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# Measuring and visualising 15-min-areas for fair $CO_2$ budget distribution

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**Abstract**

The “MyFairShare” project develops fair $CO_2$ mobility budgets for individuals. Here, “fairness” mainly depends on the people’s location as everyone should be able to access all destinations necessary to perform everyday tasks. Therefore, a basic understanding about the accessibility of facilities to visit within an area is needed, regarding all activities that must be performed. Given this, the amount of emitted $CO_2$ is computed, assuming the use of sustainable modes while regarding reasonable ranges, i.e. a travel time of 15 min. In order to achieve this, a software system for computing this metric has been developed. It is based on open source applications and uses data that—besides public transport data in GTFS format—is freely available throughout Europe. This paper describes the method and presents the results of applying it to the project’s five Living Labs Berlin, Jelgava, London, Sarpsborg, and Vienna. The results show that besides population density, the possibility to use sustainable modes of transport highly depend on the land use mix, i.e. the allocation of facilities daily activities may be performed at in the vicinity of places of inhabitancy.

**Keywords** $CO_2$ budgets, 15 min cities, Accessibility

## 1 Introduction

National undertakings throughout Europe aim at reducing the amount of $CO_2$ emissions caused by traffic in order to fight the climate crisis [1]. Usually, they concentrate on efficiency (e.g. improving vehicle technology or traffic flow) and consistency (e.g. changing from conventional to electric cars). However, these mostly technological changes will not suffice to reach climate neutrality across Europe in 2050, see [2] for the Austrian example or the German transport ministry stating that behaviour change will be necessary [3]. These observations show that efficiency and consistency strategies are significantly limited in their effectiveness, as they trigger rebound effects in the form of behavioural responses that work against the intended impact [4]. Savings in fuel consumption due to higher efficiency and in travel time due to faster connections for example have shown to be “reinvested” in more travelling or larger vehicles and longer average distances, compensating the intended effect of reducing transport emissions [5–7]. The call for “behaviour change” is therefore driven, in part, by the aim of avoiding unintended or undesirable behavioural reactions and, in other part, by the realisation that measures to merely reduce emissions from car traffic will not be sufficient and that a substantial shift to public and active forms of transport as well as a trend reversal regarding travel distances must be achieved. This approach represents a “sufficiency” strategy, which focusses on the responsible use of resources within a given framework in accordance with the principle of “as much as necessary, as little as possible”. In this perspective, “enough” is regarded as the guiding principle, whereas “more” (than necessary) is considered wasteful or even harmful [8].

Measures for achieving the intended behaviour change are extensively researched and can be basically divided

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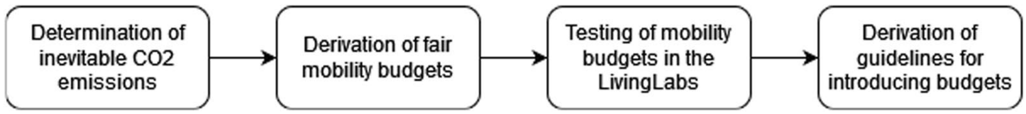


**Fig. 1** The steps undertaken in the MyFairShare project for delivering guidelines for introducing fair mobility budgets

into three categories based on the Social Practices Theory (SPT) [9, 10] stating that executing a behaviour (change) needs three mutually complementing elements: material, competences, and meaning. In the mobility context, this can be applied to barriers which may be hindering behaviour change [11]: (1) Measures to overcome barriers related to the "access" to transport options (e.g., due to reduced financial means, local unavailability of specific transport options or information, or health restrictions preventing a person from using a form of transport), (2) measures reducing complexity of services or increasing competences of persons to overcome limitations in the "ability" to use a form of transport (e.g., usability improvements, trainings), and (3) measures aiming at increasing the "ambition" to change mobility habits (e.g., by positively or negatively incentivising behaviour change by lowering or increasing costs, or by increasing motivation through awareness-raising, nudging or appeals to certain values of life). There is a vast amount of work existing on the topic of behaviour change in the mobility context exploring the effectiveness of different measures as well as potential pitfalls related to specific approaches. Financial incentives (positive and negative), for example, can have significant impact on behaviour patterns, but also bear the risk of aggravating or creating social injustice for specific groups.

The European joint undertaking "MyFairShare" therefore aims to apply the sufficiency principle in the form of fair personal mobility carbon budgets which make national carbon reduction targets comprehensible and relatable in the everyday context of individuals by scaling them down to the individual space of action. This would enable people to make responsible, informed decisions, while at the same time allowing the identification of concrete problems in the fulfilment of basic needs due to mobility deficiencies. As research indicates [12, 13] that people are rather willing to accept restrictions and disadvantages if these can be perceived as being fair, the individual $CO_2$ mobility budgets developed in the project are distributed in a fair way considering socio-regional circumstances. To achieve this task, so-called minimum mobility budgets [14] are introduced to ensure a basic right to mobility: A fair minimum $CO_2$ budget shall allow an individual to perform all necessary activities, ideally at locations in the vicinity of the individual's residence, and if no nearby locations exist by providing an appropriate supply of preferably sustainable mobility options [15]. The advantage of the minimum mobility budgets approach is that it is multi-modal and has minimal $CO_2$ emissions at its core making it a tool that is directly applicable for planning interventions to decarbonize the mobility system. The integrated view at the distribution of population and of visited places has a strong correlation to the so-called 15-min cities [16], a promising approach to reduce the amount of $CO_2$ emissions in traffic. The concept of minimum mobility budgets also extends the set of applications for accessibility measures, which so far mostly have in view the travel times to locations of single activities with different modes of transport [17, 18].

In the following, an approach for determining minimum mobility budgets is presented. While an ideal city of 15 min allows access to all facilities by walking, current cities are far from meeting this target. Hence, the approach looks at the accessibility of different types of facilities using the respectively least $CO_2$ intensive mode. It is a first step in developing fair mobility budgets that shall reveal how much $CO_2$ would be emitted by individuals, even if they try to use the most sustainable mode of transport when trying to get to their destinations within a time span of 15 min. This approach also benchmarks areas regarding their applicability for being called areas of 15 min. The term "15 min areas" is chosen herein, as the benchmark disaggregates a city into a grid on the spatial level. In subsequent steps of the MyFairShare project, depicted in Fig. 1, this information is used to derive fair mobility budgets, which are afterwards evaluated in the project's Living Labs. Finally, recommendations and guidelines for introducing mobility budgets will be derived.

Other approaches to map 15 min cities are usually based on walkability and accessibility of facilities by foot [19, 20], including scientific on-line examples like the "CityAccessMap"[1] [21]. Another web-based solution is the "PTV Access"[2] index developed by the German company PTV which extends the regarded modes to the common ones – walking, using a bicycle, public transport, and motorised individual transport. Going beyond

[1] https://www.cityaccessmap.com/ (all links have been visited on the 12th of January 2024).

[2] https://access.myptv.com/.

determining the conformity of areas with the concept of cities of 15 min, the approach presented herein computes the amount of $CO_2$ emissions inevitable for accessing the activity places and additionally weights these emissions by the respective frequencies of visiting them. For classifying activity places and determining their visit frequencies, the activity types from the major Austrian mobility survey "Österreich unterwegs" [22], which distinguishes between trips to work, education, leisure, shopping, and errands, are used. [22] considers further activity types, namely business-related trips, accompanying other persons, visiting persons, and other purposes. They were neglected as the respective destinations can be hardly determined—they may include all existing destinations. This activity classification matches the one used in the largest German mobility survey "Mobilität in Deutschland" [23].

The approach relies completely on open data and open source applications and includes the computation of the needed metrics as well as their web-based visualization. Within the MyFairShare project itself, this approach has been applied to the areas of the project's Living Labs, namely the cities of Berlin (Germany), Jelgava (Latvia), London (UK), Sarpsborg (Norway), and Vienna (Austria). The cities as well as the regions they are located within are very different in their nature regarding population density and distribution as well as land use. Thereby, the computation of the described metrics for each of them delivers heterogeneous results which broaden the view on the necessary budgets.

