

# **Synthetic Population Catalyst**

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# 1 Getting started



The Synthetic Population Catalyst (SPC) makes it easier for researchers to work with synthetic population data in England. It combines a variety of [data sources](#) and outputs a single file in [protocol buffer format](#), describing the population in a given study area. The data includes demographic, health, and daily activity data per person, and information about the venues where people conduct activities.

You can use SPC output to catalyze your own project. Rather than join together many [raw data sources](#) yourself and deal with missing and messy data, you can leverage SPC's effort and well-documented schema.

To get started:

1. [Download sample data for a county in England](#)
2. [Explore how to use the data](#)
3. If you need a different study area, [build](#) and then [run](#) SPC

You can also download this site as [a PDF](#) and find all code [on Github](#).

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# **Part I**

## **Using SPC**

## 2 Outputs for England Counties

You don't need to run SPC yourself. See [config/](#) for the list of MSOAs covered by each study area. If you want to run SPC for a different list of MSOAs, [see here](#).

- [England/2012/bedfordshire.pb.gz](#)
- [England/2012/berkshire.pb.gz](#)
- [England/2012/bristol.pb.gz](#)
- [England/2012/buckinghamshire.pb.gz](#)
- [England/2012/cambridgeshire.pb.gz](#)
- [England/2012/cheshire.pb.gz](#)
- [England/2012/cornwall.pb.gz](#)
- [England/2012/cumbria.pb.gz](#)
- [England/2012/derbyshire.pb.gz](#)
- [England/2012/devon.pb.gz](#)
- [England/2012/durham.pb.gz](#)
- [England/2012/east-sussex.pb.gz](#)
- [England/2012/east-yorkshire-with-hull.pb.gz](#)
- [England/2012/essex.pb.gz](#)
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- [England/2012/norfolk.pb.gz](#)
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- [England/2012/north-yorkshire.pb.gz](#)
- [England/2012/nottinghamshire.pb.gz](#)
- [England/2012/oxfordshire.pb.gz](#)

- [England/2012/rutland.pb.gz](#)
- [England/2012/shropshire.pb.gz](#)
- [England/2012/somerset.pb.gz](#)
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- [special/2039/northwest\\_\\_transpennine.pb.gz](#)
- [Wales/2012/bridgend-and-neath-port-talbot.pb.gz](#)
- [Wales/2012/cardiff-and-vale-of-glamorgan.pb.gz](#)
- [Wales/2012/central-valleys.pb.gz](#)
- [Wales/2012/conwy-and-denbighshire.pb.gz](#)
- [Wales/2012/flintshire-and-wrexham.pb.gz](#)
- [Wales/2012/gwent-valleys.pb.gz](#)
- [Wales/2012/gwynedd.pb.gz](#)
- [Wales/2012/isle-of-anglesey.pb.gz](#)
- [Wales/2012/monmouthshire-and-newport.pb.gz](#)
- [Wales/2012/powys.pb.gz](#)
- [Wales/2012/south-west-wales.pb.gz](#)
- [Wales/2012/swansea.pb.gz](#)

- [Wales/2020/bridgend-and-neath-port-talbot.pb.gz](#)
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- [Wales/2022/conwy-and-denbighshire.pb.gz](#)
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- [Wales/2022/swansea.pb.gz](#)
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- [Wales/2032/cardiff-and-vale-of-glamorgan.pb.gz](#)
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- [Wales/2032/conwy-and-denbighshire.pb.gz](#)
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- [Wales/2039/swansea.pb.gz](#)

If you use SPC code or data in your work, please cite using the [Zenodo DOI](#) (using the bottom-right tool to generate the citation).

## 2.1 Versioning

Over time, we may add more data to SPC or change the schema. Protocol buffers are designed to let combinations of new/old code and data files work together, but we don't intend to use this feature. We may make breaking changes, like deleting fields. We'll release a new version of the schema and output data every time and document it here. You should depend on a specific version of the data output in your code, so new releases don't affect you until you decide to update.

- v1: released 25/04/2022, [schema](#)
- v1.1, released 27/05/2022, [schema](#)
  - added `pwkstat`, `salary_hourly`, `salary_yearly`, and `idp`
  - reorganized `Identifiers` and `Employment` attributes
  - non-breaking change added 02/08/2022: added `bmi_new` field
- v1.2, released 29/12/2022, [schema](#)
  - switched to proto2 and made some fields optional
  - adjusted some numeric enum values to match ONS
- v2, released 09/03/2023, [schema](#)
  - new per-person and per-household fields
  - various changes to existing fields (adjusting enum number, removing the BMI enum, etc)
  - adding time-use diaries
  - expanding to Wales
  - adding multiple years of output

## 3 Using the SPC output file

Once you [download](#) or [generate](#) an SPC output file for your study area, how do you use it? Each study area consists of one `.pb` or [protocol buffer file](#). This file efficiently encodes data following this [schema](#). [Read more](#) about what data is contained in the output.

You can read the “protobuf” (shorthand for a protocol buffer file) in any [supported language](#), and then extract and transform just the parts of the data you want for your model.

We have examples for Python below, but feel free to request other languages.

We have a [web app](#) using Svelte to interactively explore SPC data. Its [source code](#) is great reference for how to use the proto output.

### 3.1 Python

To work with SPC protobufs in Python, you need two dependencies setup:

- The [protobuf](#) library
  - You can install system-wide with `pip install protobuf`
  - Or add as a dependency to a conda, poetry, etc environment
- The generated Python library, [synthpop\\_pb2.py](#)
  - You can download a copy of this file into your codebase, then `import synthpop_pb2`
  - You can also generate the file yourself, following the [docs](#): `protoc --python_out=python/synthpop.proto`

#### 3.1.1 Converting to Pandas data-frames and CSV

The [schema](#) expresses relationships between people, households, and venues that can’t all be captured by a simple 2D table. Nevertheless, you can extract per-person information and express as a dataframe or CSV file. See [this example Python script](#) for inspiration. You can try it out:

```
# Download a file
wget https://ramp0storage.blob.core.windows.net/spc-output/v1/rutland.pb.gz
```

```
# Uncompress
gunzip rutland.pb.gz
# Convert the .pb to JSON
python3 python/protobuf_to_csv.py --input_path data/output/rutland.pb
# View the output
less people.csv
```

### 3.1.2 Converting .pb file to JSON format

To interactively explore the data, viewing JSON is much easier. It shows the same structure as the protobuf, but in a human-readable text format. The example below uses a [small Python script](#):

```
# Download a file
wget https://ramp0storage.blob.core.windows.net/spc-output/v1/rutland.pb.gz
# Uncompress
gunzip rutland.pb.gz
# Convert the .pb to JSON
python3 python/protobuf_to_json.py data/output/rutland.pb > rutland.json
# View the output
less rutland.json
```

### 3.1.3 Converting to numpy arrays

The [ASPICS](#) project simulates the spread of COVID through a population. The code uses numpy, and [this script](#) converts the protobuf to a bunch of different numpy arrays.

Note the ASPICS code doesn't keep using the generated Python protobuf classes for the rest of the pipeline. Data frames and numpy arrays may be more familiar and appropriate. The protobuf is a format optimized for reading and writing; you don't need to use it throughout all of your model code.

### 3.1.4 Visualizing venues

Use [this script](#) to read a protobuf file, then draws a dot for every venue, color-coded by activity.





## 4 Installation

You only need to compile SPC to run for a custom set of MSOAs. Just [download existing output](#) if your study area matches what we provide.

- **Rust:** The latest stable version of Rust: <https://www.rust-lang.org/tools/install>

### 4.1 Compiling SPC

```
git clone https://github.com/alan-turing-institute/uatk-spc/  
cd uatk-spc  
# The next command will take a few minutes the first time you do it, to build external dep  
cargo build --release
```

### 4.2 Troubleshooting downloading

If you get an error `No such file or directory (os error 2)` it might be because a previous attempt to run SPC failed, and some necessary files were not fully downloaded. In these cases you could try deleting the `data/raw_data` directory and then running SPC again. It should automatically try to download the big files again.

If you have trouble downloading any of the large files, you can download them manually. The logs will contain a line such as `Downloading https://ramp0storage.blob.core.windows.net/nationaldata/ to data/raw_data/nationaldata/QUANT_RAMP_spc.tar.gz`. This tells you the URL to retrieve, and where to put the output file. Note that SPC won't attempt to download files if they already exist, so if you wind up with a partially downloaded file, you have to manually remove it.

## 5 Creating new study areas

If the area you want to model isn't [already generated](#), then you can follow this guide to run SPC on a custom area. You must first [compile SPC](#).

SPC takes a newline-separated list of MSOAs in the `config/` directory as input, like [this](#). You can generate this list from a LAD (local authority district). From the main SPC directory, run `python scripts/select_msoas.py`. Refer to `data/raw_data/referencedata/lookUp.csv` (only available after running SPC once) for all geographies available.

This script will create a new file, `config/your_region.txt`.

### 5.1 Run SPC for the new area

From the main directory, just run:

```
cargo run --release -- config/your_region.txt
```

This will download some large files the first time. You'll wind up with `data/output/your_region.pb` as output, as well as lots of intermediate files in `data/raw_data/`. The next time you run this command (even on a different study area), it should go much faster.

### 5.2 (Optional) run SPC for lots of areas

If you want to run the program over lots of areas at once and are using Mac/Linux, you can use a `for` loop in a terminal to repeatedly run SPC over all files in the `config` directory. For example, this will run SPC on all `.txt` files in the `config` directory:

```
for file in config/*.csv; do cargo run --release -- config/$file; done
```

## 5.3 Using the output

After you generate the files, see [here](#) for how to use them in your project.

If you use SPC code or data in your work, please cite using the [Zenodo DOI](#) (using the bottom-right tool to generate the citation).

## **Part II**

# **Understanding SPC**

## 6 Data schema

Here are some helpful tips for understanding the [schema](#).

Each `.pb` file contains exactly one `Population` message. In contrast to datasets consisting of multiple `.csv` files, just a single file contains everything. Some of the fields in `Population` are lists (of people and households) or maps (of venues keyed by activity, or of MSOAs). Unlike a flat `.csv` table, there may be more lists embedded later. Each `Household` has a list of `members`, for example.

The different objects refer to each other, forming a graph structure. The protobuf uses `uint64` IDs to index into other lists. For example, if some household has `members = [3, 10]`, then those two people can be found at `population.people[3]` and `population.people[10]`. Each of them will have the same `household` ID, pointing back to something in the `population.households` list.

### 6.1 Flows: modelling daily activities

SPC models daily travel behavior of people as “flows.” Flows are broken down by by an [activity](#) – shopping/retail, attending primary or secondary school, working, or staying at home. For each activity type, a person has a list of venues where they may do that activity, weighted by a probability of going to that particular venue.

Note that `flows_per_activity` is stored in `InfoPerMSOA`, not `Person`. The flows for retail and school are only known at the MSA level, not individually. So given a particular `Person` object, you first look up their household’s MSA – `msoa = population.households[ person.household ].msoa` and then look up flows for that MSA – `population.info_per_msoa[msoa].flows_per_activity`.

Each person has exactly 1 flow for home – it’s just `person.household` with probability 1. A person has 0 or 1 flows to work, based on the value of `person.workplace`.

This doesn’t mean that all people in the same MSA share the same travel behavior. Each person has their own `activity_durations` field, based on time-use survey data. Even if two people share the same set of places where they may go shopping, one person may spend much more time on that activity than another.

See the [ASPICS conversion script](#) for all of this in action – it has a function to collapse a person’s flows down into a single weighted list.

Note that per MSOA, very few venues are represented as destinations – 10 for retail and 5 for school. Only the most likely venues from QUANT are used.

