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FABILUT: The Flexible Agent-Based Integrated Land Use/Transport Model

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Abstract: Integrated land-use transport models are often accused of being too complex, too coarse or too slow. We tightly couple the microscopic land use model SILO (Simple Integrated Land Use Orchestrator) with the agent-based transport simulation model MATSim (Multi-Agent Transport Simulation). The integration of the two models is *person-centric*. It means, firstly, that travel demand is generated microscopically. Secondly, SILO agents can query individualized travel information to search for housing or jobs (and to choose among available modes). Consequently, travel time matrices (skim matrices) are not needed anymore. Travel time queries can be done for any time of the day (instead of for one or few time periods), any x/y coordinate (instead of a limited number of zones), and take into account properties of the individual. This way, we avoid aggregation issues (e.g., large zones that disguise local differences) and we can account for individual constraints (e.g., nighttime workers who cannot commute by public transport for lack of service). Therefore, the behavior of agents is represented realistically, which allows us to simulate their reaction to novel policies (e.g., emission-class-based vehicle restrictions) and to extract system-wide effects. The model is applied in two study areas: a toy scenario and the metropolitan region of Munich. We simulate various transport and land use policies to test the model capabilities, including public transport extensions, zones restricted for private cars and land use development regulations. The results demonstrate that the increase of the model resolution and model expressiveness facilitates the simulation of such policies and the interpretation of the results.

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1 Introduction

Transport and land use influence each other. The longer-term bi-directional effects between transport and land use are often described by the well-known land-use transport interaction (LUTI) cycle (Wegener 1994).

While traditionally transport policies have been mainly infrastructure-oriented (e.g., building new highways or new public transport (PT) lines), so-called demand-oriented transport policies (e.g., congestion or peak-hour pricing) and specific restrictions (e.g., environmental zones) are suggested today. Also, new transport technologies (e.g., shared mobility services, electric vehicles) demand a more detailed description of the transport systems' interactions. As such, transport models need to be more expressive in terms of representing the individual traveler.

MATSim (Horni *et al.* 2016) takes activity-travel patterns of individual synthetic persons (called agents) as input and simulates their activity participation and trip-making throughout a whole day. As the individual traveler – the central unit of analysis – can be traced throughout the whole simulated day, this approach allows for highly detailed analyses.

For many transport projects, such as PT systems, a major share of their economic contribution arises from positive impacts on land development and land value (Miller 2018). Likewise, transport has had a great impact on the development and shaping of cities. Historically, the arrival of the streetcar and later the widespread use of the automobile (Muller 2004) have contributed to shaping the spatial layout of cities and are, therefore, sometimes described as transport revolutions. Today, various new technologies and services like ride hailing, electric vehicles, and autonomous vehicles (AV) are becoming available or might soon become available. Particularly in terms of autonomous vehicles, it is speculated that their widespread introduction could constitute another transport revolution that would have significant impact on the way cities develop (Moeckel and Nagel 2016).

The impact of these developments is not known today. Are AVs going to provide additional mobility to people without the permission or ability to drive and to improve access to PT by serving as a feeder mode? Or are they going to induce additional and longer trips and, if associated costs are low, rather lead to a cannibalization of PT?

Models should be able to explore such questions. This, in turn, requires that models capture relevant actions and decisions of those entities (persons, households, etc.) who collectively induce reactions in the transport and land-use systems in a sufficiently detailed way to allow those actions and decisions to adjust to changes in the (physical, regulatory, etc.) environment. If, by contrast, the decisions of the decision-making entities are too strongly aggregated or resolved too coarsely in the model, many meaningful reactions are likely to be precluded by the model structure.

To analyze the effects of developments in the land-use and transport systems and to assess policies, Integrated Land Use/Transport Models (ILUT) models (also known as Land Use Transport Interaction (LUTI) models or Integrated Urban Models (IUMs)) have been developed. Usually, they are complex model systems in which both transport and the urban activity system (i.e., urban form or land use) co-evolve over time (Miller 2018).

Since the 1960s, ILUT models have been developed and some applied. The Lowry (1964) model, developed for the Pittsburgh urban region, was one of the first models that gained substantial interest (Timmermans 2007). It was advanced in several directions and became the foundation for many similar models. For instance, the MEPLAN model (Echenique *et al.* 1969), based on the Lowry model, includes Alonso's (Alonso 1964) bid-rent approach.