The remainder of the paper is structured as follows. First, the methods for computing minimum budgets and the data needed for this purpose are given in Sect. 2. Second, the results obtained from applying the method to the Living Labs of the MyFairShare project are presented in Sect. 3. A discussion of the results is given Sect. 4. The paper ends with conclusions presented in Sect. 5.

## 2 Methodology

### 2.1 Outline

The concept of fair minimum mobility budgets assumes that all places needed to be visited can be accessed using active transport modes—walking or bicycling—or using public transport within 15 min. Only if this is not possible, using individual motorised traffic (MIT) shall be allowed. In reality, mode choice, especially the decision for walking or using a bike, highly depends on the existence of according infrastructure and the design of the built environment [24, 25]. Yet, for determining minimum budgets, the personal possibility to choose a mode of transport is neglected and replaced by the named rules. The weekly minimum $CO_2$ budget is then the number of activities performed in a week multiplied by the $CO_2$ emitted when accessing the locations at which the respective activities can be performed using the named mode selection. Inhabitants of areas undersupplied with activity places need to use less sustainable yet faster mobility options, yielding in higher $CO_2$ emissions. A fair budget shall assure that these people can nonetheless approach all desired places.

It has to be emphasized that it is hardly realistic to regard the nearest or the fastest to reach facility per activity type only. The used activity types incorporate diverse activities which are located at different places each. Leisure activities include attending sport events, performing sport activities by oneself, as well as religious activities or visiting restaurants or bars. Shopping includes short-, middle-, and long-term shopping and even when buying groceries, people usually do not choose the nearest supermarket only. The own workplace is usually not the one located as next to one's place of inhabitancy, etc. This even counts for elementary schools as a subpart for the activity type "education" as, e.g., in Germany, one may choose one of the three nearest schools—despite the possibility to choose a private school. As such, it is necessary to define the number of places per activity a person needs to be able to reach to guarantee a satisfactory selection of different functions for each of the activity types. Currently, due to the lack of according surveys, models, or evaluations of given data, this can be only given as an educated guess. The numbers used within the research presented herein are given in Table 1. While the numbers in the last column are not based on hard facts they are based on the thoughts also given in the third column. For example, the number of reachable shops was chosen in such a way, that people would be forced to go to a shop nearby rather than drive to a larger shop further away.

### 2.2 Used data

For computing minimum $CO_2$ budgets as described in the outline, data for computing the accessibility of different location types is needed as well as a classification of mandatory activities, namely work, education, errands, leisure, and shopping as well as the frequencies of visiting them within a week by different subgroups of the population. Besides, data for computing accessibility measures is needed, namely: (a) the distribution of the population within the examined area, (b) the transport network, including the public transport supply, and (c) the distribution of the facilities or places within the area the considered activities can be performed at.

Today, the open digital map OpenStreetMap[3] (OSM), built up by volunteers, is a source of a large amount of

[3] https://www.openstreetmap.org/.

**Table 1** Activities, calculation of activities per grid cell, and chosen number of facilities for mandatory activities

| Mandatory activity | (Proxy for) Number of facilities per grid cell | Number of facilities that need to be reached in later calculations |
|---|---|---|
| Work | Number of leisure, errand and education PoIs since each of them also defines work places. Additionally, the areas of commercial and industrial land use are taken as possible work places | **1000** The number is relatively high to guarantee that different types of work places can be reached |
| Education | Number of kindergarten, school and university PoIs per grid cell | **3** Since in a 15 min city setting, the schools and kindergartens may not be chosen by the parents anymore but are assigned according to the area, only a small number of places was taken here |
| Shopping | Number of shops and marketplace PoI per grid cell | **2** Only shopping facilities for basic goods are considered, so only a small number of shops was taken |
| Leisure | Number of Leisure PoIs per grid cell (see also Table 3) | **30** To be able to reach different kind of leisure activities, the number was set to 30 |
| Errands | Number of errands PoIs per grid cell (see also Table 3) | **10** To guarantee that different facilities for errands are included, the number was set to 10 |

**Table 2** Used GTFS sources

| Living Lab | URL | Original start date | Original end date | Chosen date after adaptation |
|---|---|---|---|---|
| Berlin | https://daten.berlin.de/datensaetze/vbb-fahrplandaten-gtfs | 2021-05-20 | 2021-12-11 | 2021-06-08 |
| Jelgava | https://www.atd.lv/ | 2022-07-15 | 2023-01-15 | 2022-09-06 |
| London | https://transitfeeds.com/p/association-of-train-operating-companies | 2000-01-01 | 2099-12-31 | 2021-06-08 |
| | https://transitfeeds.com/p/traveline/1033 | 2000-01-01 | 2099-12-31 | |
| | https://transitfeeds.com/p/citymapper | 2018-01-05 | 2018-03-31 | |
| | https://storage.googleapis.com/teleport-gtfs/tflgtfs_nobus.zip | 2017-01-01 | 2018-01-01 | |
| Sarpsborg | https://gtfs.pro/ | 2022-04-08 | 2023-06-24 | 2022-09-06 |
| Vienna | https://www.mobilitydata.gv.at/daten/soll-fahrplandaten-gtfs (EVU) | 2021-12-12 | 2022-12-10 | 2021-06-08 |
| | https://www.mobilitydata.gv.at/daten/soll-fahrplandaten-gtfs (EVU) | 2021-12-12 | 2022-12-10 | |
| | https://transitfeeds.com/l/619-vienna-austria | 2019-12-15 | 2020-12-12 | |

information, though with different degrees of reliability across Europe [26, 27]. Regarding the infrastructure for active modes of transport, as well as for the motorized individual transport, it can be assumed to be the best open data source available. Public transport (PT) connections are provided in OSM as well, yet with lower quality and partially lacking the information about schedules. Therefore, Google Transit Feed Specification[4] (GTFS) files are used within the project, which are available for many cities, regions and even countries in Europe[5][6][7]. GTFS data usually comes free-to-use, yet often lacking an explicit licence or with a proprietary licence. As the areas investigated in this research go beyond the borders of metropolitan areas, public transport may be operated by multiple companies, what was the case for Vienna. In the case of London, where a unique GTFS data set is missing, GTFS descriptions were collected from different sources, respectively covering different mobility providers. The respective GTFS sets for Vienna and London were imported into a single database structure each. As they partially do not cover the same time span, they had to be aligned in time. Table 2 gives an overview about the used data sets.

Information about the areas' population was retrieved from the GEOSTAT population data (2018 version) derived from the 2011 census and given in an

[4] https://developers.google.com/transit/gtfs.

[5] https://transitfeeds.com/.

[6] https://github.com/MobilityData/mobility-database-catalogs.

[7] https://gtfs.pro/.

**Table 3** Extracted activity proxies with the respective representation

| Facility type | Proxy for | Included as |
|---|---|---|
| Buildings | Buildings | Distinct Pols |
| Schools, Colleges, Universities | Education | Distinct Pols |
| Banks, Offices, Healthcare, Hairdresser, etc | Errands | Distinct Pols |
| Kindergarten | Kindergarten | Distinct Pols |
| Bars, Restaurant, Cinema, Sports, Park, etc | Leisure | Distinct Pols |
| Park + Ride | Park + Ride | Distinct Pols |
| Public Transport Stops | PT Halts | Distinct Pols |
| Rail Stations | Rail Stations | Distinct Pols |
| Schools | Schools | Distinct Pols |
| Shops, Marketplaces | Shopping | Distinct Pols |
| Commercial | Work Places | Area (Land Use) |
| Farmyard | Work Places | Area (Land Use) |
| Industrial | Work Places | Area (Land Use) |
| Residential | Living | Area (Land Use) |
| Retail | Work Places | Area (Land Use) |

INSPIRE-conforming grid of 1 $km^2$ for whole Europe. This data source is assumed to be updated in 2023.

To some degree, facility locations can be retrieved from OSM as well. Here, different filters were used on the OSM data to retrieve the locations of facilities of different type which are assigned to daily activities. These facilities are represented as points of interest (PoI) via the geo-coordinates of their centroids. Yet, some information, especially the work places within an area, is not included in OSM. Since no other data source about the location of work places that covers all of Europe is known, the land use information stored in OSM was used in addition to relevant PoIs. The areas of commercial and industrial land use were taken as possible work places. Since there might be many jobs of the same kind within these areas, the size of the respective areas given in square meters is divided by 400 to get to the number of different possible work places located within the area. Table 3 shows the facilities and land use information included in the benchmark. The computation does not distinguish between different area types, like urban, suburban, or rural areas. They are all treated in the same way.