## 6.2 Flow weights

How do you interpret the probabilities/weights for flows? If your model needs people to visit specific places each day, you could randomly sample a venue from the flows, weighting them appropriately. For retail, you may want to repeat this sampling every day of the simulation, so they visit different venues. For primary and secondary school, it may be more appropriate to sample once and store that for the simulation – a student probably doesn’t switch schools daily.

Alternatively, you can follow what ASPICS does. Every day, each person logically visits all possible venues, but their interaction there (possibly receiving or transmitting COVID) is weighted by the probability of each venue.

## 7 Modelling methods

The principles behind the generation of the enriched [SPENSER](#) population data and behind the modelling of trips to schools and retail from [QUANT](#) are detailed in

Spooner F et al. A dynamic microsimulation model for epidemics. Soc Sci Med., 291:114461 (2021). ([DOI](#))

Lomax N et al. An Open-Source Model for Projecting Small Area Demographic and Land-Use Change. Geographical analysis, 54(3), 599-622 (2022). ([DOI](#))

In order to distribute each individual of the population to a unique physical workplace, we first created a population of all individual workplaces in England, based on a combination of the Nomis UK Business Counts 2020 dataset and the Nomis Business register and Employment Survey 2015 (see [Data sources](#)). The first dataset gives the number of individual workplace counts per industry, using the SIC 2007 industry classification, with imprecise size (i.e. number of employees) bands at MSOA level. The second dataset gives the total number of jobs available at LSOA level per SIC 2007 industry category. We found that the distribution of workplace sizes follows closely a simple  $1/x$  distribution, allowing us to draw for each workplace a size within their band, with sum constraints given by the total number of jobs available, according to the second dataset.

The workplace ‘population’ and individual population are then levelled for each SIC 2007 category by removing the exceeding part of whichever dataset lists more items. This takes into account that people and business companies are likely to over-report their working availability (e.g. part time and seasonal contracts are not counted differently than full time contracts, jobseekers or people on maternity leave might report the SIC of their last job). This process can be controlled by a threshold in the parameter file that defines the maximal total proportion of workers or jobs that can be removed. If the two datasets cannot be levelled accordingly, the categories are dropped and the datasets are levelled globally. Tests in the West Yorkshire area have shown that when the level 1 SIC, containing 21 unique categories, is used, 90% of the volume of commuting flows were recovered compared to the Nomis commuting OD matrices at MSOA level.

The employees for each workplace are drawn according to the ‘universal law of visitation’, see

Schläpfer M et al. The universal visitation law of human mobility. Nature 593, 522–527 (2021). ([DOI](#))



This framework predicts that visitors to any destination follow a simple

$$(r,f) = K / (rf)^2$$

distribution, where  $(r,f)$  is the density of visitors coming from a distance  $r$  with frequency  $f$  and  $K$  is a balancing constant depending on the specific area. In the context of commuting, it can be assumed that  $f = 1$ . Additionally, we only need to weigh potential employees against each other, which removes the necessity to compute explicitly  $K$ . In the West Yorkshire test, we found a Pearson coefficient of 0.7 between the predicted flows when aggregated at MSOA level and the OD matrix at MSOA level available from Nomis.

## 7.1 Income data

This modelling is mainly based on the 2020 revised edition of the [Earnings and hours worked, region by occupation by four-digit SOC: ASHE Table 15](#) database from ONS. Some percentiles for employees' gross hourly salaries are provided for each full-time and part-time job according to their four-digit SOC classification per region, and separated by sex.

### 7.1.1 Methods

The data are far from complete (only about 15% of all possible values), especially for the highest deciles. We found that an order 3 polynomial fit was satisfactory for most categories (93.11%) to complete the partially filled SOC. SOC with too many missing values are given the value for the category that is immediately higher in the SOC hierarchy. Some jobs appear to have a 'ceiling' for the highest percentiles, making the polynomial fit fail. In that case, we have replaced the unknown values by the highest known value in the raw data (as there is no clear and systemic fit for these special cases). In addition, there is no information for the highest decile in all cases, which means that the highest salaries are underestimated (and exceptionally high salaries cannot be obtained). The result of this phase is four tables {male full-time, male part-time, female full-time, female part-time} containing the coefficients of the fitted order 3 polynomial, with an optional ceiling percentile when relevant.

A percentile is chosen randomly (uniformly) for each individual, and the salary is then deduced according to their full-time/part-time status, region, sex and SOC category. A basic hourly salary column is added to the unprocessed SPC data, as well as a corresponding annual salary based on their estimated hours worked per day, according to the Time Use Survey matching. In addition, we repeat this process for all individuals that are categorised as 'Self-employed' or 'Employee unspecified' by the Time Use Survey matching, as if they were full time employees. These values are recorded in the columns `IncomeHAsIf` and `IncomeYAsIf`. We noticed that a high number of employees were given no worked hours by the Time Use Survey. We have added to the `IncomeYAsIf` column an estimation of their annual salary based on [Table 15.9a](#):

[Paid hours worked - Total 2020](#), and also depending on the same four variables as above (full-time/part-time status, region, sex and SOC category).

In addition, [age data](#) are made available by ONS. Part of the differences that can be observed between different age groups are already taken into account through the fact that the SOC category can evolve during a career. To take into account that dependence, we first run the above method without weighing by age. The results are shown in the age validation section below. The residual impact of age alone is then added to the model in the following way. When the percentile is drawn for a specific individual, it is morphed to fit within the usual percentage range accessible to that age category. The function that operates this morphing is inferred beforehand and takes into account the salary distribution per age computed by the previous non-age weighted iteration of the modelling (see figure - TBA - for a more detailed description of this function).

The R codes for this modelling are [here](#).

The methods are validated in the next section. Since it is not possible to optimise every criterion at once, this next section can also be used as a reference to re-adjust some values to match exactly the ONS estimated means for one particular criterion of interest.

### 7.1.2 Comparison to reference values from ONS

We compare the results of the modelling to the raw datasets from ONS.

- Mod for modelled
- M for male
- F for female
- H for hourly gross salary
- Y for annual gross salary
- FT for full-Time
- PT for part-Time
- Only individuals recorded as employees (i.e. not self-employed) are taken into account in this section.

#### Number of employees per sex and full-time/part-time classification

The numbers given by ONS vary from dataset to dataset and are reported by ONS as indicative only. For the modelled values, we give the total number of individuals with a non-zero salary in each category.

| Variable | All    | FT     | PT   | M      | M     |        | F      | F FT     | F PT     |
|----------|--------|--------|------|--------|-------|--------|--------|----------|----------|
|          |        |        |      |        | FT    | M PT   |        |          |          |
| ONS tot  | 22-26k | 16-19k | 6-8k | 11-13k | 9-11k | 1.5-2k | 11-13k | 6.5-7.5k | 4.5-5.5k |

| Variable  | All   | FT    | PT   | M     | M FT | M PT | F     | F FT | F PT |
|-----------|-------|-------|------|-------|------|------|-------|------|------|
| Mod tot H | 23.1k | 18.5k | 4.6k | 11.8k | 11k  | 0.8k | 11.3k | 7.5k | 3.8k |
| Mod tot Y | 17.6k | 14.8k | 2.8k | 9.4k  | 8.9k | 0.5k | 8.2k  | 5.9k | 2.3k |

A significant number of individuals listed as working either full or part time have 0 effective worked hours per day according to the Time Use Survey matching. In those cases, an hourly salary is modelled depending on their SOC, region and sex, as for any other employee, but the annual salary will be displayed as 0. It is possible to estimate their likely true number of hours worked from the same ONS dataset (Table 15.9a: Paid hours worked - Total 2020), also depending on their sex, soc and region. This calculation has been added to the “As If” column.

#### Hourly gross salary per sex and full-time/part-time classification

| Variable   | All   | FT    | PT    | M     | M FT  | M PT  | F     | F FT  | F PT  |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| ONS mean   | 17.63 | 18.32 | 13.93 | 18.81 | 19.12 | 14.69 | 16.19 | 17.08 | 13.68 |
| ONS median | 13.71 | 15.15 | 10.38 | 14.84 | 15.58 | 10.12 | 12.58 | 14.42 | 10.47 |
| Mod mean   | 16.45 | 17.19 | 13.45 | 17.50 | 17.84 | 12.75 | 15.35 | 16.23 | 13.60 |
| Mod median | 13.55 | 14.46 | 10.23 | 14.27 | 14.72 | 9.16  | 12.79 | 14.12 | 10.51 |

The median values are quite close to the ONS values, but the mean values are always lower. This is expected, see the description of the modelling above.

#### Annual gross salary per sex and full-time/part-time classification

Only values > 0 are retained for these calculations.

| Variable   | All    | FT     | PT     | M      | M FT   | M PT   | F      | F FT   | F PT   |
|------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| ONS mean   | 31,646 | 38,552 | 13,819 | 38,421 | 42,072 | 14,796 | 24,871 | 33,253 | 13,512 |
| ONS median | 25,886 | 31,487 | 11,240 | 31,393 | 33,915 | 10,883 | 20,614 | 28,002 | 4,743  |
| Mod mean   | 34,317 | 36,595 | 22,257 | 37,574 | 38,496 | 20,698 | 30,594 | 33,729 | 22,585 |
| Mod median | 28,713 | 30,942 | 17,928 | 31,404 | 32,382 | 17,382 | 25,875 | 29,028 | 18,137 |

The average salary for part-time employees is correct when values equal to 0 are taken into account. This suggests that the total number of hours worked for part-time employees is

correct, but the way they are distributed among individuals is not. It could be due to the TUS taking a snapshot of the situation during a particular week, rather than averaging their data over the year. It appears that the TUS matching also overestimates the average number of hours worked for female employees.

### Regional differences (hourly gross salary)

| Region     | East<br>East<br>lands | East<br>Mid-<br>lands | London | North<br>East | North<br>West | South<br>East | South<br>West | West<br>Mid-<br>lands | Yorkshire and<br>The Humber |
|------------|-----------------------|-----------------------|--------|---------------|---------------|---------------|---------------|-----------------------|-----------------------------|
| ONS mean   | 16.74                 | 15.87                 | 23.78  | 15.69         | 16.36         | 17.88         | 16.36         | 16.34                 | 15.76                       |
| ONS median | 13.28                 | 12.65                 | 18.30  | 12.40         | 12.90         | 14.33         | 12.74         | 12.92                 | 12.46                       |
| Mod mean   | 16.67                 | 15.29                 | 19.39  | 15.05         | 15.22         | 17.34         | 15.92         | 15.47                 | 14.41                       |
| Mod median | 13.69                 | 12.79                 | 16.25  | 12.42         | 12.44         | 14.84         | 13.35         | 12.64                 | 12.44                       |

The pearson correlations for mean and median between the modelled and raw values are 0.92 and 0.93.

### Hourly gross salary per one-digit SOC

| 1d SOC     | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| ONS mean   | 26.77 | 23.38 | 18.29 | 13.42 | 13.35 | 10.87 | 10.94 | 12.23 | 10.77 |
| ONS median | 20.96 | 21.34 | 15.66 | 11.54 | 12.04 | 10.08 | 9.52  | 10.93 | 9.22  |
| Mod mean   | 21.52 | 22.14 | 16.00 | 12.76 | 12.55 | 10.49 | 10.50 | 12.05 | 9.87  |
| Mod median | 17.22 | 20.66 | 14.12 | 11.46 | 11.34 | 9.71  | 9.59  | 10.82 | 9.12  |

1. Managers, directors and senior officials
2. Professional occupations
3. Associate professional and technical occupations
4. Administrative and secretarial occupations
5. Skilled trades occupations
6. Caring, leisure and other service occupations
7. Sales and customer service occupations
8. Process, plant and machine operatives
9. Elementary occupations.

The pearson correlations for mean and median between the modelled and raw values are 0.98 and 0.98.