These models – sometimes called the first generation of ILUT models – have in common that they aim to generate an equilibrium between transport and land use. The critique by Lee (1973) on this generation of models has had a major impact on model development. Next to complicatedness, expensivess, and (data) hungriness, Lee mentioned that those models are "designed to replicate too complex a system in a single shot, and (...) expected to serve too many purposes at the same time" (Lee 1973, p. 164, "hypercomprehensiveness"); they are "too coarse to be of use to most policymakers. In generating forecasts for the city or metropolitan area as a whole, in several dimensions of its attributes, the models [cannot] provide adequate richness of detail for a less-than-comprehensive view" (Lee 1973, p. 165, "grossness") and their structure can preclude adequate model reactions, while underlying limitations or unintended constraints resulting from the model structure are almost impossible to perceive ("wrongheadeness" and "mechanicalness"). Although this critique was written almost half a century ago, it is still relevant today as the avoidance of the 'seven sins of large-scale models' may be regarded as a guideline to develop usable models. As such, it seems reasonable to defend the novel approach to be presented in this paper also against Lee's criticism.

Most equilibrium-based models, such as TRANUS (de la Barra 1989), MUSSA (Martínez 1996) or PECAS (Hunt and Abraham 2003) are based on input-output models that try to find an equilibrium between housing supply and demand. A later generation of models applied discrete choice theory, trying to mimic decisions made by households rather than computing an equilibrium of the whole system, e.g., IRPUD (Wegener 1982) and DELTA (Simmonds 1999). Most recent models are based on microsimulation, e.g., ILUTE (Miller and Salvini 2001), UrbanSim (Waddell *et al.* 2003), and ILUMASS (Beckmann *et al.* 2007). For more comprehensive reviews of existing integrated land use/transport models, the reader may refer to Acheampong and Silva (2015); Moeckel (2018); Wegener (2014).

The integration of land use and transport models has been realized in that the transport model provides travel times (and sometimes travel distances and costs) in the form of matrices to the land-use model. In the other direction, the land-use model provides the location of households/persons and firms/jobs by zone, which are used in the transport model as trip origins and destinations.

As people have different preferences, their decision-making is very heterogeneous. While ILUT models have been very aggregate in nature because of computational limitations, this constraint has eased with the advancement of computers. Disaggregated microscopic models help capturing heterogeneity in travel behavior and household relocation (Davidson *et al.* 2007; Wegener and Spiekermann 2009). Instead of modeling the urban areas on an aggregate level, in the microsimulation approach, the aggregate-level outcomes emerge as the sum of decisions of the individual agents in the system (Miller 2018).

However, also in newer approaches that apply microsimulation on the land-use side, the critical representation of the transport system has so far been aggregate in nature. The ILUMASS (Integrated Land-Use Modelling and Transportation System Simulation, Beckmann *et al.* 2007) approach – well aware of "deficiencies of existing urban land-use transport models, which are too aggregate in their spatial and temporal resolution to model aspects that are crucial for achieving sustainable urban transport" (Strauch *et al.* 2005, p. 4) – uses microsimulation in all its main components. It includes a microscopic dynamic simulation model of urban traffic flows into a comprehensive model system incorporating changes of land use. However, the rich information that the transport model provides is not used by the land-use component directly, but only through the mediator of accessibilities, which disguises a lot of relevant detail (Strauch *et al.* 2005).

Furthermore, it is reported that due to the complexity of the project, very long model run times, and a file-based data transfer, the ambitious goals were not met. The problem of software integration and computational difficulties in microscopic integrated models have been discussed by Wagner and Wegener (2007).

In the Sustaincity project (Thomas *et al.* 2015), the microscopic land-use model UrbanSim (Waddell 2002) was coupled with the agent-based transport simulation MATSim. While microscopic accessibilities were computed, the integration is file-based such that it is not possible for simulated persons making choices in UrbanSim to retrieve transport information from the MATSim transport model directly (de Palma *et al.* 2015). Similar to the ILUMASS project, Nicolai and Nagel (2015) also discuss technical difficulties in the integration, mainly due to different programming languages of UrbanSim (Python) and MATSim (Java).

MOEBIUS is another microscopic ILUT model (Gerber *et al.* 2018) that uses MATSim as transport model. Like in Sustaincity, the integration is file-based, such that individual travel information is not available as the land-use model cannot interact with the transport model directly.

Therefore, in the ILUT models developed so far, the model structure largely prevents to take the effects of individual reactions in the transport system into account in terms of land-use decisions in a behaviorally sound way. This is, however, critical. As Miller (2018, p. 1029) has described it so aptly "agents simultaneously exist and act within multiple systems and their actions 'flow' within and between the [transport and land-use] systems". For an agent who does not have access to a car (potentially a 'PT captive'), it will likely not be sufficient to live in an area that offers decent accessibilities by PT in general. Instead, this agent will be more specifically interested in living in short distance of a PT stop and, in particular, such a stop from where the specific connection at an intended departure time to the agent's specific workplace is acceptable.