The number of obtained facilities of a certain type as well as the area covered by the respectively regarded land use types is afterwards collected for each cell of the 1 $km^2$ grid that is used to describe the population.

## 2.3 Computation

Given the input data named in the prior section, the regions of interest are determined in the first step. In order to avoid boundary issues as well as to include suburban and rural areas into the investigation, wide areas beyond the borders of the MyFairShare Living Labs were chosen. Table 4 compares the Living Labs' original sizes and the respectively selected areas. The surrounding areas were chosen based on NUTS regions, including all NUTS 2 regions near to the respective Living Lab city. As the project's Living Labs cities differ highly in their size, no other spatial segregation data that would deliver homogeneous areas was available.

**Table 4** The sizes of the Living Lab and the size of respectively chosen area

| Living Lab | City size ($km^2$) | Size of the chosen area ($km^2$) |
|---|---|---|
| Berlin | 891.70 | 30,546.34 |
| Jelgava | 60.56 | 21,188.02 |
| London | 1572.03 | 24,171.72 |
| Sarpsborg | 405.61 | 62,373.20 |
| Vienna | 414.82 | 23,576.23 |

The overall workflow of the subsequent computation of needed $CO_2$ budgets is depicted in Fig. 2. The single steps performed for this purpose are described in the following.

For the determined areas, the population grid was extracted from the GEOSTAT population data ("*Extract population grid*" in Fig. 2), as well as the area's representation within the OSM database ("*Extract facilities and network from OpenStreetMap*"), first. For retrieving the latter, it is usually convenient to download a complete country and filter the area of interest from this data, e.g., using the tool osmconvert[8]. The information about facilities and land use as well as the road networks are extracted from the resulting OSM data using own scripts, available as open source[9]. By doing so, database tables containing the road network, the facilities for each activity type as points of interest, and the land use information given as (multi-)polygons are built for each Living Lab. In addition, GTFS data needed for computing public transport travel times within the respective area was collected, see Sect. 2.2.

In a next step, the travel times between the centres of the population grid's cells were computed ("*Compute accessibility measures*") using the accessibility computation tool "UrMoAC" ("Urban Mobility Accessibility

[8] https://wiki.openstreetmap.org/wiki/Osmconvert.

[9] The scripts and definitions used within the project are included in the UrMoAC package.

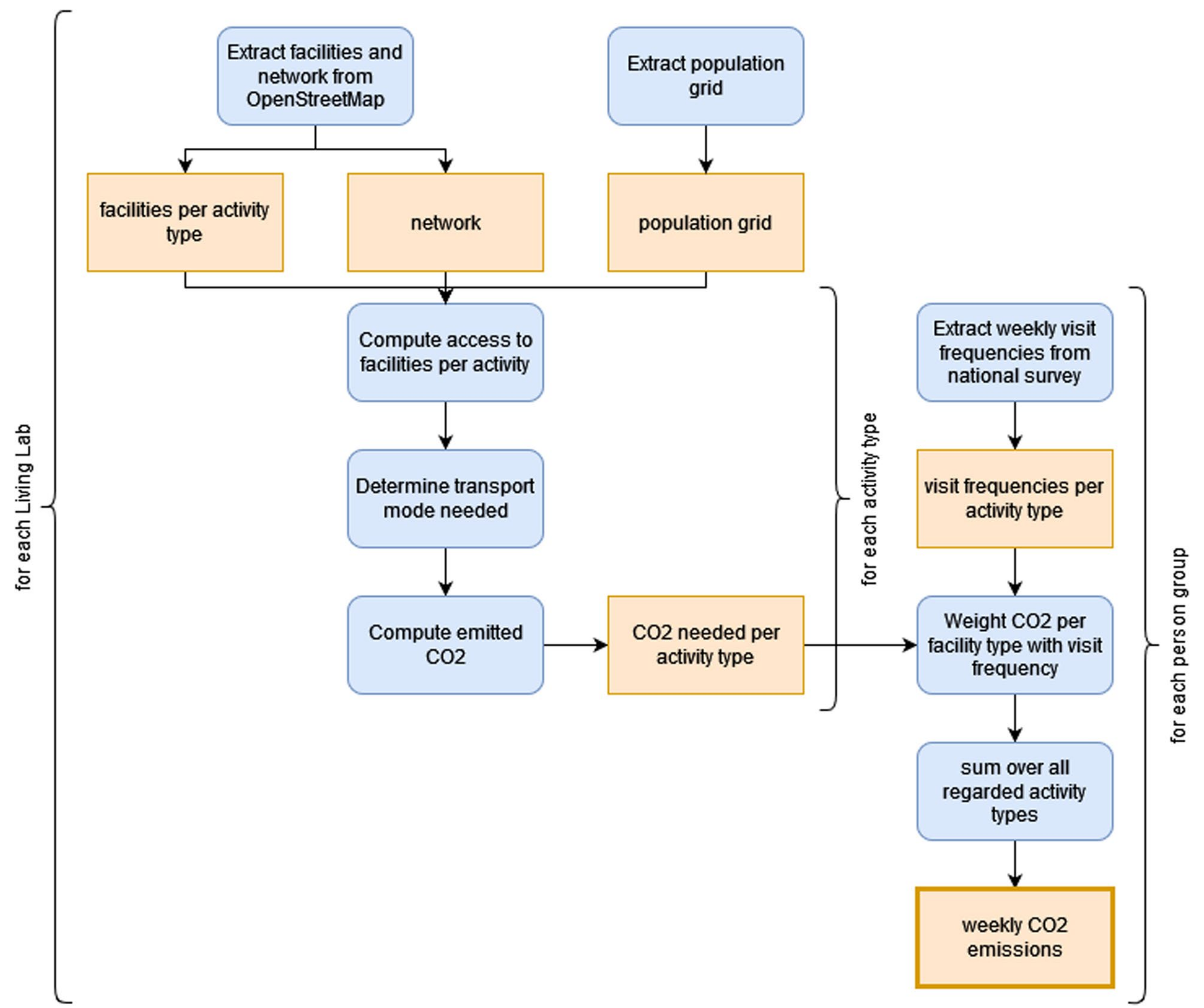


**Fig. 2** The overall workflow for computing the weekly $CO_2$ budgets for different person groups and Living Labs

Computer") [28, 29], which is available as open source[10]. UrMoAC computes different accessibility metrics between a set of sources and a set of destinations along a given, mode-specific road network and supports public transport schedules provided in the GTFS format. UrMoAC is a highly flexible and fast tool, which can be run on the command line and can thereby be scripted for computing a large set of different measures in batch. This reduces the number of manual interactions needed when using GIS-based accessibility computation solutions, such as ESRI's "Network Analyst"[11] or QGIS-based openrouteservice[12]. In comparison to routing APIs like, e.g., GoogleMaps API[13] or openrouteservice, UrMoAC can be used for free with no limits and is faster due to being executed locally.

Even though UrMoAC has proved to be applicable to large scale areas with sources and destinations given on a disaggregated level of single buildings [30], it was decided to use the centres of the population grid within the project for different reasons. First, the distribution of the respective population within a 1 $km^2$ grid cell is unknown and can be derived only to some degree from OSM data and only within some areas. Second, due to the explorative nature of the research, accessibility measures for wide areas were computed. Using single buildings for such areas would generate very big result sets. Even though being aggregated to a 1 $km^2$ grid, the current

[10] https://github.com/DLR-VF/UrMoAC.

[11] https://www.esri.com/en-us/arcgis/products/arcgis-network-analyst/overview.

[12] https://openrouteservice.org/.

[13] https://developers.google.com/maps/apis-by-platform.