### Hourly gross salary per age

The reference for this table is: [Table 6.5a Hourly pay - Gross 2020](#)

Table before weighting by age:

| Age        | 16-17 | 18-21 | 22-29 | 30-39 | 40-49 | 50-59 | 60+   |
|------------|-------|-------|-------|-------|-------|-------|-------|
| ONS mean   | 7.21  | 9.59  | 14.09 | 18.13 | 20.04 | 19.12 | 16.32 |
| ONS median | 6.36  | 9.00  | 12.26 | 15.08 | 15.89 | 14.39 | 12.17 |
| Mod mean   | 12.77 | 14.96 | 16.33 | 16.93 | 16.83 | 16.66 | 16.29 |
| Mod median | 10.93 | 12.71 | 13.88 | 14.02 | 13.96 | 13.85 | 13.65 |

The pearson correlations for mean and median between the modelled and raw values are 0.92 and 0.92.

Table after weighting by age:

| Age        | 16-17 | 18-21 | 22-29 | 30-39 | 40-49 | 50-59 | 60+   |
|------------|-------|-------|-------|-------|-------|-------|-------|
| ONS mean   | 7.21  | 9.59  | 14.09 | 18.13 | 20.04 | 19.12 | 16.32 |
| ONS median | 6.36  | 9.00  | 12.26 | 15.08 | 15.89 | 14.39 | 12.17 |
| Mod mean   | 9.05  | 11.15 | 14.87 | 17.35 | 17.96 | 17.47 | 15.41 |
| Mod median | 8.20  | 9.51  | 12.86 | 14.41 | 14.78 | 14.43 | 12.56 |

The pearson correlations for mean and median between the modelled and raw values are 0.99 and 0.99.

## 7.2 BMI data

Body Mass Index (BMI) is calculated for each individual from the [Health Survey for England 2019](#) (access needs to be requested to the UK Data Service). This calculation is completely independent from the PSM to the HSE 2017, and therefore the new BMI values will not fit within the categories indicated by this earlier PSM. As the BMI variable is not necessarily independent from the other health variables (diabetes etc.), the new variable should only be used for studies where all other variables are considered equal. The new variable is continuous (a float).

According to the HSE 2019, the distribution of BMI values should follow figure 1. Socio-economic category was discarded for the modelling as it is not independent from the other variables and “mixed” and “other” ethnicities have been merged due to small sample sizes.

Figure 1. BMI per age. Columns represent ethnicity (White, Black, Asian, Other), and the rows sex (female, male).

The distribution for each age group is a gamma distribution. See figure 2.

Figure 2. Distribution of BMI values for white females aged 30-34.

Due to small sample sizes, the BMI is calculated for each individual depending on their age according to a gamma distribution whose mean is the mean for the corresponding age, sex and ethnicity (thick line in figure 1), but whose variance is only determined by the total variance by sex and ethnicity. The resulting BMI were validated for Bedfordshire, and correlations of 0.93 and 0.97 were found between the mean and variance of the modelled data compared to those for the reference HSE 2019 data. See figure 3. The distribution per age, as in figure 1, were also validated.

Figure 3. Modelled mean and variance compared to the reference mean and variance from the HSE 2019 data for each of the eight categories of figure 1.

The R codes for this modelling are [here](#).

## 8 Data sources

The data is sorted around the 2011 Middle-layer Super Output Area (MSOA) geographical unit. These units were created for census collection and are designed to be relatively homogeneous, with an average population size of 8000. Any list of MSOAs in England can be run, with the exception of the MSOAs forming the City of London (i.e the London borough called the City, not London as a whole).

The data from Open Street Map (OSM) is downloaded directly from <https://www.openstreetmap.org>. Everything else is hosted as local copies on one Azure repository that interacts automatically with the model, and divided into utilities, county level data and national data.

`lookUp.csv`

The look-up table links different geographies together. It is used internally by the model, but can also help the user define their own study area. `MSOA11CD`, `MSOA11NM`, `LAD20CD`, `LAD20NM`, `ITL321CD`, `ITL321NM`, `ITL221CD`, `ITL221NM`, `ITL121CD`, `ITL121NM` are all standard denominations fully compatible with ONS fields of the same name. They are based on ONS [lookups](#). See ONS documentation for more details. `CTY20NM` and `CCTY20NM` are custom denominations for the counties of England (used to sort the county level population data) and the ceremonial counties of England respectively. Their spelling may vary in different data sources and the field `CTY20NM` is not compatible with the ONS field of the same name (which excludes all counties that are also unitary authorities). `GoogleMob` and `OSM` are different spellings for the counties of England used by Google and OSM for their data releases.

### 8.1 County level data

Contains 47 files, each representing the population in 2020 of one of the counties of England mentioned above, and named

`pop_<county_name>.gz`

This data is based on the [2011 UK census](#), the [Time Use Survey 2014-15](#) and the [Health Survey for England 2017](#). The SPENSER (Synthetic Population Estimation and Scenario Projection) microsimulation model ([reference](#)) distributes a synthetic population based on the census at MSOA scale and projects it to 2020 according to estimates from the Office for National Statistics (ONS). This information was enriched with some of the content of the other two datasets through propensity score matching (PSM) by Prof. Karyn Morrissey (Technical University of Denmark). The rest of the datasets can be added *a posteriori* from the identifiers provided.

The fields currently contained are:

- `idp`: a unique global individual identifier across all counties
- `MSOA11CD`: MSOA code where the individual lives
- `hid`: household identifier, includes communal establishments
- `pid`: identifier linking to the 2011 Census
- `pid_tus`: identifier linking to the Time Use Survey 2015
- `pid_hse`: identifier linking to the Health Survey for England 2017
- `sex`: 0 female; 1 male
- `age`: in years
- `origin`: 1 White; 2 Black; 3 Asian; 4 Mixed; 5 Other
- `nssec5`: National Statistics Socio-economic classification:
  - 1: Higher managerial, administrative and professional occupations
  - 2: Intermediate occupations
  - 3: Small employers and own account workers
  - 4: Lower supervisory and technical occupations
  - 5: Semi-routine and routine occupations
  - 0: Never worked and long-term unemployed
- `soc2010`: Previous version of the [Standard Occupational Classification](#)
- `sic1d07`: Standard [Industrial Classification of Economic Activities 2007](#), 1st layer (number corresponding to the letter in alphabetical order)
- `sic2d07`: Standard [Industrial Classification of Economic Activities 2007](#), 2nd layer
- `pwkstat`: Employment status according to the TUS
- Proportion of 24h spent doing different daily activities:
  - `punknown + pwork + pschool + pshop + pservices + pleasure + pescort + ptransport = pnothome`
  - `phome + pworkhome = phometot`
  - `pnothome + phometot = 1`
- `IncomeX`: hourly (X = “H”) and annual (X = “Y”) income for employees, see [modelling methods](#) for more details
- `cvd`: has a cardio-vascular disease (0 or 1)
- `diabetes`: has diabetes (0 or 1)



- **bloodpressure**: has high blood pressure (0 or 1)
- **BMIvg6**: Body Mass Index:
  - Not applicable
  - Underweight: less than 18.5
  - Normal: 18.5 to less than 25
  - Overweight: 25 to less than 30
  - Obese I: 30 to less than 35
  - Obese II: 35 to less than 40
  - Obese III: 40 or more
- **bmiNew** is a float estimated value for the BMI of the individual. These were drawn directly according to age, sex and ethnicity and are completely independent of the above values (see [modelling methods](#)).
- **lng**: longitude of the MSOA11CD centroid
- **lat**: latitude of the MSOA11CD centroid

Some other fields were kept from and for other specific projects but are not from official sources and should generally not be used.

## 8.2 National data

### `businessRegistry.csv`

Contains a breakdown of all business units (i.e. a single workplace) in England at LSOA scale (smaller than MSOA), estimated by the project contributors from two nomis datasets: [UK Business Counts - local units by industry and employment size band 2020](#) and [Business Register and Employment Survey 2015](#). Each item contains the **size** of the unit and its main **sic1d07** code in reference to standard [Industrial Classification of Economic Activities 2007](#) (number corresponding to the letter in alphabetical order). It is used to compute commuting flows.

The R codes to compute this file are [here](#).

### `MSOAS_shp.tar.gz`

Is a simple shapefile taken from ONS [boundaries](#).

### `QUANT_RAMP.tar.gz`

See: Milton R, Batty M, Dennett A, dedicated [RAMP Spatial Interaction Model GitHub repository](#). It is used to compute the flows towards schools and retail.

`timeAtHomeIncreaseCTY.csv`

This file is a subset from [Google COVID-19 Community Mobility Reports](#), cropped to England. It describes the daily reduction in mobility, averaged at county level, due to lockdown and other COVID-19 restrictions between the 15th of February 2020 and 15th of April 2022. Missing values have been replaced by the national average. These values can be used directly to reduce `pnothome` and increase `phometot` (and their sub-categories) to simulate more accurately the period.

The R codes to process these data are [here](#).

**Part III**

**Advanced**

## 9 Developer guide

The site is built with [Quarto](#). You can iterate on it locally: `cd docs; quarto preview`

### 9.1 Code hygiene

We use automated tools to format the code.

```
cargo fmt

# Format Markdown docs
prettier --write *.md
prettier --write docs/*.qmd --parser markdown
```

Install [prettier](#) for Markdown.

### 9.2 Some tips for working with Rust

There are two equivalent ways to rebuild and then run the code. First:

```
cargo run --release -- devon
```

The `--` separates arguments to `cargo`, the Rust build tool, and arguments to the program itself. The second way:

```
cargo build --release
./target/release/aspics devon
```

You can build the code in two ways – **debug** and **release**. There’s a simple tradeoff – debug mode is fast to build, but slow to run. Release mode is slow to build, but fast to run. For the ASPICS codebase, since the input data is so large and the codebase so small, I’d recommend always using `--release`. If you want to use debug mode, just omit the flag.

If you’re working on the Rust code outside of an IDE like [VSCode](#), then you can check if the code compiles much faster by doing `cargo check`.

## 9.3 Docker

We provide a Dockerfile in case it's helpful for running, but don't recommend using it. If you want to, then assuming you have Docker setup:

```
docker build -t spc .  
docker run --mount type=bind,source="$(pwd)"/data,target=/spc/data -t spc /spc/target/rele
```

This will make the `data` directory in your directory available to the Docker image, where it'll download the large input files and produce the final output.

# 10 Code walkthrough

SPC is implemented in [Rust](#), and its code can be found [here](#). This is an unusual implementation choice in the data science world, so this page has some notes about it.

The code-base makes use of some techniques that may be generally applicable to other projects, independent of the language chosen.

## 10.0.1 Split code into two stages

Agent-based models and spatial interaction models require some kind of input. Often the effort to transform external data into this input can exceed that of the simulation component. Cleanly separating the two problems has some advantages:

- iterate on the simulation faster, without processing raw data every run
- reuse the prepared input for future projects
- force thinking about the data model needed by the simulation, and transform the external data into that form

SPC is exactly this first stage, originally split from [ASPICS](#) when further uses of the same population data were identified.

## 10.0.2 Explicit data schema

Dynamically typed languages like Python don't force you to explicitly list the shape of input data. It's common to read CSV files with [pandas](#), filter and transform the data, and use that throughout the program. This can be quick to start prototyping, but is hard to maintain longer-term. Investing in the process of writing down types:

- makes it easier for somebody new to understand your system – they can first focus on **what** you're modeling, instead of how that's built up from raw data sources
- clarifies what data actually matters to your system; you don't carry forward unnecessary input
- makes it impossible to express invalid states

- One example is [here](#) – per person and activity, there’s a list of venues the person may visit, along with a probability of going there. If the list of venues and list of probabilities are stored as separate lists or columns, then their length may not match.
- reuse the prepared input for future projects

There’s a variety of techniques for expressing strongly typed data:

- [protocol buffers](#) or [flatbuffers](#)
- [JSON schemas](#)
- [Python data classes](#) and [optional type hints](#)
- [statically typed languages like Rust](#)

### 10.0.3 Type-safe IDs

Say your data model has many different objects, each with their own ID – people, households, venues, etc. You might store these in a list and use the index as an ID. This is fine, but nothing stops you from confusing IDs and accidentally passing in venue 5 to a function instead of household 5. In Rust, it’s easy to create “wrapper types” like [this](#) and let the compiler prevent these mistakes.