This simple example already includes three levels of specification that most existing models are not able to provide without limitations: Personal, spatial (residence location) and temporal (time-of-day of intended departure) constraints should be taken into account adequately. The model structure should acknowledge that the trip-making individual (in the transport component) is the same individual that – together with its household context – takes decisions that are represented by the land-use component of the ILUT model.

To progress in this direction, the person-centric ILUT model FABLIUT (flexible, agent-based integrated land use/transport model) has been developed. FABILUT consists of the microscopic land-use model SILO (Simple, Integrated Land-use Orchestrator, Moeckel 2016) and the agent-based transport simulation model MATSim (Multi-Agent Transport Simulation, Horni *et al.* 2016), which are integrated in a tight, behaviorally sound way.

2 The FABILUT Modeling Suite

In an initial study (Ziemke *et al.* 2016), SILO was coupled with MATSim such that individual information from the land-use model was transferred to the transport model, which simulated the resulting commute travel patterns. Replacing an aggregated transport model that was used for this task in SILO before, MATSim produced zone-to-zone skim matrices that were provided to the land-use model like the output of the replaced aggregate model, resulting in a similar type of integration as some of the aforementioned ILUT models.

Based on that, a query architecture was implemented, which allows agents for decisions in the land-use model to query individual travel information from the transport model. The query architecture removes the aggregation break that exists when travel information is accumulated into travel time matrices or zonal accessibilities. The query architecture makes highly specific travel information available to the components of the land-use model *upon request*. As such, the requests can be very specific. A request mimics a person's consideration of transport-level information in land-use decisions. If, for instance, a household decides to search a new residence, the transport simulation model is queried for each potential new dwelling for the travel effort to work. This is done for all workers in the household individually and for all modes of transport taking into account specific transport tool availabilities, e.g., a household car that cannot be used by two household members separately. To obtain such detailed individualized travel information, the submodules of SILO have access to MATSim's trip router, which finds travel options based on the traffic state that emerges from the MATSim transport simulation.

The crucial advancement of the FABILUT model is that its model structure does not require conceptually unnecessary aggregation. Instead of the pre-emptive collection of travel information in form of matrices, the individually resolved decision maker (person, household) in the SILO land-use component of the FABILUT model has access to principally the full level of detail of travel information that exists in the MATSim transport component itself and can retrieve it as required for a specific modeled decision. Beyond existing models that are disaggregate in the individual transport and land-use model components, in FABILUT also the connection between transport and land use works on a microscopic level.

Optionally, a travel demand model may be included. A trip-based transport demand model has been integrated (cf. section 2.5), while the integration of an activity-based transport demand model is currently underway. For studies with no travel demand model available, the FABILUT modeling suite can also be run with SILO and MATSim only, which allows to simulate the commute segment of traffic (Ziemke *et al.* 2016).

FABILUT addresses issues and/or makes a contribution to the field in terms of the following aspects:

- Aggregation issues by increased spatial and temporal resolution
- Consistently include demographic detail for increased validity and expressiveness of analyses
- Policy analyses turn from aggregate approximation to a behaviorally richer representation of individual decision making
- Better capabilities to model new transport technologies and services
- Realistic modeling of environmental impacts
- Better analysis of equity aspects
- Increase computational efficiency of disaggregate models

2.1 SILO: FABILUT's Land-Use Model Component

SILO simulates the development of a metropolitan region, specified by the households, persons, dwellings, and jobs in the study area, into the future. Based on an initial synthetic population for a base year, in which each dwelling, household, person, and job is represented individually (Moreno and Moeckel 2018), SILO updates the members of these four categories and their properties incrementally on a year-by-year basis. To do so, demographic events like birth, marriage, and death, household relocation as well as real-estate updates like construction, renovation, and price changes are explicitly simulated by corresponding submodels. In the latest version of SILO, each dwelling and job is geo-referenced to a microscopic coordinate (Kuehnel *et al.* 2021). Also, SILO models work start times for each job explicitly.

Next to the demographic module (cf. upper part of fig. 1) SILO contains a developer and a household relocation module. The developer model simulates investment decisions of developers who build new residential buildings if a corresponding demand exists. Also, it simulates renovation, deterioration, demolition and price changes.