**Table 5** The speeds and $CO_2$ emissions used per mode

| Mode | Speed | $CO_2$ emissions (g/km) |
|---|---|---|
| Walking | 3.6 km/h | 0 |
| Bicycling | 12 km/h | 18 |
| PT | Schedule from GTFS | 80 |
| MIT | Speed allowed on respective road, 200 km/h if not given | 140 |

results from the accessibility computation are several Gigabytes in size and as such cumbersome to handle. In later processing steps, intermediate data could be reduced to some 100 MB, so future applications should be transferable to higher spatial resolutions.

The results of the accessibility computation are distance and travel time matrices for each of the regarded modes of transport between the cell centres of the respective grid of a Living Lab. Here, the following modes of transport are distinguished: walking, cycling, public transport and motorized individual traffic. The latter would usually need the real travel times as OSM only contains the allowed velocities on the roads. UrMoAC is capable to load additional travel times, but this information is not available for all Living Labs. It is assumed that this lack of data can be neglected in this scope as motorized individual transport is the mode of transport that shall be avoided in any case due to its highest $CO_2$ emission per passenger and therefore is always the worst option. The used velocities and $CO_2$ emissions per mode are presented in Table 5. The high maximum velocity of MIT is overridden by local speed limits included in OSM in most cases.

Not all connections between all cells were considered when computing the accessibility measures per mode. Instead, only the connections from inhabited cells to cells that are either inhabited or have at least one facility were computed.

To calculate the travel time from a cell to the mandatory number of an activity type's facilities ("*Determine transport mode and travel time needed*", see also Sect. 2.2) when using one of the four modes—walking, bicycling, public transport, and a motorised vehicle—, the destination grid cells were ordered by the respective travel time needed to access them, first. The travel time and distance to perform an activity was defined as the travel time to the cell where the respective number of facilities the activity can be performed at was first reached. The distance information is then used to compute the resulting $CO_2$ emissions ("*Compute emitted $CO_2$*"). Please note that due to the grid size, only the facilities located in the starting cell are considered for walking.

The computations described up to now deliver the inevitable $CO_2$ emissions needed to access each of the regarded activity types' facilities once for each population grid cell. To obtain the weekly $CO_2$ budget for a person that belongs to a certain person group living in this cell, these values have to be multiplied with the frequency the respective activity is performed by this person group in a week ("*Weight $CO_2$ per facility type with visit frequency*") and summed up ("*Sum over all regarded activity types*").

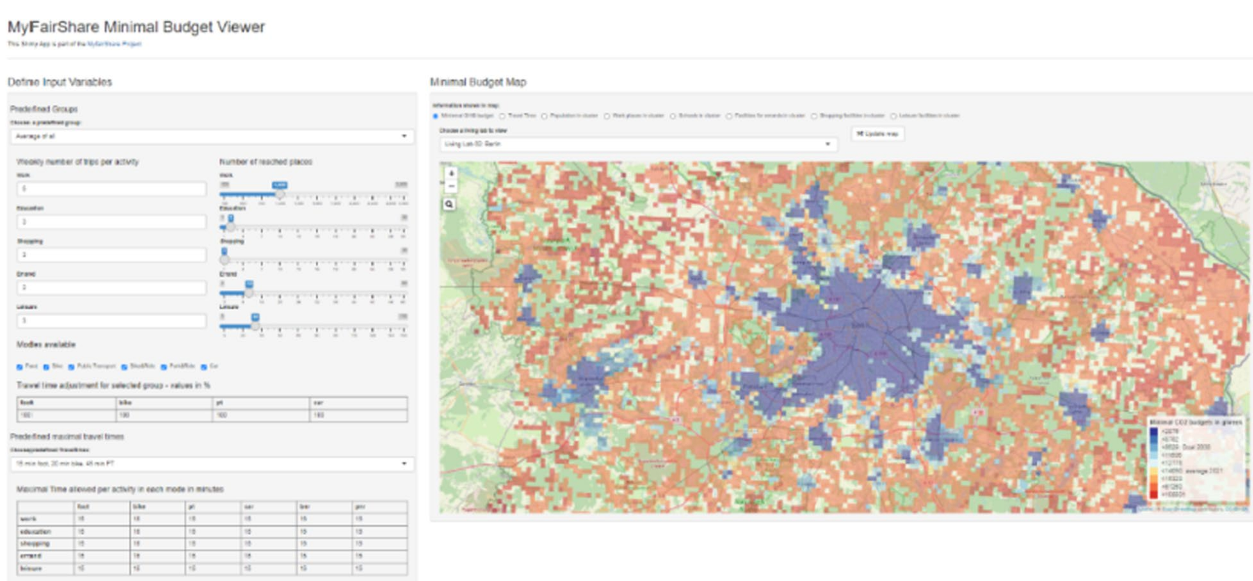


**Fig. 3** The MyFairShare visualization tool

**Table 6** Numbers of a Living Lab's inhabitants divided by the respective number of facilities of the investigated types within the Living Labs

| Living Lab | Work | Education | Shopping | Errand | Leisure |
|---|---|---|---|---|---|
| Berlin | 8.29 | 4121.79 | 206.84 | 451.02 | 87.40 |
| Jelgava | 5.91 | 2499.45 | 209.65 | 688.58 | 124.07 |
| London | 22.85 | 2231.83 | 301.89 | 825.01 | 147.08 |
| Sarpsborg | 11.28 | 1692.86 | 347.99 | 682.16 | 110.59 |
| Vienna | 9.97 | 2978.00 | 183.23 | 386.88 | 75.36 |

### 2.4 Visualization and user interaction

Besides developing and computing the minimum budgets, a web-based visualisation tool has been developed in the scope of the project that allows investigating the results in an interactive manner. Figure 3 shows a screenshot of the tool[14].

The tool allows for computing different scenarios. E.g., one can choose the number of times an activity is performed per day. Also, predefined groups like children, working or not working adults or elderly can be chosen, predefining the activity visit factors (see also Table 6). In addition, the number of facilities that need to be accessible can be chosen in the panel on the left-hand side, and the allowed modes, maximum travel times per mode, and the activities to consider can be defined. On the right-hand side, a map is shown, showing one of: (a) minimal $CO_2$ needed to perform all mandatory activities, (b) the travel time needed to perform these activities with a minimal amount of $CO_2$, as well as (c) the number of facilities per cell for the five activities per grid cell.

## 3 Results

### 3.1 Access to activity locations

In a first step, the accessibility of the different activity types in the Living Labs is discussed. Figure 4 shows which activity locations—the number of facilities or areas defined as a limit of facilities to visit, see Table 1—can be accessed in 15 min using the respective mode of transport by the population. When e.g. looking at the left-most bar which represents the access to work places in Berlin, the necessary number can be accessed by walking by a low share (1.8%) of the population only (light blue). Almost 80% (77.96%) of the inhabitants have enough work places in their vicinity for accessing the necessary number by bike, while for about 20% the use of a car is needed. The black part of the next bar that describes the possibilities to access education facilities in Berlin in 15 min shows that for a low share of the population (1.35%) less than three education facilities are located in a range of 15 min even when using a car. To avoid boundary issues, all cells from which the respective Living Lab's border can be accessed in 15 min or less using any mode of transport, were omitted from the subsequently presented evaluations.

Figure 4 holds some remarkable information. First, one may overlook public transport (though it's appearing). The reason is that public transport cannot compete with bicycling on short ways (≤ 15 min). Second, one may find parts in the areas where the minimum number of needed locations cannot be accessed even when using motorized private transport ("none"). Throughout the areas, the access to work (W) places performs worst, followed by education (E) and errands (D). The required number of shopping facilities (S) can be accessed best.

There may be different explanations for the differences in accessibility values of facilities between the Living Labs. We assume that the major one is due to differences in the population densities and their distributions across the Living Labs. As Fig. 5 (top) shows, most of the investigated areas are only sparsely populated with the majority of cells having less than 1000 inhabitants. When zooming into the cells with population densities of more than 10,000 inhabitants (Fig. 5, bottom), one can see that Vienna has the densest cells, followed by Berlin and London.

The assumption is as well supported by (surprisingly) similar results when looking at the relation between the areas' populations and the respective numbers of facilities, given in Table 6 as the number of persons per facility. Even though the Living Labs include metropolitan areas as well as rural regions with no big cities, the minimum and maximum values for each of the regarded activity types do not deviate by a factor larger than about four (3.86 for work places per person in Sarpsborg and London).