This technique is also useful when preparing external data. [GTFS data](#) describing public transit routes and timetables contains many string IDs – shapes, trips, stops, routes. As soon as you read the raw input, you can [store the strings in more precise types](#) that prevent mixing up a stop ID and route ID.

### 10.0.4 Idempotent data preparation

If you’re iterating on your initialisation pipeline’s code, you probably don’t want to download a 2GB external file every single run. A common approach is to first test if a file exists and don’t download it again if so. In practice, you may also need to handle unzipping files, showing a progress bar while downloading, and printing clear error messages. This codebase has some [common code](#) for doing this in Rust. We intend to publish a separate library to more easily call in your own code.

### 10.0.5 Logging with structure

It’s typical to print information as a complex pipeline runs, for the user to track progress and debug problems. But without any sort of organization, it’s hard to follow what steps take a long time or encounter problems. What if your logs could show the logical structure of your pipeline and help you understand where time is spent?

```

[192.30s] [get_info_per_msoa] Loading buildings from data/raw_data/countydata/OSM/west-yorkshire-latest-free/
[192.64s] [get_info_per_msoa] Found 474,207 buildings from data/raw_data/countydata/OSM/west-yorkshire-latest-free/gis
osm_buildings_a_free_1.shp
[192.70s] [get_info_per_msoa] Matching 474,207 points to 299 polygons. Building R-Tree...
[194.22s] [calculate_lockdown_per_day] Calculating per-day lockdown values
[194.24s] [load_events] Loading events data
[194.25s] [initialisation] By the end, Memory usage: 1.53GiB
[200.89s] [Writing snapshot] Merging flows for all activities

212.24s      initialisation WestYorkshireLarge
31.18ms      grab_raw_data
192.04s      creating_population
8.20s        read_individual_time_use_and_health_data
4.35s        Reading "data/raw_data/countydata/tus_hse_west-yorkshire.csv"
3.83s        Creating households
152.38s      create_commuting_flows
8.30s        setup_venue_flows Retail
6.59s        Copying flows to people Retail
7.47s        setup_venue_flows Nightclub
6.63s        Copying flows to people Nightclub
8.68s        setup_venue_flows PrimarySchool
6.58s        Copying flows to people PrimarySchool
7.00s        setup_venue_flows SecondarySchool
6.50s        Copying flows to people SecondarySchool
2.03s        get_info_per_msoa
24.48ms      calculate_lockdown_per_day
251.20µs     load_events "model_parameters/eventDataConcerts.csv"
1.07s        Writing population to "data/processed_data/WestYorkshireLarge/rust_cache.bin"
16.93s        Writing snapshot

```

The screenshot above shows a summary printed at the end of a long pipeline run. It's immediately obvious that the slowest step is creating commuting flows.

This codebase uses the [tracing](#) framework for logging, with a [custom piece](#) to draw the tree. (We'll publish this as a separate library once it's more polished.) The tracing framework is hard to understand, but the main conceptual leap over regular logging frameworks is the concept of a **span**. When your code starts one logical step, you call a method to create a new span, and when it finishes, you close that span. Spans can be nested in any way – `create_commuting_flows` happens within the larger step of `creating_population`.

### 10.0.6 Determinism

Given the same inputs, your code should always produce identical output, no matter where it's run or how many times. Otherwise, debugging problems becomes very tedious, and it's more difficult to make conclusions from results. Of course, many projects have a stochastic element – but this should be controlled by a random number generator (RNG) seed, which is part of the input. You vary the seed and repeat the program, then reason about the distribution of results.

Aside from organizing your code to let a single RNG seed influence everything, another possible source of non-determinism is iteration order. In Rust, a `HashMap` could have different order every time it's used, so we use a `BTreeMap` instead when this matters. In Python, dictionaries are ordered. Be sure to check for your language.



## 10.1 Protocol buffers

SPC uses protocol buffers v2 for output. This has some advantages explained the “explicit data schema” section above.

Note that we chose proto2 instead of proto3, because proto3 doesn’t support [required fields](#). This is done to allow schemas to evolve better over time, but this isn’t a feature SPC makes use of. There’s no need to have new code work with old data, or vice versa – if the schema is updated, downstream code should adapt accordingly and use the updated input files.

Note also that protocol buffers don’t easily support type-safe wrappers around numeric IDs, so downstream code has to be careful not to mix up household, venue, and person IDs. For this reason, SPC internally doesn’t use the auto-generated protobuf code until the very end of the pipeline. It’s always possible to be more precise with native Rust types, and convert to the less strict types later.

## 10.2 An example of the power of static type checking

Imagine we want to add a new activity type to represent people going to university and higher education. SPC already has activities for primary and secondary school, so we’ll probably want to follow those as a guide. In any language, we could search the codebase for relevant terms to get a sense of what to update. In languages like Python without an up-front compilation step, if we fail to update something or write blatantly incorrect code (such as making a typo in variable names or passing a list where a string was expected), we only find out when that code happens to run. In pipelines with many steps and large input files, it could be a while before we reach the problematic code.

Let’s walk through the same exercise for SPC’s Rust code. We start by adding a new `University` case to the [Activity enum](#). If we try to compile the code here (with `cargo check` or an IDE), we immediately get 4 errors.

```

error[E0004]: non-exhaustive patterns: `University` not covered
--> src/init/quant.rs:38:44
38 |         let (population_csv, prob_sij) = match activity {
    |                                           ^^^^^^^^^ pattern `University` not covered
    |
    ::: src/lib.rs:129:1
129 | / pub enum Activity {
130 | |     Retail,
131 | |     PrimarySchool,
132 | |     SecondarySchool,
    | |     ...
135 | |     University,
    | |     ----- not covered
136 | | }
    | |_- `Activity` defined here
    |
= help: ensure that all possible cases are being handled, possibly by adding wildcards or more
match arms
= note: the matched value is of type `Activity`

```

Three of the errors are in the QUANT module. The first is [here](#). It's immediately clear that for retail and primary/secondary school, we read in two files from QUANT representing venues where these activities take place and the probability of going to each venue. Even if we were unfamiliar with this codebase, the compiler has told us one thing we'll need to figure out, and where to wire it up.

```

error[E0004]: non-exhaustive patterns: `University` not covered
--> src/protobuf.rs:135:11
135 |         match activity {
    |             ^^^^^^^^^ pattern `University` not covered
    |
    ::: src/lib.rs:129:1
129 | / pub enum Activity {
130 | |     Retail,
131 | |     PrimarySchool,
132 | |     SecondarySchool,
    | |     ...
135 | |     University,
    | |     ----- not covered
136 | | }
    | |_- `Activity` defined here
    |
= help: ensure that all possible cases are being handled, possibly by adding wildcards or more
match arms
= note: the matched value is of type `Activity`

```

The other error is in the [code that writes the protobuf output](#). Similarly, we need a way to represent university activities in the protobuf scheme.

Extending an unfamiliar code-base backed by compiler errors is a very guided experience. If you wanted to add more demographic attributes to people or energy use information to households, you don't need to guess all of the places in the code you'll need to update. You can just add the field, then let the compiler tell you all places where those objects get created.

# 11 Performance

The following tables summarizes the resources SPC needs to run in different areas.

| year | study_area           | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|----------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2012 | England/bedfordshire | 74        | 245,166        | 647,272    | 256.83 MiB | 10 seconds | 3 seconds      | 849.02 MiB   |
| 2020 | England/bedfordshire | 74        | 272,875        | 674,044    | 271.65 MiB | 9 seconds  | 3 seconds      | 922.88 MiB   |
| 2022 | England/bedfordshire | 74        | 309,706        | 703,582    | 277.74 MiB | 9 seconds  | 3 seconds      | 929.80 MiB   |
| 2032 | England/bedfordshire | 74        | 309,706        | 703,582    | 277.74 MiB | 9 seconds  | 3 seconds      | 929.80 MiB   |
| 2039 | England/bedfordshire | 74        | 329,061        | 715,797    | 278.39 MiB | 11 seconds | 3 seconds      | 927.77 MiB   |
| 2012 | England/berkshire    | 107       | 342,167        | 890,543    | 356.04 MiB | 14 seconds | 7 seconds      | 1.06 GiB     |
| 2020 | England/berkshire    | 107       | 365,905        | 918,258    | 373.35 MiB | 14 seconds | 7 seconds      | 1.10 GiB     |
| 2022 | England/berkshire    | 107       | 394,446        | 941,655    | 368.37 MiB | 14 seconds | 7 seconds      | 1.08 GiB     |
| 2032 | England/berkshire    | 107       | 394,446        | 941,655    | 368.37 MiB | 14 seconds | 7 seconds      | 1.08 GiB     |
| 2039 | England/berkshire    | 107       | 408,604        | 949,986    | 367.21 MiB | 14 seconds | 7 seconds      | 1.08 GiB     |
| 2012 | England/bristol      | 55        | 182,299        | 448,233    | 173.74 MiB | 6 seconds  | 2 seconds      | 527.23 MiB   |
| 2020 | England/bristol      | 55        | 196,940        | 470,039    | 183.99 MiB | 6 seconds  | 2 seconds      | 547.49 MiB   |

| year | study_area            | num_msas | soas_households | chholspeople | file_size  | runtime    | commuting_time | memory_usage |
|------|-----------------------|----------|-----------------|--------------|------------|------------|----------------|--------------|
| 2022 | England/bristol       | 55       | 216,197         | 503,014      | 192.51 MiB | 7 seconds  | 2 seconds      | 559.78 MiB   |
| 2032 | England/bristol       | 55       | 216,197         | 503,014      | 192.51 MiB | 7 seconds  | 2 seconds      | 559.78 MiB   |
| 2039 | England/bristol       | 55       | 227,770         | 521,371      | 199.72 MiB | 7 seconds  | 2 seconds      | 573.40 MiB   |
| 2012 | England/buckinghamsh  | 99       | 99,235          | 261,340      | 108.30 MiB | 5 seconds  | 1 second       | 310.38 MiB   |
| 2020 | England/buckinghamsh  | 99       | 108,999         | 271,050      | 114.31 MiB | 5 seconds  | 1 second       | 400.87 MiB   |
| 2022 | England/buckinghamsh  | 99       | 123,578         | 278,548      | 112.39 MiB | 5 seconds  | 1 second       | 393.64 MiB   |
| 2032 | England/buckinghamsh  | 99       | 123,578         | 278,548      | 112.39 MiB | 5 seconds  | 1 second       | 393.64 MiB   |
| 2039 | England/buckinghamsh  | 99       | 130,393         | 281,773      | 112.14 MiB | 5 seconds  | 1 second       | 391.52 MiB   |
| 2012 | England/cambridgeshir | 98       | 327,257         | 832,980      | 323.35 MiB | 11 seconds | 5 seconds      | 1013.16 MiB  |
| 2020 | England/cambridgeshir | 98       | 348,522         | 863,250      | 341.16 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2022 | England/cambridgeshir | 98       | 377,634         | 907,166      | 348.75 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2032 | England/cambridgeshir | 98       | 377,634         | 907,166      | 348.75 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2039 | England/cambridgeshir | 98       | 392,478         | 924,170      | 351.39 MiB | 12 seconds | 5 seconds      | 1.04 GiB     |
| 2012 | England/cheshire      | 139      | 441,084         | 1,042,064    | 402.14 MiB | 16 seconds | 7 seconds      | 1.13 GiB     |
| 2020 | England/cheshire      | 139      | 464,134         | 1,070,597    | 416.35 MiB | 16 seconds | 7 seconds      | 1.46 GiB     |
| 2022 | England/cheshire      | 139      | 489,476         | 1,125,198    | 425.27 MiB | 16 seconds | 7 seconds      | 1.47 GiB     |

