$\text{daily intake dose (mg/kg} - \text{day)} = \frac{\text{total exposure}\left(\frac{\text{ug}}{m^3}\right) * \text{daily breathing rate}\left(\frac{m^3}{\text{day}}\right)}{\text{body weight (kg)} * 1000\left(\frac{\text{ug}}{\text{mg}}\right)}$$ **Equation 4**

4.2.2 Urban Thessaloniki, first ICARUS city model

Following the approach described above, a model was developed for urban Thessaloniki, Greece, that simulates behaviours of all the agents the system (city) is composed of. City's population and sociodemographic data -retrieved by the Hellenic Statistical Authority- as well as road and buildings network data -retrieved by the by the Prefecture of Central Macedonia- were transformed into human, road and building agents respectively. HETUS survey outputs with time-use data were associated with human agent rules, aiming to model representative to real-world behavioural patterns for different sociodemographic groups of the society. At the end of a model run, activity patterns are determined for every individual based on the prevalence of specific preferences and decision-making. Coupling position information with spatially resolved pollution levels allows us to assign pollutant concentrations to an individual.

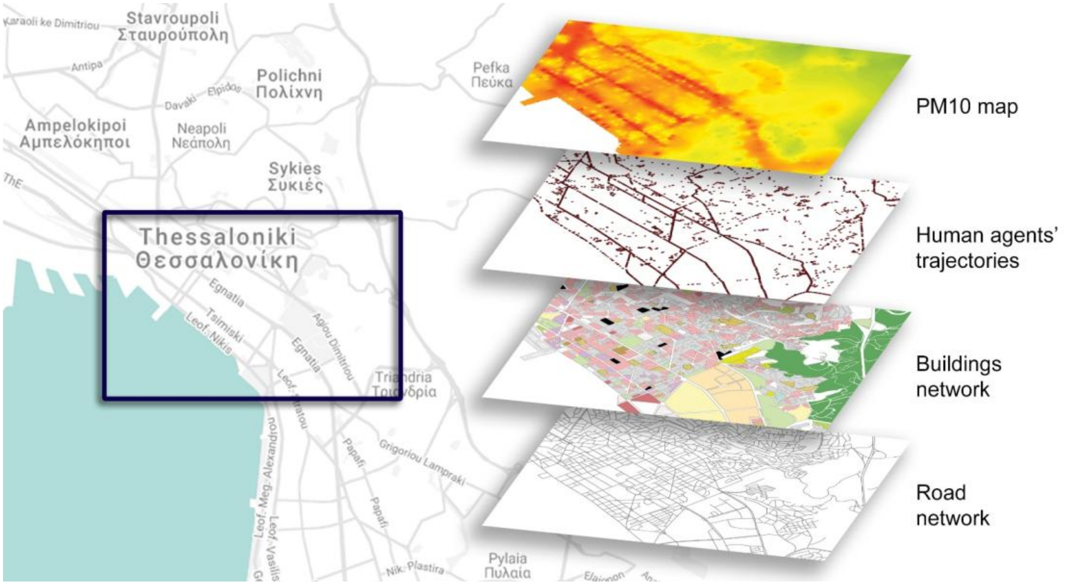


Figure 13. GIS layers - Exposure assessment at personal/community level, using ABM.

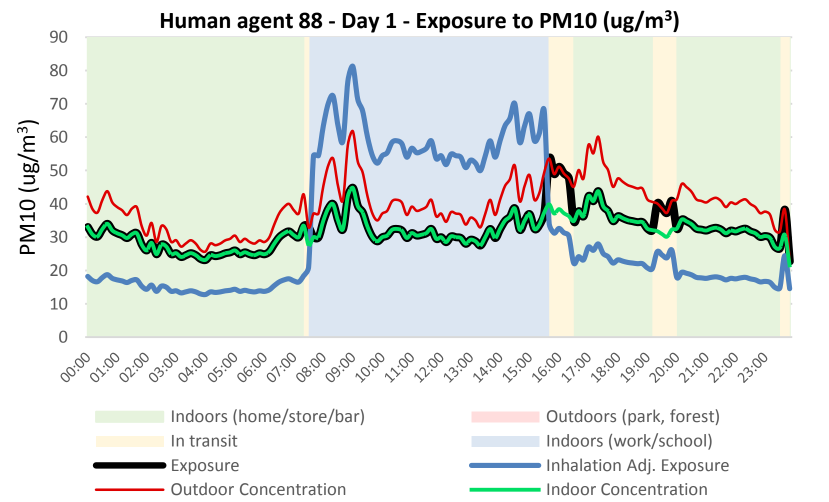
In this study, an hourly variation PM10 map was used, which was the outcome of data fusion from ground observations, pollutants dispersion modelling and satellite images for the Thessaloniki region (Sarigiannis, Kontoroupis et al. 2017). The spatial resolution of this map is below 100 m and exposure is calculated at the level of building block (30-40 m).