Figure 6 shows the cumulative travel times needed to access the regarded types of facilities within the Living Labs. Please note that due to the big cell sizes, all facilities accessible by foot have a travel time of 0 as only the facilities within the cell the place of inhabitancy is located in are counted.

When zooming into the lower travel times of up to 15 min (Fig. 7) one can see further differences between the areas. Inhabitants of the London area need longer to get to the work places, what indicates a separation of those from the places of inhabitancy. In all investigated areas, almost all persons are capable to get to the next shop in less than 15 min, yet not necessarily using sustainable modes of transport.

[14] https://mytrips.ait.ac.at/myfairshare/.

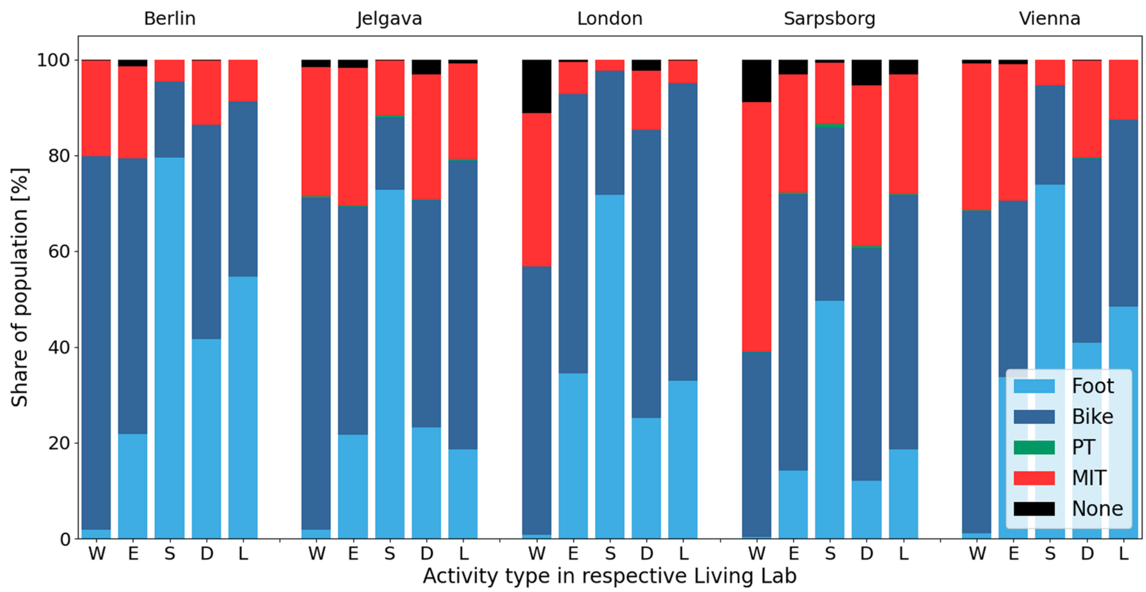


**Fig. 4** Modes of transport needed to access considered activity locations within the project's Living Labs. Activity types are denoted as following: W: work, E: education, S: shopping, D: errands ("duty"), L: leisure