| year | study_area         | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|--------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2032 | England/cheshire   | 139       | 489,476        | 1,125,198  | 25.27 MiB  | 16 seconds | 7 seconds      | 1.47 GiB     |
| 2039 | England/cheshire   | 139       | 501,501        | 1,149,514  | 31.10 MiB  | 16 seconds | 7 seconds      | 1.48 GiB     |
| 2012 | England/cornwall   | 74        | 232,659        | 549,616    | 208.07 MiB | 8 seconds  | 2 seconds      | 742.92 MiB   |
| 2020 | England/cornwall   | 74        | 247,105        | 577,414    | 219.74 MiB | 8 seconds  | 3 seconds      | 764.95 MiB   |
| 2022 | England/cornwall   | 74        | 270,134        | 634,940    | 233.36 MiB | 8 seconds  | 3 seconds      | 828.45 MiB   |
| 2032 | England/cornwall   | 74        | 270,134        | 634,940    | 233.36 MiB | 8 seconds  | 3 seconds      | 828.45 MiB   |
| 2039 | England/cornwall   | 74        | 280,546        | 658,610    | 239.72 MiB | 8 seconds  | 3 seconds      | 838.14 MiB   |
| 2012 | England/cumbria    | 64        | 222,586        | 498,624    | 188.03 MiB | 7 seconds  | 2 seconds      | 547.33 MiB   |
| 2020 | England/cumbria    | 64        | 226,893        | 499,873    | 188.73 MiB | 7 seconds  | 2 seconds      | 548.52 MiB   |
| 2022 | England/cumbria    | 64        | 230,206        | 499,840    | 183.18 MiB | 7 seconds  | 2 seconds      | 533.99 MiB   |
| 2032 | England/cumbria    | 64        | 230,206        | 499,840    | 183.18 MiB | 7 seconds  | 2 seconds      | 533.99 MiB   |
| 2039 | England/cumbria    | 64        | 231,202        | 498,475    | 181.58 MiB | 7 seconds  | 2 seconds      | 530.96 MiB   |
| 2012 | England/derbyshire | 131       | 436,276        | 1,035,356  | 97.75 MiB  | 15 seconds | 7 seconds      | 1.12 GiB     |
| 2020 | England/derbyshire | 131       | 459,743        | 1,064,406  | 109.76 MiB | 16 seconds | 8 seconds      | 1.44 GiB     |
| 2022 | England/derbyshire | 131       | 489,764        | 1,122,078  | 119.52 MiB | 16 seconds | 7 seconds      | 1.45 GiB     |
| 2032 | England/derbyshire | 131       | 489,764        | 1,122,078  | 119.52 MiB | 16 seconds | 7 seconds      | 1.45 GiB     |
| 2039 | England/derbyshire | 131       | 505,314        | 1,152,518  | 129.01 MiB | 16 seconds | 8 seconds      | 1.47 GiB     |

| year | study_area          | num_msaas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|---------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2012 | England/devon       | 156       | 494,106        | 1,165,952  | 238.60 MiB | 18 seconds | 8 seconds      | 1.49 GiB     |
| 2020 | England/devon       | 156       | 523,033        | 1,212,387  | 259.44 MiB | 18 seconds | 8 seconds      | 1.53 GiB     |
| 2022 | England/devon       | 156       | 567,011        | 1,304,874  | 278.71 MiB | 19 seconds | 9 seconds      | 1.64 GiB     |
| 2032 | England/devon       | 156       | 567,011        | 1,304,874  | 278.71 MiB | 19 seconds | 9 seconds      | 1.64 GiB     |
| 2039 | England/devon       | 156       | 589,178        | 1,342,774  | 288.23 MiB | 19 seconds | 9 seconds      | 1.66 GiB     |
| 2012 | England/durham      | 117       | 390,472        | 911,601    | 349.78 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2020 | England/durham      | 117       | 407,828        | 930,184    | 359.59 MiB | 12 seconds | 5 seconds      | 1.05 GiB     |
| 2022 | England/durham      | 117       | 425,611        | 952,801    | 356.63 MiB | 12 seconds | 5 seconds      | 1.04 GiB     |
| 2032 | England/durham      | 117       | 425,611        | 952,801    | 356.63 MiB | 12 seconds | 5 seconds      | 1.04 GiB     |
| 2039 | England/durham      | 117       | 434,593        | 959,555    | 357.66 MiB | 12 seconds | 5 seconds      | 1.04 GiB     |
| 2012 | England/east-sussex | 102       | 355,257        | 827,703    | 313.71 MiB | 12 seconds | 5 seconds      | 987.31 MiB   |
| 2020 | England/east-sussex | 102       | 380,894        | 853,970    | 324.02 MiB | 12 seconds | 6 seconds      | 1006.13 MiB  |
| 2022 | England/east-sussex | 102       | 423,181        | 895,907    | 329.56 MiB | 12 seconds | 5 seconds      | 1008.58 MiB  |

| year | study_area                       | num_msas | soas_households | people    | file_size  | runtime    | commuting_time | memory_usage |
|------|----------------------------------|----------|-----------------|-----------|------------|------------|----------------|--------------|
| 2032 | England/east-sussex              | 102      | 423,181         | 895,907   | 329.56 MiB | 12 seconds | 5 seconds      | 1008.58 MiB  |
| 2039 | England/east-sussex              | 102      | 446,000         | 915,014   | 335.45 MiB | 12 seconds | 5 seconds      | 1020.75 MiB  |
| 2012 | England/east-yorkshire-with-hull | 75       | 255,848         | 593,271   | 227.49 MiB | 8 seconds  | 3 seconds      | 778.75 MiB   |
| 2020 | England/east-yorkshire-with-hull | 75       | 262,609         | 602,286   | 233.14 MiB | 8 seconds  | 3 seconds      | 835.04 MiB   |
| 2022 | England/east-yorkshire-with-hull | 75       | 272,805         | 613,721   | 230.34 MiB | 8 seconds  | 3 seconds      | 824.50 MiB   |
| 2032 | England/east-yorkshire-with-hull | 75       | 272,805         | 613,721   | 230.34 MiB | 8 seconds  | 3 seconds      | 824.50 MiB   |
| 2039 | England/east-yorkshire-with-hull | 75       | 277,770         | 617,357   | 230.45 MiB | 8 seconds  | 3 seconds      | 825.00 MiB   |
| 2012 | England/essex                    | 211      | 722,974         | 1,786,316 | 690.77 MiB | 30 seconds | 19 seconds     | 2.06 GiB     |
| 2020 | England/essex                    | 211      | 773,454         | 1,857,205 | 726.02 MiB | 32 seconds | 20 seconds     | 2.13 GiB     |
| 2022 | England/essex                    | 211      | 858,552         | 1,981,994 | 761.40 MiB | 33 seconds | 20 seconds     | 2.19 GiB     |
| 2032 | England/essex                    | 211      | 858,552         | 1,981,994 | 761.40 MiB | 33 seconds | 20 seconds     | 2.19 GiB     |
| 2039 | England/essex                    | 211      | 906,640         | 2,042,404 | 777.71 MiB | 33 seconds | 21 seconds     | 2.21 GiB     |
| 2012 | England/gloucestershire107       | 107      | 365,240         | 889,836   | 344.16 MiB | 13 seconds | 5 seconds      | 1.02 GiB     |
| 2020 | England/gloucestershire107       | 107      | 392,643         | 933,909   | 362.90 MiB | 13 seconds | 6 seconds      | 1.06 GiB     |
| 2022 | England/gloucestershire107       | 107      | 432,216         | 1,025,073 | 389.56 MiB | 14 seconds | 6 seconds      | 1.10 GiB     |

| year | study_area                 | num_msoas | num_households | num_people | file_size  | time commuting | memory_usage |
|------|----------------------------|-----------|----------------|------------|------------|----------------|--------------|
| 2032 | England/gloucestershire    | 107       | 432,216        | 1,025,073  | 89.56 MiB  | 14 seconds     | 1.10 GiB     |
| 2039 | England/gloucestershire    | 107       | 453,383        | 1,068,484  | 103.87 MiB | 14 seconds     | 1.43 GiB     |
| 2012 | England/greater-london     | 983       | 3,283,305      | 8,581,243  | 3.27 GiB   | 12 minutes     | 11.80 GiB    |
| 2020 | England/greater-london     | 983       | 3,574,266      | 8,983,773  | 3.48 GiB   | 12 minutes     | 12.22 GiB    |
| 2022 | England/greater-london     | 983       | 3,997,548      | 9,452,043  | 3.55 GiB   | 12 minutes     | 12.25 GiB    |
| 2032 | England/greater-london     | 983       | 3,997,548      | 9,452,043  | 3.55 GiB   | 12 minutes     | 12.25 GiB    |
| 2039 | England/greater-london     | 983       | 4,229,017      | 9,688,503  | 3.58 GiB   | 12 minutes     | 12.95 GiB    |
| 2012 | England/greater-manchester | 346       | 1,128,371      | 2,745,451  | 1.05 GiB   | 70 seconds     | 3.56 GiB     |
| 2020 | England/greater-manchester | 346       | 1,192,547      | 2,840,431  | 1.10 GiB   | 71 seconds     | 3.66 GiB     |
| 2022 | England/greater-manchester | 346       | 1,272,689      | 2,974,954  | 1.13 GiB   | 73 seconds     | 3.69 GiB     |
| 2032 | England/greater-manchester | 346       | 1,272,689      | 2,974,954  | 1.13 GiB   | 74 seconds     | 3.69 GiB     |
| 2039 | England/greater-manchester | 346       | 1,319,090      | 3,049,721  | 1.15 GiB   | 76 seconds     | 3.73 GiB     |
| 2012 | England/hampshire          | 225       | 733,611        | 1,810,513  | 98.03 MiB  | 32 seconds     | 2.07 GiB     |



| year | study_area            | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|-----------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2020 | England/hampshire     | 225       | 777,116        | 1,861,250  | 721.62 MiB | 32 seconds | 20 seconds     | 2.12 GiB     |
| 2022 | England/hampshire     | 225       | 836,451        | 1,931,667  | 728.97 MiB | 32 seconds | 20 seconds     | 2.12 GiB     |
| 2032 | England/hampshire     | 225       | 836,451        | 1,931,667  | 728.97 MiB | 33 seconds | 20 seconds     | 2.12 GiB     |
| 2039 | England/hampshire     | 225       | 867,417        | 1,960,190  | 735.50 MiB | 33 seconds | 20 seconds     | 2.13 GiB     |
| 2012 | England/herefordshire | 23        | 79,083         | 188,362    | 72.21 MiB  | 4 seconds  | 1 second       | 234.89 MiB   |
| 2020 | England/herefordshire | 23        | 83,238         | 195,194    | 74.71 MiB  | 4 seconds  | 1 second       | 239.36 MiB   |
| 2022 | England/herefordshire | 23        | 89,574         | 209,784    | 77.63 MiB  | 4 seconds  | 1 second       | 242.83 MiB   |
| 2032 | England/herefordshire | 23        | 89,574         | 209,784    | 77.63 MiB  | 4 seconds  | 1 second       | 242.83 MiB   |
| 2039 | England/herefordshire | 23        | 92,605         | 216,508    | 79.43 MiB  | 4 seconds  | 1 second       | 245.69 MiB   |
| 2012 | England/hertfordshire | 153       | 457,276        | 1,160,151  | 458.65 MiB | 19 seconds | 11 seconds     | 1.56 GiB     |
| 2020 | England/hertfordshire | 153       | 494,661        | 1,190,041  | 477.18 MiB | 19 seconds | 11 seconds     | 1.59 GiB     |
| 2022 | England/hertfordshire | 153       | 546,573        | 1,219,124  | 476.55 MiB | 19 seconds | 11 seconds     | 1.67 GiB     |
| 2032 | England/hertfordshire | 153       | 546,573        | 1,219,124  | 476.55 MiB | 19 seconds | 11 seconds     | 1.67 GiB     |
| 2039 | England/hertfordshire | 153       | 575,179        | 1,233,571  | 476.97 MiB | 19 seconds | 11 seconds     | 1.67 GiB     |
| 2012 | England/isle-of-wight | 18        | 61,636         | 139,732    | 53.88 MiB  | 3 seconds  | 1 second       | 188.79 MiB   |
| 2020 | England/isle-of-wight | 18        | 65,140         | 143,268    | 54.99 MiB  | 3 seconds  | 1 second       | 190.45 MiB   |