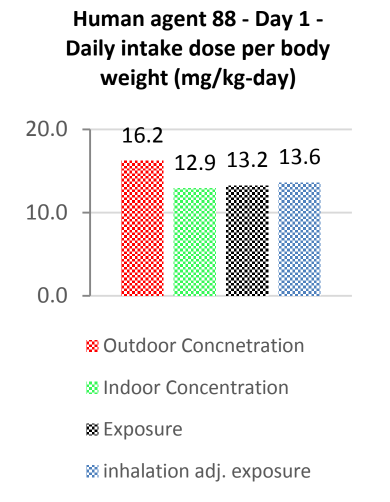
Table 1 showcases the activity and exposure profiles of two randomly picked human agents, as derived by the ABM model.

This study goes beyond the approach of classic epidemiology where outdoor PM concentration is the main proxy for assessing exposure. Here, exposure timeseries are based on outdoor (***red line***) as well as indoor (***green line***) concentrations that were estimated based on personal trajectories. Then exposure to PM_{10} (***black line***) as well as inhalation adjusted exposure (***blue line***) was also calculated. Furthermore, exposure assessment was extended to the calculation of **intake dose,** taking into account a representative body weight and breathing rate, based on the agent's age and gender. It is interesting to observe how the value of intake dose changes depending on what we use as a proxy.

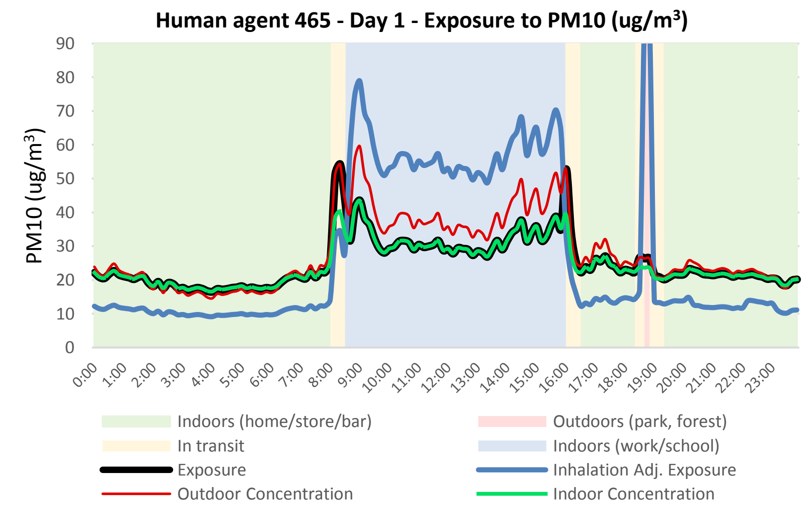
Table 1. Activity and exposure profiles of two randomly picked human agents

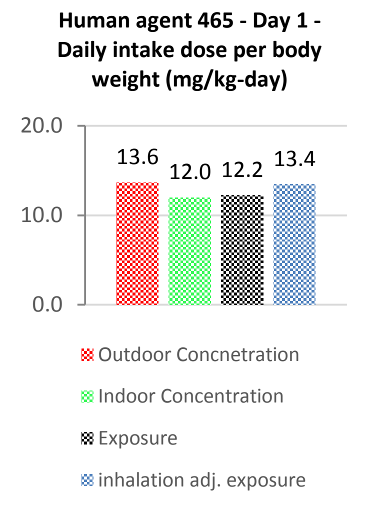
TIME	ACTIVITY
00:00	sleep
07:30	commute (car)
07:40	paidwork
15:40	commute (car)
16:30	volorgwk
19:20	commute (car)
20:00	compint
23:40	commute (bus)