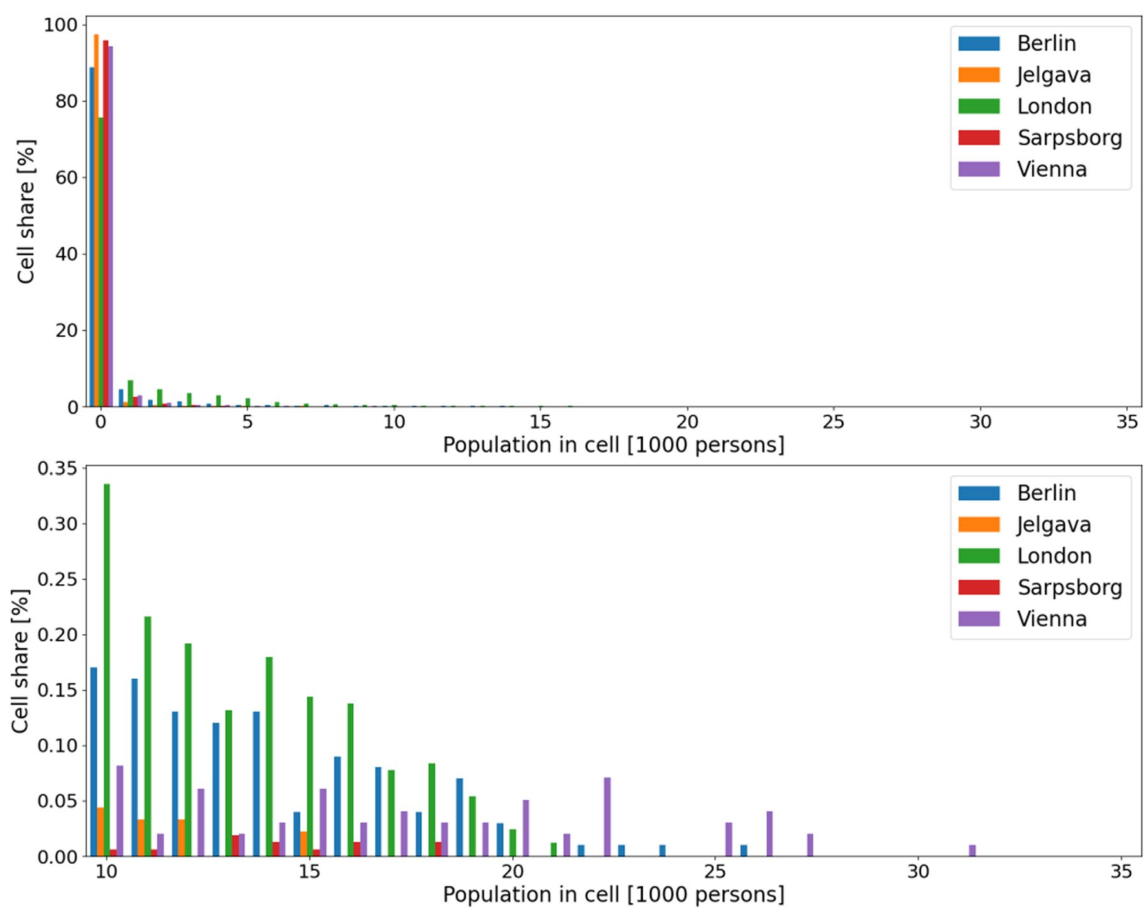


**Fig. 5** Distributions of population densities within the Living Labs'

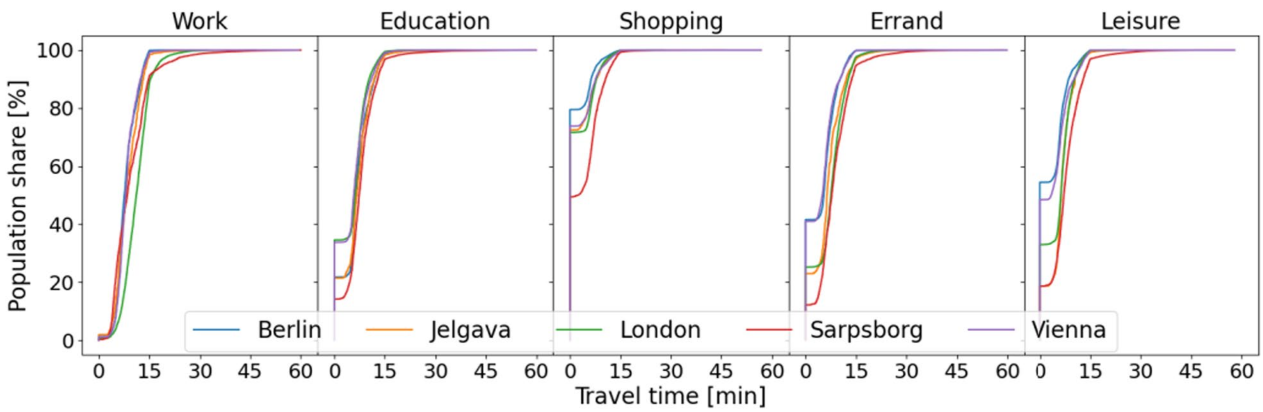


**Fig. 6** Cumulative distribution of travel time needed to access the considered facility types

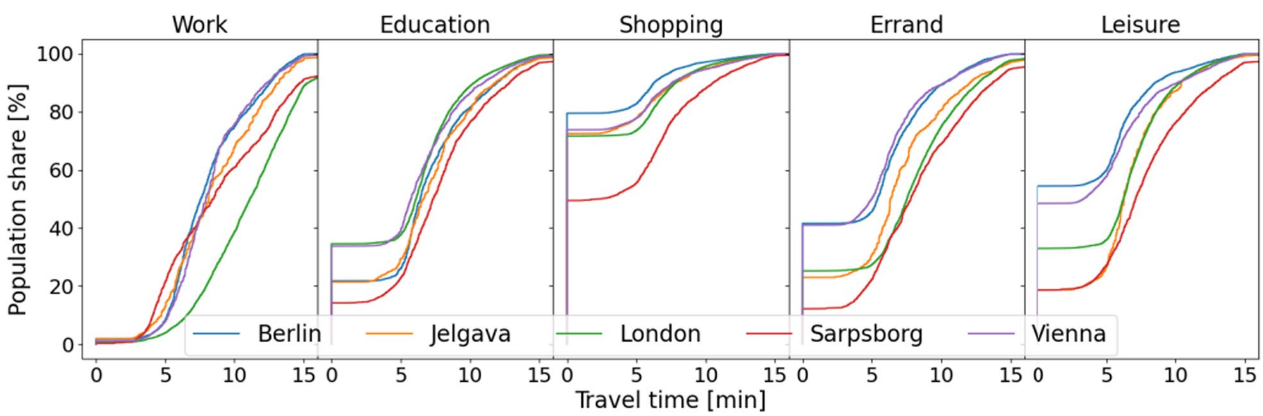


**Fig. 7** Cumulative distribution of travel time needed to access the considered facility types—zoom at travel times shorter than 15 min

### 3.2 Weekly activities

The frequencies of performing the considered activities within a week were obtained for different person groups from [22]. Table 7 shows them for selected groups.

Given these figures, the access to the different locations can be weighted by the frequencies of visiting them and summed up to obtain a weekly budget of inevitable $CO_2$ emissions for a person. Figure 8 shows the cumulative distribution of the $CO_2$ emitted by an average person during one week, assuming the used mode choice. The long tail (Fig. 8, top) beyond 10 kg/week belongs to sparsely populated rural areas with very heterogeneous—and low—supply with activity locations. When zooming at the values below 10 kg/week that belong to urban areas, the development of emissions is steep due to the high population densities and the increased share of MIT is visible, beginning with about 1 kg/week.

**Table 7** Frequencies of performing activities per week for different person groups

| Person Group | Work | Education | Shopping | Errand | Leisure |
|---|---|---|---|---|---|
| Average | 2.61 | 0.89 | 2.43 | 1.97 | 3.13 |
| Children | 0.03 | 5.33 | 0.76 | 0.74 | 3.52 |
| Elderly | 0.20 | 0.04 | 3.90 | 3.38 | 3.76 |
| Teenagers | 1.02 | 4.15 | 0.84 | 0.86 | 3.16 |
| Adults work/no children | 4.93 | 0.10 | 2.00 | 1.65 | 2.75 |
| Adults no work/no children | 0.92 | 0.86 | 3.21 | 2.54 | 3.52 |
| Adults work/children | 4.03 | 0.18 | 2.98 | 0.53 | 2.80 |

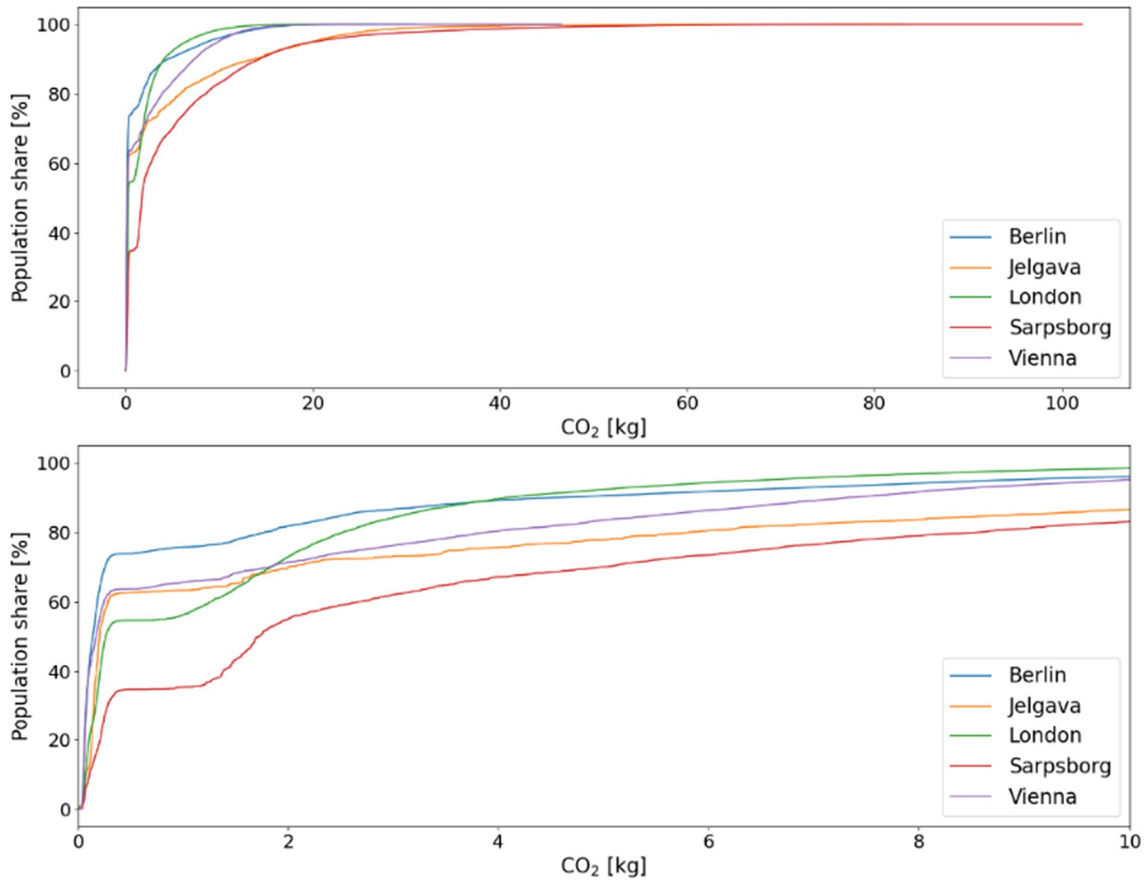


**Fig. 8** Cumulative distributions of $CO_2$ emitted by an average person during a week; top: all measures, bottom: zoom at values < 10 kg/week

Figure 9 shows how the minimum $CO_2$ budget depends on population densities in the different Living Lab areas. The plot presents the population per square kilometre and the minimum $CO_2$ budget per cell in logarithmic scales. Dots with less than one kilogram of $CO_2$ per week are the ones where all activities are accessible by active modes (walking and bicycling) within 15 min. In addition, tendencies of the data points were added to this figure using the R-function *geom_smooth*, that applies a generalized additive model to provide a smoothness estimation. In Sarpsborg and Jelgava, the minimum budgets for less densely populated areas are considerably higher than in the other three sites, suggesting that there are fewer facilities to perform activities at in more remote rural areas. However, once the population densities become higher the accessibility in Jelgava is similar to that in Berlin and Vienna, while the accessibility in London and Sarpsborg with active modes is worse even at very high densities. This might suggest that the facilities at which the activities are performed are spatially separated from the residential areas.