| year | study_area             | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|------------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2022 | England/isle-of-wight  | 18        | 70,496         | 151,582    | 55.55 MiB  | 3 seconds  | 1 second       | 200.99 MiB   |
| 2032 | England/isle-of-wight  | 18        | 70,496         | 151,582    | 55.55 MiB  | 3 seconds  | 1 second       | 200.99 MiB   |
| 2039 | England/isle-of-wight  | 18        | 72,968         | 154,841    | 56.14 MiB  | 3 seconds  | 1 second       | 202.13 MiB   |
| 2012 | England/kent           | 220       | 718,544        | 1,793,707  | 200.10 MiB | 29 seconds | 17 seconds     | 2.08 GiB     |
| 2020 | England/kent           | 220       | 781,933        | 1,873,457  | 237.20 MiB | 30 seconds | 18 seconds     | 2.15 GiB     |
| 2022 | England/kent           | 220       | 875,515        | 2,008,857  | 273.24 MiB | 31 seconds | 19 seconds     | 2.21 GiB     |
| 2032 | England/kent           | 220       | 875,515        | 2,008,857  | 273.24 MiB | 32 seconds | 19 seconds     | 2.21 GiB     |
| 2039 | England/kent           | 220       | 926,571        | 2,069,087  | 288.47 MiB | 35 seconds | 19 seconds     | 2.23 GiB     |
| 2012 | England/lancashire     | 191       | 619,861        | 1,476,465  | 171.94 MiB | 24 seconds | 14 seconds     | 1.83 GiB     |
| 2020 | England/lancashire     | 191       | 640,196        | 1,511,896  | 189.78 MiB | 24 seconds | 14 seconds     | 1.87 GiB     |
| 2022 | England/lancashire     | 191       | 663,637        | 1,567,396  | 194.49 MiB | 24 seconds | 14 seconds     | 1.87 GiB     |
| 2032 | England/lancashire     | 191       | 663,637        | 1,567,396  | 194.49 MiB | 24 seconds | 14 seconds     | 1.87 GiB     |
| 2039 | England/lancashire     | 191       | 674,387        | 1,591,908  | 200.02 MiB | 25 seconds | 14 seconds     | 1.88 GiB     |
| 2012 | England/leicestershire | 120       | 370,305        | 958,470    | 373.02 MiB | 14 seconds | 7 seconds      | 1.08 GiB     |

| year | study_area             | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|------------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2020 | England/leicestershire | 120       | 397,467        | 1,016,632  | 297.28 MiB | 14 seconds | 7 seconds      | 1.13 GiB     |
| 2022 | England/leicestershire | 120       | 438,413        | 1,118,737  | 426.12 MiB | 15 seconds | 8 seconds      | 1.48 GiB     |
| 2032 | England/leicestershire | 120       | 438,413        | 1,118,737  | 426.12 MiB | 15 seconds | 8 seconds      | 1.48 GiB     |
| 2039 | England/leicestershire | 120       | 459,655        | 1,164,678  | 440.87 MiB | 16 seconds | 8 seconds      | 1.50 GiB     |
| 2012 | England/lincolnshire   | 134       | 449,394        | 1,064,403  | 403.05 MiB | 15 seconds | 7 seconds      | 1.43 GiB     |
| 2020 | England/lincolnshire   | 134       | 475,646        | 1,098,403  | 419.31 MiB | 15 seconds | 7 seconds      | 1.46 GiB     |
| 2022 | England/lincolnshire   | 134       | 507,295        | 1,152,299  | 427.55 MiB | 15 seconds | 7 seconds      | 1.47 GiB     |
| 2032 | England/lincolnshire   | 134       | 507,295        | 1,152,299  | 427.55 MiB | 16 seconds | 7 seconds      | 1.47 GiB     |
| 2039 | England/lincolnshire   | 134       | 523,548        | 1,172,923  | 430.83 MiB | 16 seconds | 7 seconds      | 1.47 GiB     |
| 2012 | England/merseyside     | 184       | 603,483        | 1,399,205  | 533.96 MiB | 20 seconds | 11 seconds     | 1.75 GiB     |
| 2020 | England/merseyside     | 184       | 632,617        | 1,435,755  | 553.33 MiB | 20 seconds | 11 seconds     | 1.79 GiB     |
| 2022 | England/merseyside     | 184       | 665,766        | 1,498,518  | 570.21 MiB | 20 seconds | 10 seconds     | 1.82 GiB     |
| 2032 | England/merseyside     | 184       | 665,766        | 1,498,518  | 570.21 MiB | 21 seconds | 11 seconds     | 1.82 GiB     |

| year | study_area               | num_msoas | soas_households | householdspeople | file_size  | runtime    | commuting_time | memory_usage |
|------|--------------------------|-----------|-----------------|------------------|------------|------------|----------------|--------------|
| 2039 | England/merseyside       | 184       | 685,165         | 1,528,037        | 777.48 MiB | 21 seconds | 11 seconds     | 1.83 GiB     |
| 2012 | England/norfolk          | 110       | 374,491         | 882,793          | 333.07 MiB | 12 seconds | 5 seconds      | 1017.16 MiB  |
| 2020 | England/norfolk          | 110       | 397,770         | 916,799          | 348.41 MiB | 12 seconds | 5 seconds      | 1.02 GiB     |
| 2022 | England/norfolk          | 110       | 432,187         | 982,755          | 362.27 MiB | 13 seconds | 5 seconds      | 1.04 GiB     |
| 2032 | England/norfolk          | 110       | 432,187         | 982,755          | 362.27 MiB | 13 seconds | 5 seconds      | 1.04 GiB     |
| 2039 | England/norfolk          | 110       | 450,068         | 1,013,214        | 471.39 MiB | 13 seconds | 5 seconds      | 1.06 GiB     |
| 2012 | England/northamptonshire | 91        | 289,575         | 720,263          | 284.39 MiB | 10 seconds | 4 seconds      | 941.33 MiB   |
| 2020 | England/northamptonshire | 91        | 316,553         | 762,382          | 304.36 MiB | 10 seconds | 4 seconds      | 981.14 MiB   |
| 2022 | England/northamptonshire | 91        | 352,529         | 828,003          | 320.81 MiB | 11 seconds | 5 seconds      | 1005.64 MiB  |
| 2032 | England/northamptonshire | 91        | 352,529         | 828,003          | 320.81 MiB | 11 seconds | 5 seconds      | 1005.64 MiB  |
| 2039 | England/northamptonshire | 91        | 370,555         | 855,812          | 328.03 MiB | 11 seconds | 5 seconds      | 1016.86 MiB  |
| 2012 | England/northumberland   | 40        | 138,928         | 315,894          | 120.66 MiB | 5 seconds  | 1 second       | 423.11 MiB   |
| 2020 | England/northumberland   | 40        | 143,516         | 322,616          | 121.94 MiB | 5 seconds  | 1 second       | 423.87 MiB   |
| 2022 | England/northumberland   | 40        | 148,792         | 333,456          | 122.06 MiB | 5 seconds  | 1 second       | 421.48 MiB   |
| 2032 | England/northumberland   | 40        | 148,792         | 333,456          | 122.06 MiB | 5 seconds  | 1 second       | 421.48 MiB   |

| year | study_area              | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|-------------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2039 | England/northumberland  | 40        | 150,259        | 337,186    | 122.24 MiB | 5 seconds  | 1 second       | 421.48 MiB   |
| 2012 | England/north-yorkshire | 138       | 460,050        | 1,085,067  | 113.05 MiB | 16 seconds | 7 seconds      | 1.45 GiB     |
| 2020 | England/north-yorkshire | 138       | 478,639        | 1,107,928  | 123.18 MiB | 16 seconds | 7 seconds      | 1.47 GiB     |
| 2022 | England/north-yorkshire | 138       | 499,392        | 1,134,723  | 120.60 MiB | 16 seconds | 7 seconds      | 1.45 GiB     |
| 2032 | England/north-yorkshire | 138       | 499,392        | 1,134,723  | 120.60 MiB | 16 seconds | 7 seconds      | 1.45 GiB     |
| 2039 | England/north-yorkshire | 138       | 509,099        | 1,143,897  | 121.52 MiB | 16 seconds | 7 seconds      | 1.46 GiB     |
| 2012 | England/nottinghamshire | 138       | 460,022        | 1,123,007  | 132.35 MiB | 16 seconds | 8 seconds      | 1.49 GiB     |
| 2020 | England/nottinghamshire | 138       | 486,163        | 1,169,489  | 153.68 MiB | 16 seconds | 8 seconds      | 1.53 GiB     |
| 2022 | England/nottinghamshire | 138       | 522,944        | 1,248,804  | 173.35 MiB | 17 seconds | 8 seconds      | 1.56 GiB     |
| 2032 | England/nottinghamshire | 138       | 522,944        | 1,248,804  | 173.35 MiB | 17 seconds | 8 seconds      | 1.56 GiB     |
| 2039 | England/nottinghamshire | 138       | 543,291        | 1,281,812  | 182.21 MiB | 18 seconds | 9 seconds      | 1.66 GiB     |
| 2012 | England/oxfordshire     | 86        | 261,235        | 671,997    | 260.43 MiB | 9 seconds  | 3 seconds      | 852.84 MiB   |
| 2020 | England/oxfordshire     | 86        | 274,908        | 695,490    | 271.62 MiB | 10 seconds | 4 seconds      | 918.90 MiB   |
| 2022 | England/oxfordshire     | 86        | 293,368        | 729,866    | 275.40 MiB | 10 seconds | 4 seconds      | 919.34 MiB   |

| year | study_area          | num_msas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|---------------------|----------|----------------|------------|------------|------------|----------------|--------------|
| 2032 | England/oxfordshire | 86       | 293,368        | 729,866    | 275.40 MiB | 10 seconds | 4 seconds      | 919.34 MiB   |
| 2039 | England/oxfordshire | 86       | 303,035        | 743,227    | 277.51 MiB | 10 seconds | 4 seconds      | 922.19 MiB   |
| 2012 | England/rutland     | 5        | 14,912         | 38,314     | 16.37 MiB  | 3 seconds  | 1 second       | 54.07 MiB    |
| 2020 | England/rutland     | 5        | 16,698         | 40,381     | 17.09 MiB  | 3 seconds  | 1 second       | 57.95 MiB    |
| 2022 | England/rutland     | 5        | 18,198         | 44,193     | 18.26 MiB  | 3 seconds  | 1 second       | 60.08 MiB    |
| 2032 | England/rutland     | 5        | 18,198         | 44,193     | 18.26 MiB  | 3 seconds  | 1 second       | 60.08 MiB    |
| 2039 | England/rutland     | 5        | 18,914         | 45,659     | 18.71 MiB  | 3 seconds  | 1 second       | 61.20 MiB    |
| 2012 | England/shropshire  | 62       | 197,768        | 483,414    | 186.29 MiB | 7 seconds  | 2 seconds      | 550.97 MiB   |
| 2020 | England/shropshire  | 62       | 211,035        | 508,233    | 195.76 MiB | 7 seconds  | 2 seconds      | 568.62 MiB   |
| 2022 | England/shropshire  | 62       | 228,285        | 558,755    | 207.29 MiB | 7 seconds  | 2 seconds      | 740.58 MiB   |
| 2032 | England/shropshire  | 62       | 228,285        | 558,755    | 207.29 MiB | 7 seconds  | 2 seconds      | 740.58 MiB   |
| 2039 | England/shropshire  | 62       | 236,015        | 581,476    | 213.23 MiB | 7 seconds  | 2 seconds      | 749.82 MiB   |
| 2012 | England/somerset    | 124      | 329,040        | 790,346    | 303.62 MiB | 11 seconds | 4 seconds      | 970.03 MiB   |
| 2020 | England/somerset    | 124      | 353,976        | 822,271    | 317.43 MiB | 11 seconds | 4 seconds      | 996.71 MiB   |
| 2022 | England/somerset    | 124      | 388,675        | 880,441    | 331.61 MiB | 12 seconds | 4 seconds      | 1018.53 MiB  |
| 2032 | England/somerset    | 124      | 388,675        | 880,441    | 331.61 MiB | 12 seconds | 4 seconds      | 1018.53 MiB  |
| 2039 | England/somerset    | 124      | 406,157        | 906,545    | 339.87 MiB | 12 seconds | 4 seconds      | 1.01 GiB     |