TIME	ACTIVITY
00:00	sleep
08:10	commute (motorbike)
08:40	paidwork
16:00	commute (motorbike)
16:30	selfcare
17:50	eatdrink
18:10	foodprep
18:30	commute (foot)
18:40	sportex
19:00	commute (foot)
19:20	eatdrink
20:00	cleanetc
20:20	tvradio
22:10	eatdrink
23:10	compint





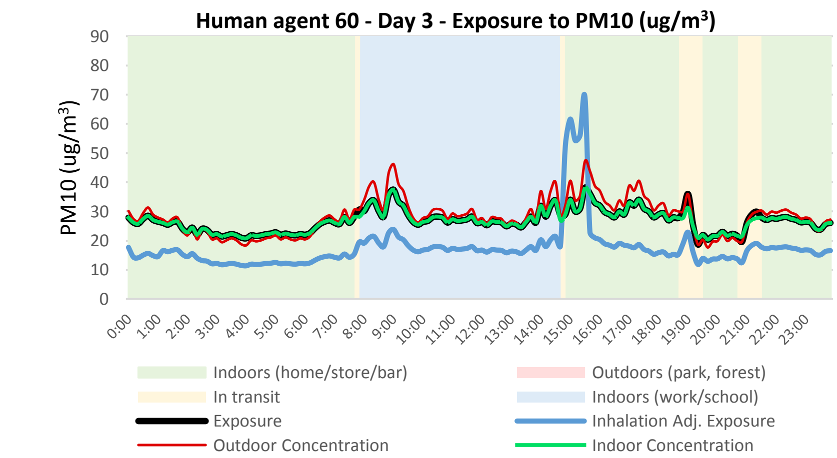
Human agent 88 is a 58 years old female, married, with a full-time job, medium income and a post-secondary education. She lives in west Thessaloniki (Municipality of Abelokipoi) and her office is located in the centre of Thessaloniki.

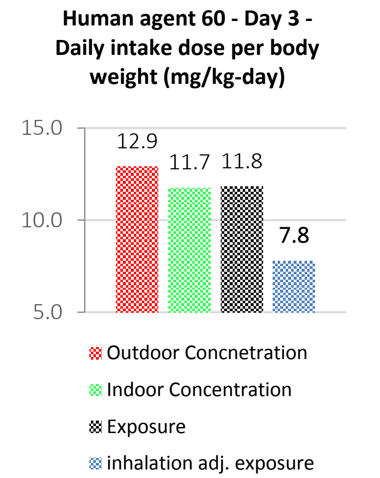
Human agent 465 is a 43 years old male, married, with a full-time job, medium income and a higher education. He lives in east Thessaloniki (Municipality of Kalamaria) and his office is located in west Thessalonoiki (Municipality of Abelokipoi)

A key outcome of the applied methodology is that it allows us to incorporate multiple sociodemographic attributes directly in exposure assessment. It is possible to observe the differences of the outdoor, indoor and microenvironmental levels of air pollution encountered, based on the daily spatio-temporal behaviour of the virtual individuals. Personal exposure, therefore, is connected to a) the every-day activity pattern of a human agent (which is related to age, gender and SES) and b) the spatial distribution of air pollution across the urban agglomeration, which is also strongly affected by the city economic activities. Moreover, this approach permits the identification of differences with regards to intake dose. People of different age and gender perform different activities, with a different inhalation rate. This eventually affects the overall daily intake dose based on their inhalation adjusted exposure. The effect of the sociodemographic attributes in exposure refinement are clearly illustrated in the following example, where the exposure profiles of another two human agents are presented.