For determining which budgets are "fair", different person groups and the distributions of the $CO_2$ amounts they emit to perform tasks within a week should be investigated. Figure 10 shows the median of needed $CO_2$ for the considered Living Labs and person groups, yet not looking at the inhabitants but on the respective cells. The differences in the Living Labs are obvious. As can be expected, more $CO_2$ is needed in rural areas—the ones around Jelgava and Sarpsborg—with a low population density than in Living Labs with high population density areas.

The differences between the considered person groups are not as prominent and homogenous as between the Living Labs. When looking at adults only, one can see that the group of working adults with no children needs the most $CO_2$. This group is the one that is visiting the work locations most often (see Table 6), which results, in combination with the low accessibility of work places (see Fig. 4), in a high $CO_2$ consumption. It should be mentioned, that in the subsequent formulation of mobility budgets, persons belonging to households are grouped. Then, ways to schools are included into a household's

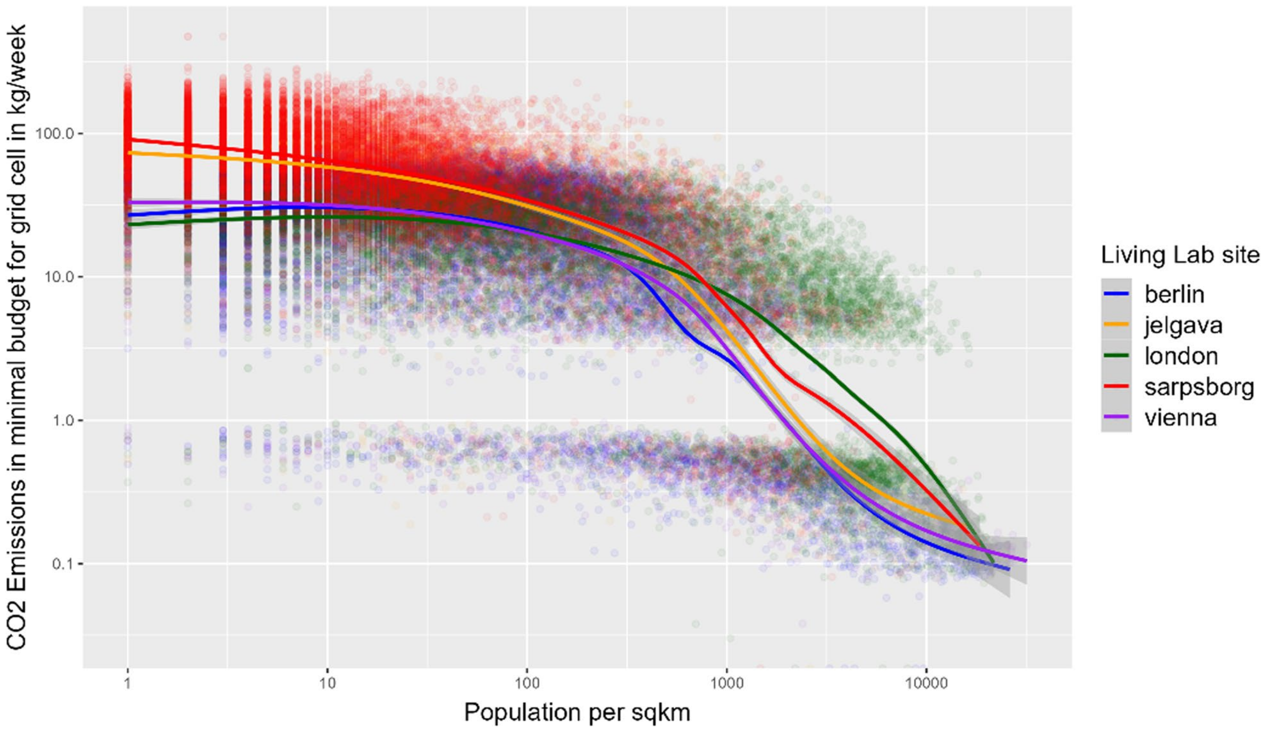


**Fig. 9** Minimum Mobility Budget for each 1 km$^2$ grid cell by population density for the Living Lab sites

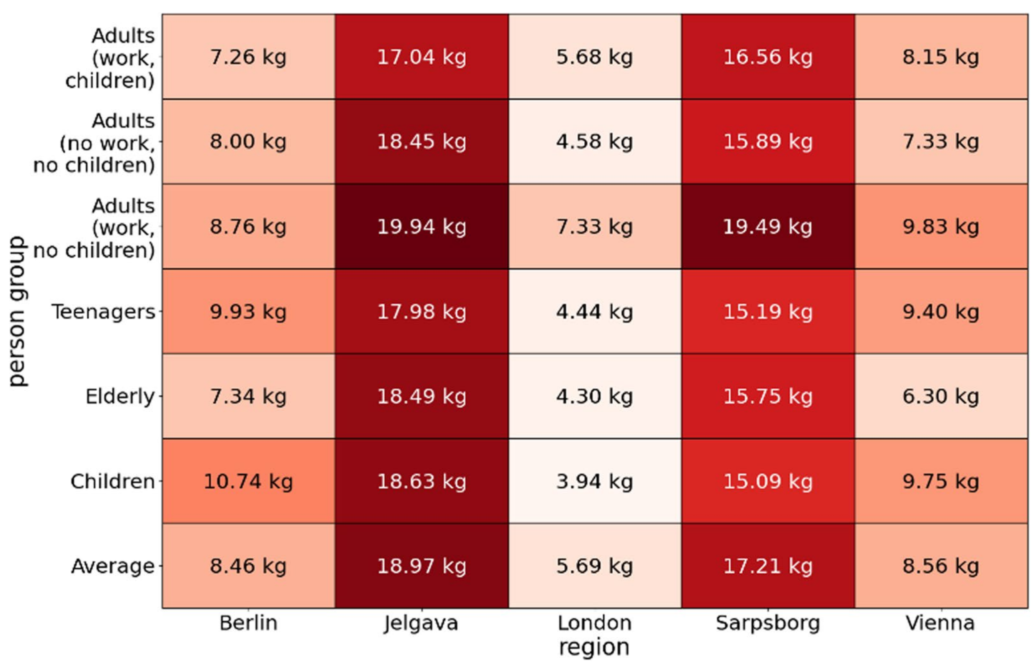


**Fig. 10** Medians of needed $CO_2$ for the considered Living Labs and person groups in dependence of the place of inhabitancy (not weighted by the respective number of inhabitants)

budget via the children that attend them. An overview of the minimum and maximum values as well as the 25%, 50%, and 75% percentiles of the $CO_2$ amounts needed by different person groups is given in the Appendix.

## 4 Discussion

The presented results do not resemble the current behaviour of the population, but rather the attempt to quantify a minimal $CO_2$ budget needed if everyone would use the most sustainable mode of transport, yet assuming a reasonable travel time of 15 min. Besides forcing a certain mode choice behaviour, the model also takes harsh influence on the location choice, see Table 1. These choice constraints may be realisable for work place locations—e.g. by reinforcing work from home or co-working spaces—and partially already match the real world as, e.g., in Germany children visiting an elementary school are assigned to one of the three nearest to their home. Yet, one should expect that limiting the access to a certain number of shopping or leisure activities would not be accepted by a large part of the population. However, in the debate regarding transport justice in low carbon energy transitions, critics of the political philosophy of liberal egalitarianism and its distrust of constraining individualism argue that "liberal choice" assumes that people can decide as if in a vacuum and independent of context, which is considered an implausible idea of how people act, as they exist in relation to the world, the society, and the rules and social norms within this context. The context in which people make their choices is therefore never unrestricted and prone to many influences, for example a societal goal to reduce inequalities [31]. In this context, Pereira et al. [32] advocate that transport policies should be evaluated by setting minimum standards of accessibility to key destinations in order to analyse the distributional impact of transport policies and to assess the extent to which these policies respect individual rights and favour disadvantaged groups, reduce inequality of opportunity and mitigate the externalities of transport. The approach developed in MyFairShare sets an important first step towards the definition of such a minimum standard.

The results can be used by policy makers to estimate the amount of inevitable $CO_2$ emissions, given the current land-use, population distribution, and mobility offers. At this level, the differences between the supply with activity places between urban and rural areas can be clearly seen. Disaggregated by activity types, the results reveal which kinds of facilities should be implemented to improve local accessibility and thereby to reduce necessary trips.