| year | study_area              | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|-------------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2012 | England/south-yorkshire | 172       | 566,664        | 1,372,435  | 28.11 MiB  | 20 seconds | 11 seconds     | 1.75 GiB     |
| 2020 | England/south-yorkshire | 172       | 597,694        | 1,418,846  | 48.59 MiB  | 21 seconds | 11 seconds     | 1.79 GiB     |
| 2032 | England/south-yorkshire | 172       | 637,411        | 1,493,545  | 63.91 MiB  | 21 seconds | 11 seconds     | 1.81 GiB     |
| 2039 | England/south-yorkshire | 172       | 659,843        | 1,531,313  | 75.31 MiB  | 22 seconds | 12 seconds     | 1.83 GiB     |
| 2012 | England/staffordshire   | 143       | 464,441        | 1,111,144  | 25.27 MiB  | 16 seconds | 8 seconds      | 1.47 GiB     |
| 2020 | England/staffordshire   | 143       | 486,645        | 1,139,752  | 37.51 MiB  | 16 seconds | 8 seconds      | 1.49 GiB     |
| 2022 | England/staffordshire   | 143       | 510,634        | 1,188,857  | 44.87 MiB  | 17 seconds | 8 seconds      | 1.50 GiB     |
| 2032 | England/staffordshire   | 143       | 510,634        | 1,188,857  | 44.87 MiB  | 17 seconds | 8 seconds      | 1.50 GiB     |
| 2039 | England/staffordshire   | 143       | 522,882        | 1,215,006  | 52.94 MiB  | 17 seconds | 8 seconds      | 1.52 GiB     |
| 2012 | England/suffolk         | 90        | 136,142        | 327,349    | 128.13 MiB | 5 seconds  | 1 second       | 440.37 MiB   |
| 2020 | England/suffolk         | 90        | 146,277        | 333,781    | 130.90 MiB | 5 seconds  | 1 second       | 445.14 MiB   |
| 2022 | England/suffolk         | 90        | 159,882        | 344,534    | 130.76 MiB | 5 seconds  | 1 second       | 442.14 MiB   |
| 2032 | England/suffolk         | 90        | 159,882        | 344,534    | 130.76 MiB | 5 seconds  | 1 second       | 442.14 MiB   |
| 2039 | England/suffolk         | 90        | 166,718        | 350,358    | 132.54 MiB | 5 seconds  | 1 second       | 446.24 MiB   |
| 2012 | England/surrey          | 151       | 458,108        | 1,168,112  | 56.50 MiB  | 21 seconds | 13 seconds     | 1.55 GiB     |

| year | study_area            | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|-----------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2020 | England/surrey        | 151       | 480,930        | 1,195,509  | 72.89 MiB  | 21 seconds | 13 seconds     | 1.58 GiB     |
| 2022 | England/surrey        | 151       | 518,720        | 1,214,557  | 76.03 MiB  | 21 seconds | 13 seconds     | 1.56 GiB     |
| 2032 | England/surrey        | 151       | 518,720        | 1,214,557  | 76.03 MiB  | 21 seconds | 13 seconds     | 1.56 GiB     |
| 2039 | England/surrey        | 151       | 538,941        | 1,221,227  | 76.71 MiB  | 21 seconds | 13 seconds     | 1.64 GiB     |
| 2012 | England/tyne-and-wear | 145       | 483,909        | 1,119,030  | 72.35 MiB  | 15 seconds | 7 seconds      | 1.47 GiB     |
| 2020 | England/tyne-and-wear | 145       | 501,383        | 1,143,194  | 73.09 MiB  | 15 seconds | 7 seconds      | 1.50 GiB     |
| 2022 | England/tyne-and-wear | 145       | 521,777        | 1,168,078  | 74.03 MiB  | 15 seconds | 7 seconds      | 1.49 GiB     |
| 2032 | England/tyne-and-wear | 145       | 521,777        | 1,168,078  | 74.03 MiB  | 14 seconds | 6 seconds      | 1.49 GiB     |
| 2039 | England/tyne-and-wear | 145       | 532,652        | 1,177,340  | 74.36 MiB  | 15 seconds | 7 seconds      | 1.58 GiB     |
| 2012 | England/warwickshire  | 108       | 361,467        | 896,673    | 347.44 MiB | 13 seconds | 6 seconds      | 1.03 GiB     |
| 2020 | England/warwickshire  | 108       | 392,639        | 958,833    | 373.63 MiB | 14 seconds | 6 seconds      | 1.08 GiB     |
| 2022 | England/warwickshire  | 108       | 432,682        | 1,061,957  | 405.95 MiB | 15 seconds | 7 seconds      | 1.44 GiB     |
| 2032 | England/warwickshire  | 108       | 432,682        | 1,061,957  | 405.95 MiB | 14 seconds | 7 seconds      | 1.44 GiB     |



| year | study_area             | num_msoas | num_households | num_people | file_size  | runtime    | commuting_time | memory_usage |
|------|------------------------|-----------|----------------|------------|------------|------------|----------------|--------------|
| 2039 | England/warwickshire   | 108       | 454,732        | 1,112,230  | 124.10 MiB | 15 seconds | 7 seconds      | 1.47 GiB     |
| 2012 | England/west-midlands  | 314       | 958,034        | 2,477,399  | 190.27 MiB | 56 seconds | 38 seconds     | 3.24 GiB     |
| 2020 | England/west-midlands  | 314       | 1,002,273      | 2,572,395  | 1.01 GiB   | 58 seconds | 40 seconds     | 3.33 GiB     |
| 2022 | England/west-midlands  | 314       | 1,046,146      | 2,664,228  | 1.04 GiB   | 60 seconds | 41 seconds     | 3.37 GiB     |
| 2032 | England/west-midlands  | 314       | 1,079,612      | 2,706,242  | 1.04 GiB   | 61 seconds | 41 seconds     | 3.55 GiB     |
| 2039 | England/west-midlands  | 314       | 1,128,890      | 2,787,990  | 1.07 GiB   | 62 seconds | 42 seconds     | 3.59 GiB     |
| 2012 | England/west-sussex    | 100       | 348,766        | 836,646    | 321.17 MiB | 11 seconds | 5 seconds      | 1004.45 MiB  |
| 2020 | England/west-sussex    | 100       | 375,837        | 871,029    | 337.76 MiB | 12 seconds | 5 seconds      | 1.01 GiB     |
| 2022 | England/west-sussex    | 100       | 419,347        | 931,573    | 350.11 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2032 | England/west-sussex    | 100       | 419,347        | 931,573    | 350.11 MiB | 12 seconds | 5 seconds      | 1.03 GiB     |
| 2039 | England/west-sussex    | 100       | 442,292        | 958,567    | 356.77 MiB | 12 seconds | 5 seconds      | 1.04 GiB     |
| 2012 | England/west-yorkshire | 299       | 921,242        | 2,271,833  | 193.87 MiB | 46 seconds | 31 seconds     | 3.05 GiB     |
| 2020 | England/west-yorkshire | 299       | 963,460        | 2,339,930  | 130.47 MiB | 48 seconds | 33 seconds     | 3.12 GiB     |

| year | study_area                     | num_msaas | houses    | households | people     | file_size  | runtime    | commuting_time | memory_usage |
|------|--------------------------------|-----------|-----------|------------|------------|------------|------------|----------------|--------------|
| 2022 | England/west-yorkshire         | 299       | 1,021,830 | 2,434,902  | 245.77 MiB | 48 seconds | 33 seconds | 3.13 GiB       |              |
| 2032 | England/west-yorkshire         | 299       | 1,021,830 | 2,434,902  | 245.77 MiB | 49 seconds | 33 seconds | 3.13 GiB       |              |
| 2039 | England/west-yorkshire         | 299       | 1,053,859 | 2,481,359  | 257.40 MiB | 49 seconds | 33 seconds | 3.32 GiB       |              |
| 2012 | England/wiltshire              | 89        | 285,600   | 704,491    | 274.58 MiB | 9 seconds  | 3 seconds  | 921.08 MiB     |              |
| 2020 | England/wiltshire              | 89        | 309,159   | 735,088    | 288.20 MiB | 9 seconds  | 3 seconds  | 947.43 MiB     |              |
| 2022 | England/wiltshire              | 89        | 335,400   | 774,105    | 292.69 MiB | 10 seconds | 3 seconds  | 949.16 MiB     |              |
| 2032 | England/wiltshire              | 89        | 335,400   | 774,105    | 292.69 MiB | 10 seconds | 3 seconds  | 949.16 MiB     |              |
| 2039 | England/wiltshire              | 89        | 348,866   | 792,075    | 296.40 MiB | 10 seconds | 3 seconds  | 955.08 MiB     |              |
| 2012 | England/worcestershire85       | 85        | 240,958   | 578,628    | 221.47 MiB | 8 seconds  | 3 seconds  | 770.62 MiB     |              |
| 2020 | England/worcestershire85       | 85        | 255,594   | 601,116    | 231.59 MiB | 8 seconds  | 3 seconds  | 790.42 MiB     |              |
| 2022 | England/worcestershire85       | 85        | 274,309   | 644,922    | 241.99 MiB | 8 seconds  | 3 seconds  | 849.84 MiB     |              |
| 2032 | England/worcestershire85       | 85        | 274,309   | 644,922    | 241.99 MiB | 8 seconds  | 3 seconds  | 849.84 MiB     |              |
| 2039 | England/worcestershire85       | 85        | 283,275   | 666,303    | 248.38 MiB | 8 seconds  | 3 seconds  | 861.38 MiB     |              |
| 2012 | special/northwest_transpennine | 829       | 2,653,096 | 6,416,492  | 2.45 GiB   | 5 minutes  | 4 minutes  | 7.74 GiB       |              |
| 2020 | special/northwest_transpennine | 829       | 2,788,624 | 6,616,112  | 2.56 GiB   | 5 minutes  | 4 minutes  | 7.95 GiB       |              |
| 2022 | special/northwest_transpennine | 829       | 2,960,285 | 6,908,374  | 2.62 GiB   | 5 minutes  | 4 minutes  | 8.02 GiB       |              |