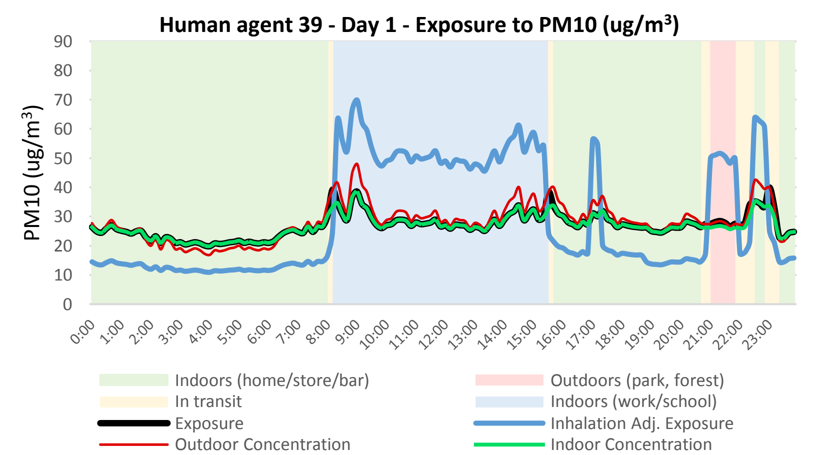
Table 2. Activity and exposure profile of human agent 60 and human agent 39.

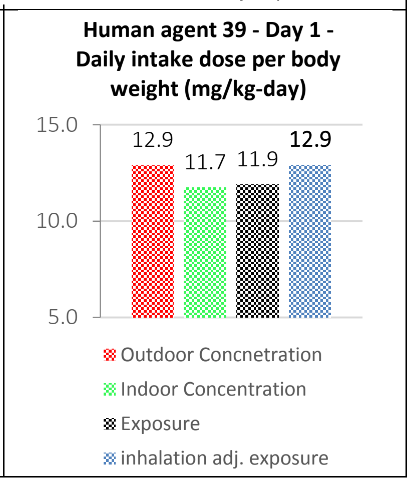
TIME	ACTIVITY
00:10	tvradio
01:10	leisure
01:30	sleep
07:50	commute
08:00	educatn
14:40	commute
14:50	selfcare
15:40	leisure
17:00	tvradio
17:50	read
18:50	commute
19:30	restrnt
20:50	commute
21:30	leisure





TIME	ACTIVITY
00:00	sleep
08:10	commute
08:20	paidwork
15:30	commute
15:40	leisure
17:00	petcare
17:20	leisure
18:50	tvradio
20:50	commute
21:00	sportex
22:00	commute
22:30	shopserv
23:00	commute
23:20	pkidcare





Human agent 60 is a 16 years old female student, single with a low income. She lives in the centre of Thessaloniki (Municipality of Thessaloniki) and her school is in the same municipality.

Human agent 39 is a 55 years old male, married, with a full-time job, higher education and a medium income. He also lives and works in the Municipality of Thessaloniki.

These two human agents both reside in the same region. Even though they are both phenomenally exposed to similar outdoor air pollution levels, the actual exposure in terms of daily intake, taking into account the intensity of their activities, changes by 65%, as a result of different behaviours due to different sociodemographic backgrounds. **If we would only use outdoor concentration as a proxy, we wouldn't be able identify this major difference.**

This time-dynamic profile of exposure assessment allows the identification of exposure peaks and troughs throughout the day and the way they coincide with the inhalation and the actual uptake rate, leading to useful conclusions regarding capping exposure to high pollution levels Moreover, the dynamic nature of intake dose assessment at the individual level allows for the derivation of guidance regarding behavioural options that limit exposure to high levels of pollution.

4.2.3 Model validation

The compatibility (within a logical range) between virtual and real data will be examined. The ABM model can be validated against real “time-geography” of exposure data, retrieved by the exposure assessment campaigns. Virtual time-activity data (time, type of location, activity) retrieved by human agents can be compared to and validate against the real data of participants with a similar sociodemographic background.

Simulated time-activity data derived by the emerging behaviour of human agents will be compared to real time-activity data, obtained through the combined use of portable GPS receivers (Fitbit, Moves) and time activity diaries. Fitbit and Moves provide data over space and time including activity intensity that supplemented with the questionnaire information can locate individuals’ daily movements during a day in all microenvironments.

Moreover, air quality data will be collected through the sensor campaign described above and will be available in the ICARUS portal. Data corresponds to a number of air pollutants measured within the individual personal zone (PM, CO, NO2, O3, SVOC) and the residential place of individuals (NO2, CO, VOC, PM10 and temperature, RH, noise as well) and will be allocated in space according to information provided by the GPS sensors (personal trajectories) and the questionnaires (coordinates of residential place).