As to methodology, one should note some shortcomings of our approach that could be improved in the future. The first to name is the choice of the 1 $km^2$ grid as a starting point. This coarse resolution aggregates areas that may be heterogeneous internally, e.g. because the area is divided by water or because the population is not distributed uniformly. In addition, the grid size of one kilometre matches a walking time for 1 km, assuming a speed of 3.6 km/h, which in fact yields in looking into the origin cell's facilities when computing accessibilities for walking, which may overestimate their accessibility by the cell's population.

Currently, no distributions of socio-demographics on the spatial level were considered. One should assume that to some degree persons are choosing their home location considering their mobility needs and options. Yet, information about socio-demographics is usually available on an even higher spatial aggregation level only, and breaking it down would require models what we wanted to avoid. Accordingly, one could assume different speeds for walking and using a bicycle for different person groups. Again, this was not included in our approach due to the lack of according information about, e.g., age distribution at the spatial level we have chosen. For specific questions, other person groups than the ones used herein could be investigated. One though has to remind that the information about the groups' individual's behaviour obtained from the Austrian national survey may lose its statistical relevance when increasingly disaggregating the population due to a too low number of surveyed persons that belong to a population's subgroup. One possibility to obtain a higher sample would be to derive a synthetic population and compute its behaviour using e.g. agent-based demand model. Yet, again, one would have to involve additional models and rely on their outputs in this case, instead of relying on data only.

Up to now, only the Austria mobility patterns as derived from [22] were used. Where available—e.g. "Mobilität in Deutschland" for Germany—other national surveys could be used for computing the frequencies of visiting facilities of different kinds in accordance to the behaviour of the population of the investigated country. In addition, emission factors for the different modes of transport were also taken for Austria[15]. Due to differences in fleets and electricity production, the emission factors should also be chosen per country.

The use of European open data and open source applications allows for applying the benchmark to almost all areas in Europe, as long GTFS data about public transport is given. Yet, when looking at the results, one could

[15] https://www.umweltbundesamt.at/fileadmin/site/themen/mobilitaet/daten/ekz_pkm_tkm_verkehrsmittel.pdf.

argue that public transport does not compete with using a bicycle on short trips, see Fig. 4. Of course, the named metrics can be as well computed for other parts of the world as long as the needed data is available.

It has to be mentioned that the used data has different shortcomings. The population grid is based on Census data from the year 2011, so it can be assumed that the population distribution is different today. Even more critical is the lack of information about work places so that the presented computation has to rely on proxies. As well, better information on leisure activities and their spatial distribution would be needed.

Despite all these shortcomings and simplifications, we think that the attempt presented herein is a valid approach for budgeting $CO_2$ at the level of single individuals and for benchmarking how well areas comply with the city of 15 min idea.

## 5 Conclusions

A solution for determining minimum $CO_2$ budgets needed to access all weekly activity places using most sustainable transport modes while assuring reasonable travel times was presented. In addition, the results can be used for benchmarking areas for being compliant with the concept of a city of 15 min. For this purpose, the locations within the respective areas were determined from the freely available OpenStreetMap database, first. This data was then merged with the information about the population within these areas into a grid with cells of a size of 1 km$^2$, conforming to the INSPIRE standard. Finally, accessibility measures between the cells' centroids were computed for determining which parts of the respective Living Lab may be called "15 min areas"—areas where all necessary activities can be accessed using active modes within 15 min.

The described approach relies completely on open source software and freely available data. It is, to a wide degree, applicable to the complete area of the European Union. Only the needed GTFS data is not available for all European regions. The information included in the OpenStreetMap database is sufficient for many types of activity, yet a better source of information on the distribution of working places would improve the quality of the benchmark. Though, no open data sets covering this topic seem to exist for Europe in a sufficient resolution.

Fair mobility budgets will be derived within the next project steps based on the computed measures. In addition, local tests, surveys, and workshops will be performed to determine the users' acceptance of the mobility budgets. The methodology presented herein will be refined to work on higher spatial resolutions and will be applied to benchmark areas in order to comply with the idea of the city of 15 min.

## Appendix

Table 8 shows the quantiles of the needed $CO_2$ amounts for the regarded population groups and Living Labs.

**Table 8** The respective minimum, 25%, 50%, 75% quantiles, and the maximum values for $CO_2$ needed (in kg) when accessing all needed facilities within a week by different person groups based on cell values (not weighted by the respective population)

| Person group | Berlin | Jelgava | London | Sarpsborg | Vienna |
|---|---|---|---|---|---|
| Average | 0 | 0 | 0 | 0 | 0 |
| | 3.31 | 12.48 | 2.27 | 10.14 | 4.75 |
| | 8.46 | 18.97 | 5.69 | 17.21 | 8.56 |
| | 12.62 | 25.24 | 9.24 | 30.18 | 12.08 |
| | 30.76 | 83.45 | 26.82 | 102.11 | 46.56 |
| Children | 0 | 0 | 0 | 0 | 0 |
| | 5.14 | 12.71 | 0.34 | 8.47 | 5.95 |
| | 10.74 | 18.63 | 3.94 | 15.09 | 9.75 |
| | 15.06 | 25.15 | 7.49 | 27.2 | 13.64 |
| | 32.84 | 81.11 | 26 | 96.04 | 41.82 |
| Elderly | 0 | 0 | 0 | 0 | 0 |
| | 2.14 | 12.11 | 0.48 | 8.96 | 2.55 |
| | 7.34 | 18.49 | 4.3 | 15.75 | 6.3 |
| | 11.49 | 24.96 | 8.07 | 27.86 | 9.72 |
| | 31.34 | 84.93 | 29.68 | 101.43 | 42.84 |
| Teenagers | 0 | 0 | 0 | 0 | 0 |
| | 4.73 | 12.2 | 1.09 | 8.79 | 5.73 |
| | 9.93 | 17.98 | 4.44 | 15.19 | 9.4 |
| | 14.03 | 24.14 | 7.83 | 27.11 | 13.08 |
| | 30.88 | 77.98 | 24.67 | 93.11 | 41.77 |
| Adults work/no children | 0 | 0 | 0 | 0 | 0 |
| | 3.63 | 12.95 | 3.62 | 11.3 | 5.74 |
| | 8.76 | 19.94 | 7.33 | 19.49 | 9.83 |
| | 13.21 | 26.67 | 11.01 | 33.89 | 13.72 |
| | 30.92 | 86.7 | 27.03 | 108.01 | 51.86 |
| Adults no work/no children | 0 | 0 | 0 | 0 | 0 |
| | 2.69 | 12.23 | 1.11 | 9.21 | 3.52 |
| | 8 | 18.45 | 4.58 | 15.89 | 7.33 |
| | 12.04 | 24.75 | 8.24 | 28.21 | 10.7 |
| | 31.01 | 83.35 | 28.17 | 100.26 | 43.52 |
| Adults work/children | 0 | 0 | 0 | 0 | 0 |
| | 2.89 | 11.13 | 2.81 | 9.57 | 4.52 |
| | 7.26 | 17.04 | 5.68 | 16.56 | 8.15 |
| | 11.21 | 23.07 | 9.08 | 29.26 | 11.7 |
| | 27.18 | 79.3 | 24.01 | 96.78 | 45.5 |

**Abbreviations**

GTFS Google transit feed specification
MIT Motorised individual traffic
OSM OpenStreetMap
PT Public transport
UrMoAC Urban mobility accessibility computer (a tool for computing accessibility measures)

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Not applicable.

**Author contributions**
DK: Method development, input data acquisition and processing; computation of the accessibility measures; results preparation; CR: Method development, viewer implementation, indicator computation, results preparation; MS: Input data acquisition and processing; AM: Research outline. All authors contributed to the manuscript, and read and approved the final version.

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**Availability of data and materials**
All input data are available at open data portals as listed in the text. The software "UrMoAC" used for computing the accessibility measures is available as open source at https://github.com/DLR-VF/UrMoAC/. Changes performed during the project contribute to the open source release.

## Declarations

**Competing interests**
The authors declare no competing interests.

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## Publisher's Note