| year | study_area                           | num_msas | num_households | num_people | file_size  | time       | commuting_time | memory_usage |
|------|--------------------------------------|----------|----------------|------------|------------|------------|----------------|--------------|
| 2032 | special/northwest_transpennine       | 829      | 2,960,285      | 6,908,374  | 2.62 GiB   | 5 minutes  | 5 minutes      | 8.02 GiB     |
| 2039 | special/northwest_transpennine       | 829      | 3,058,114      | 7,059,122  | 2.66 GiB   | 5 minutes  | 5 minutes      | 8.08 GiB     |
| 2012 | Wales/bridgend-and-neath-port-talbot | 38       | 119,725        | 283,159    | 108.21 MiB | 5 seconds  | 1 second       | 382.24 MiB   |
| 2020 | Wales/bridgend-and-neath-port-talbot | 38       | 123,909        | 289,896    | 111.10 MiB | 5 seconds  | 1 second       | 387.45 MiB   |
| 2022 | Wales/bridgend-and-neath-port-talbot | 38       | 124,921        | 292,227    | 111.51 MiB | 4 seconds  | 1 second       | 387.72 MiB   |
| 2032 | Wales/bridgend-and-neath-port-talbot | 38       | 128,601        | 301,529    | 113.58 MiB | 5 seconds  | 1 second       | 390.82 MiB   |
| 2039 | Wales/bridgend-and-neath-port-talbot | 38       | 129,740        | 307,260    | 114.33 MiB | 5 seconds  | 1 second       | 391.29 MiB   |
| 2012 | Wales/cardiff-and-vale-of-glamorgan  | 63       | 199,208        | 484,182    | 187.17 MiB | 6 seconds  | 2 seconds      | 558.19 MiB   |
| 2020 | Wales/cardiff-and-vale-of-glamorgan  | 63       | 214,676        | 499,272    | 194.70 MiB | 7 seconds  | 2 seconds      | 572.89 MiB   |
| 2022 | Wales/cardiff-and-vale-of-glamorgan  | 63       | 218,981        | 502,763    | 196.11 MiB | 6 seconds  | 2 seconds      | 576.04 MiB   |
| 2032 | Wales/cardiff-and-vale-of-glamorgan  | 63       | 240,112        | 522,526    | 199.42 MiB | 7 seconds  | 2 seconds      | 577.84 MiB   |
| 2039 | Wales/cardiff-and-vale-of-glamorgan  | 63       | 254,162        | 531,549    | 201.82 MiB | 7 seconds  | 2 seconds      | 737.29 MiB   |
| 2012 | Wales/central-valleys                | 38       | 124,691        | 296,581    | 115.15 MiB | 5 seconds  | 1 second       | 396.20 MiB   |
| 2020 | Wales/central-valleys                | 38       | 130,072        | 301,907    | 117.77 MiB | 18 seconds | 1 second       | 400.97 MiB   |
| 2022 | Wales/central-valleys                | 38       | 131,383        | 303,557    | 118.40 MiB | 8 seconds  | 1 second       | 424.47 MiB   |
| 2032 | Wales/central-valleys                | 38       | 136,404        | 310,032    | 118.04 MiB | 5 seconds  | 1 second       | 421.13 MiB   |
| 2039 | Wales/central-valleys                | 38       | 138,735        | 314,703    | 119.17 MiB | 5 seconds  | 1 second       | 423.02 MiB   |
| 2012 | Wales/conwy-and-denbighshire         | 30       | 92,732         | 211,205    | 80.50 MiB  | 4 seconds  | 1 second       | 251.47 MiB   |
| 2020 | Wales/conwy-and-denbighshire         | 30       | 95,314         | 213,302    | 81.56 MiB  | 4 seconds  | 1 second       | 253.63 MiB   |

| year | study_area                   | num_msas | soas_households | chholspeople | file_size  | time      | commuting | mentions   | usage |
|------|------------------------------|----------|-----------------|--------------|------------|-----------|-----------|------------|-------|
| 2022 | Wales/conwy-and-denbighshire | 30       | 95,881          | 214,182      | 81.85 MiB  | 4 seconds | 1 second  | 254.21 MiB |       |
| 2032 | Wales/conwy-and-denbighshire | 30       | 97,683          | 218,122      | 81.11 MiB  | 4 seconds | 1 second  | 251.17 MiB |       |
| 2039 | Wales/conwy-and-denbighshire | 30       | 97,687          | 220,933      | 80.92 MiB  | 4 seconds | 1 second  | 249.76 MiB |       |
| 2012 | Wales/flintshire-and-wrexham | 38       | 122,180         | 288,696      | 113.32 MiB | 5 seconds | 1 second  | 393.63 MiB |       |
| 2020 | Wales/flintshire-and-wrexham | 38       | 127,660         | 292,056      | 114.58 MiB | 5 seconds | 1 second  | 395.27 MiB |       |
| 2022 | Wales/flintshire-and-wrexham | 38       | 129,007         | 292,644      | 115.03 MiB | 5 seconds | 1 second  | 396.56 MiB |       |
| 2032 | Wales/flintshire-and-wrexham | 38       | 134,527         | 292,817      | 112.37 MiB | 5 seconds | 1 second  | 410.92 MiB |       |
| 2039 | Wales/flintshire-and-wrexham | 38       | 136,425         | 293,540      | 112.22 MiB | 5 seconds | 1 second  | 410.77 MiB |       |
| 2012 | Wales/gwent-valleys          | 46       | 144,178         | 341,543      | 132.17 MiB | 5 seconds | 1 second  | 451.03 MiB |       |
| 2020 | Wales/gwent-valleys          | 46       | 148,386         | 344,566      | 132.83 MiB | 5 seconds | 1 second  | 450.89 MiB |       |
| 2022 | Wales/gwent-valleys          | 46       | 149,374         | 345,498      | 132.72 MiB | 5 seconds | 1 second  | 450.23 MiB |       |
| 2032 | Wales/gwent-valleys          | 46       | 151,842         | 347,976      | 130.50 MiB | 5 seconds | 1 second  | 442.86 MiB |       |
| 2039 | Wales/gwent-valleys          | 46       | 151,729         | 350,397      | 130.58 MiB | 5 seconds | 1 second  | 443.03 MiB |       |
| 2012 | Wales/gwynedd                | 17       | 52,926          | 122,595      | 48.28 MiB  | 3 seconds | 1 second  | 141.47 MiB |       |
| 2020 | Wales/gwynedd                | 17       | 55,064          | 124,569      | 49.28 MiB  | 3 seconds | 1 second  | 143.70 MiB |       |
| 2022 | Wales/gwynedd                | 17       | 55,683          | 125,030      | 49.20 MiB  | 3 seconds | 1 second  | 143.45 MiB |       |
| 2032 | Wales/gwynedd                | 17       | 58,372          | 128,844      | 49.81 MiB  | 3 seconds | 1 second  | 143.80 MiB |       |
| 2039 | Wales/gwynedd                | 17       | 59,746          | 130,948      | 50.64 MiB  | 3 seconds | 1 second  | 145.62 MiB |       |
| 2012 | Wales/isle-of-anglesey       | 9        | 30,797          | 69,919       | 27.65 MiB  | 3 seconds | 1 second  | 96.81 MiB  |       |
| 2020 | Wales/isle-of-anglesey       | 9        | 31,366          | 69,845       | 27.85 MiB  | 3 seconds | 1 second  | 97.39 MiB  |       |

| year | study_area                      | num_msoas | households | people  | file_size  | time      | commuting | memory_usage |
|------|---------------------------------|-----------|------------|---------|------------|-----------|-----------|--------------|
| 2022 | Wales/isle-of-anglesey          | 9         | 31,488     | 69,864  | 27.91 MiB  | 3 seconds | 1 second  | 97.71 MiB    |
| 2032 | Wales/isle-of-anglesey          | 9         | 31,601     | 69,502  | 27.09 MiB  | 3 seconds | 1 second  | 95.51 MiB    |
| 2039 | Wales/isle-of-anglesey          | 9         | 31,337     | 69,423  | 26.91 MiB  | 3 seconds | 1 second  | 95.37 MiB    |
| 2012 | Wales/monmouthshire-and-newport | 31        | 100,402    | 240,491 | 94.44 MiB  | 4 seconds | 1 second  | 280.40 MiB   |
| 2020 | Wales/monmouthshire-and-newport | 31        | 104,394    | 250,185 | 98.11 MiB  | 4 seconds | 1 second  | 286.97 MiB   |
| 2022 | Wales/monmouthshire-and-newport | 31        | 105,481    | 253,282 | 99.27 MiB  | 4 seconds | 1 second  | 289.03 MiB   |
| 2032 | Wales/monmouthshire-and-newport | 31        | 109,752    | 265,785 | 102.21 MiB | 4 seconds | 1 second  | 371.39 MiB   |
| 2039 | Wales/monmouthshire-and-newport | 31        | 111,246    | 273,319 | 103.90 MiB | 4 seconds | 1 second  | 373.82 MiB   |
| 2012 | Wales/powys                     | 19        | 59,028     | 132,725 | 51.21 MiB  | 4 seconds | 1 second  | 185.06 MiB   |
| 2020 | Wales/powys                     | 19        | 59,972     | 132,328 | 50.60 MiB  | 4 seconds | 1 second  | 183.38 MiB   |
| 2022 | Wales/powys                     | 19        | 60,190     | 132,467 | 50.46 MiB  | 4 seconds | 1 second  | 182.88 MiB   |
| 2032 | Wales/powys                     | 19        | 59,586     | 133,010 | 49.63 MiB  | 4 seconds | 1 second  | 180.64 MiB   |
| 2039 | Wales/powys                     | 19        | 57,969     | 133,514 | 49.35 MiB  | 4 seconds | 1 second  | 179.80 MiB   |
| 2012 | Wales/south-west-wales          | 50        | 165,004    | 383,260 | 145.79 MiB | 5 seconds | 1 second  | 474.32 MiB   |
| 2020 | Wales/south-west-wales          | 50        | 170,327    | 385,937 | 146.53 MiB | 5 seconds | 1 second  | 474.47 MiB   |
| 2022 | Wales/south-west-wales          | 50        | 171,623    | 386,901 | 147.00 MiB | 5 seconds | 1 second  | 476.10 MiB   |
| 2032 | Wales/south-west-wales          | 50        | 175,897    | 392,107 | 145.19 MiB | 6 seconds | 1 second  | 469.31 MiB   |
| 2039 | Wales/south-west-wales          | 50        | 176,482    | 394,303 | 144.53 MiB | 6 seconds | 1 second  | 467.47 MiB   |
| 2012 | Wales/swansea                   | 31        | 104,423    | 242,128 | 93.10 MiB  | 4 seconds | 1 second  | 276.14 MiB   |
| 2020 | Wales/swansea                   | 31        | 110,304    | 247,820 | 95.72 MiB  | 4 seconds | 1 second  | 281.38 MiB   |

| year | study_area    | num_msas | as_households | chordspeople | pb_file_size | runtime        | commuting_runtime | memory_usage  |
|------|---------------|----------|---------------|--------------|--------------|----------------|-------------------|---------------|
| 2022 | Wales/swansea | 31       | 111,940       | 249,098      | 96.10<br>MiB | 4 sec-<br>onds | 1 second          | 282.16<br>MiB |
| 2032 | Wales/swansea | 31       | 119,141       | 257,653      | 98.28<br>MiB | 4 sec-<br>onds | 1 second          | 285.53<br>MiB |
| 2039 | Wales/swansea | 31       | 123,450       | 262,306      | 99.93<br>MiB | 4 sec-<br>onds | 1 second          | 366.61<br>MiB |

Notes:

- `pb_file_size` refers to the size of the uncompressed protobuf file in `data/output/`
- The total `runtime` is usually dominated by matching workers to businesses, so `commuting_runtime` gives a breakdown
- Measuring memory usage of Linux processes isn't straightforward, so `memory_usage` should just be a guide
- These measurements were all taken on one developer's laptop, and they don't represent multiple runs. This table just aims to give a general sense of how long running takes.
  - That machine has 24 cores, which matters for the parallelized commuting calculation.
- The time *usually* doesn't include downloading or decompressing raw data. For some areas, it might!
- `scripts/collect_stats.py` produces the table above