4.3 Data availability

This approach will be established for all 9 ICARUS cities, without the need of changing the basic programming architecture. Population and sociodemographic data, geospatial information (roads, buildings networks, administrative boundaries) and time activity data, that all serve as input to the ABM platform, are now being retrieved and gathered in a dedicated repository.

5 Conclusions

Sensors

There are many possibilities for using wearable sensors, mobile apps and other devices for exposure assessment. A systematic approach is needed in order to understand and overcome the challenges in using these technologies to quantify external exposure.

A point that should be taken into consideration is the fact that the majority of sensor technologies that can be used in exposure studies are now in testing phase without always clearly demonstrated fitness of purpose, mainly as a result of sensitivity, specificity and stability issues in sensor performance. Studies on the reliability and validity of sensors and apps and how they compare to gold standards are needed before sensors are officially included to the campaigns' equipment. They should demonstrate a consistent relationship with reference methods, so that even if the sensors do not record values as accurately, they may be corrected for any bias. For environmental sensors, some may not be as sensitive to environmental levels as reference methods, which are often more expensive and more cumbersome. This has particularly been an issue for air quality sensors, although sensitivity has been improving.

Another issue that should be taken into account is the fact that often a bulky setup, especially in the case of multi-sensor approach, and complicated usage for non-technical people, might make users unwilling to participate to such campaigns and to use these devices in everyday life.

These major points raised above have been indeed taken into consideration when designing the study protocol for the ICARUS campaigns. Deliverable D1.3 and Milestone MS9 provide useful recommendations and a suggested outline.

Overall, the ICARUS sensors investigations offer valuable information on the utility of several wearable/smart devices as modular add-ons to exposure studies. The key question that needs to be answered in this context is what is the overall uncertainty introduced by the use of ubiquitous personal sensors against the uncertainty resulting from the temporally and spatially deficient regulatory monitoring networks. Finding the right balance between limited amounts of high quality data from standardized environmental monitoring campaigns and large amounts of moderate quality data by sensor networks can transform the way we understand and interact with our environment.

ABM

One of the advantages of ABM is that is is extremely well suited to exploring how the interactions and behaviours of individual people can lead to the emergences of interesting phenomena. We release an initial population of agent-objects into a simulated environment and watch for organisation into recognisable macroscopic social patterns. Group behaviours emerge from the interaction of individual human agents operating in an artificial environment (city) under rules that place only bounded demands on each agent's information and computational capacity. By observing phenomena through local level interaction we can move from the top-down studying of a city to that of a bottom-up approach which allows us to witness the emergence of previously unexpected macroscopic phenomenon from individual-level interactions (Heppenstall, Malleson et al. 2016).

The ICARUS ABM approach, by modelling the heterogeneous routine of human agents, permits the cost-effective construction of refined time-activity diaries and diurnal exposure profiles.

Human agents follow behavioural rules that determine the actions they should take in a given situation. As the model is being executed, human agents observe their surroundings and based on their sociodemographic background and taking into account the distance that needs to be covered (when applicable) they make decisions and perform actions.

Pollutants concentrations are being recorded for every microenvironment a virtual individual has stayed/passed through during the day. This then leads to the assessment of individual level of exposure, where exposure can be viewed as the summation of an individual's travel through "hazard fields" in space over time. The dynamic nature of intake dose assessment at the individual level allows for the derivation of guidance regarding behavioural options that limit exposure to high levels of pollution.

The capacity for aggregation and analysis at various levels of population size and the model's ability for integration of SES indicators are features that enable a refined exposures assessment. Such a model can be useful especially for vulnerable groups of population, such as children, the elderly and people with low SES. This study represents the first step towards improving the calculation process of population exposure to environmental substances so that we would be able to draw better conclusions on the association between environment and health.

It should be mentioned that this approach can be established for different cities, without changing the basic programming architecture. The realistic representation of the surrounding geography makes the ICARUS ABM a valuable tool for forecasting the impacts of new policies on a local and regional area. The computational platform developed can be further used as a means for estimating and comparing the probable effects of different public health strategies prior to implementation, therefore reducing the time and expense required to identify effective policies in all ICARUS cities.

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