The household relocation module represents one of the decisions that affects the spatial development of a region most strongly. Household relocation, in turn, is strongly affected by relevant travel times (e.g., travel times to the jobs of the workers in the household). In SILO, household relocation is modeled in the following steps:

First, every household decides whether they want to move. This is based on a comparative evaluation between the current own housing satisfaction and the average satisfaction of households of the same type in the current region. This satisfaction is computed based on size, quality, and price of the current dwelling, and auto and PT accessibilities of the dwelling zone. Also, the commute time for each worker is included in the evaluation, where the availability and performance of different modes are taken into account. Next to satisfaction, household relocation can also be triggered by other events that require the search of a new dwelling, e.g., when couples marry or divorce.

Second, if a household has decided to move, it evaluates all regions of the study area. Regions are sets of zones, usually grouping them to a higher administrative level (e.g., county). This evaluation takes into account region-wide average rent prices, regional accessibilities, regional population, optionally racial or nationality shares, and the commute time between the region and employment zones of working household members. The evaluation result is scaled by the number of vacant dwellings in each region. The probability of a region to be selected is computed by a logit model.

Third, to select a vacant dwelling in the selected region, households evaluate a sample of up to 20 randomly drawn vacant dwellings in a region. Again, a logit model is used to compute the probability of choosing a dwelling based on the utility of the dwelling in comparison to the utilities of all other dwelling alternatives. The utility computation works as described for the housing satisfaction in the first step. The computation of the travel time included in this evaluation works principally the same way for a potential commute trip originating from a potential new dwelling as for the current commute trip from the actual dwelling.

2.2 MATSim: FABILUT's Transport Model Component

MATSim (Horni *et al.* 2016) is an agent-based transport simulation framework. Every person is resolved as an agent and has one or more daily plan(s). A plan is a sequence of activities at their respective locations on a representative day that the agent intends to take part in and trips which connect them. MATSim is based on a co-evolutionary algorithm, which iterates over the three components traffic simulation, plan scoring, and replanning (cf. lower left part of fig. 1). In this process, which eventually leads to a stochastic user equilibrium, every agent aims to improve their plan by trying out different travel options and evaluating them based on the notion of utility maximization.

For the traffic simulation, MATSim uses a computationally efficient queue model, in which every link is modeled as a first-in-first-out (FIFO) queue, which makes MATSim suitable to simulate large metropolitan regions while maintaining the integrity of the agents throughout all simulation stages. Agents evaluate their plan (plan scoring) based on their individual simulated travel experience. Finally, agents have the chance to modify their daily plan (replanning) with regard to different choice dimensions (route choice, mode choice, departure time choice etc.). New plans are tried out in the transport simulation of the next iteration. To reduce computing times, it is possible to 'scale down' scenarios such that only a sample of the full population of agents is simulated on the transport network whose capacities are scaled down correspondingly. The validity of this downscaling approach has been assessed by Llorca and Moeckel (2019).

As MATSim simulates complete daily activity-travel patterns, precedence constraints, such as the fact that a person cannot leave an activity location before having arrived, are automatically resolved. The individual traveler is a consistent entity with knowledge of previous trips. This allows (e.g., to model vehicle emissions, which depend on the engine temperature and, as such, on previous driving, or to model the battery charge of an electric vehicle consistently throughout the day. Its high temporal and spatial resolution allows to compute highly-resolved noise emissions and immissions (Kaddoura *et al.* 2017), pollutant emissions (Kickhöfer and Kern 2015) or mode- and time-specific accessibilities (Ziemke *et al.* 2017).

In contrast to SILO, the modeled entities (agents) do not change their properties as a progression over time in MATSim. Instead, one representative day is simulated, which may be interpreted as one typical day in the life of a SILO person in the currently modeled SILO year, while SILO models the progression of persons and their households from year to year.

2.3 Microscopic simulation of traveling of microscopically modeled household members

Fig. 1 visualizes the FABILUT model schematically. Based on SILO, which models the development of households, persons, dwellings, and jobs microscopically with coordinate-based locations (cf. section 2.1), the home, work and education locations of all members of the synthetic population (next to various other individual attributes) are known. These activity locations constitute important fix-points to derive the demand for transport that is then simulated in MATSim (cf. section 2.2).

FABILUT offers different options to derive the transport demand of the population to be simulated. These options are provided in form of scenario assemblers, which create the demand of transport of a given year based on the synthetic population and the properties of its members.

The *Simple MATSim Scenario Assembler* based on Ziemke *et al.* (2016) creates simple daily plans of the individuals including home and work activities based on properties of the household like employment of its members and car availability. This approach allows to simulate peak-hour car traffic realistically and, in many contexts, to generate plausible commute patterns (Moeckel and Nagel 2016).

The *Simple Commute Mode Choice Scenario Assembler* adds mode choice. Based on the individualized travel information provision (described in more detail in sec. 2.5), every employed SILO person queries MATSim for the travel time of their individual commute to work from their home to their workplace at their preferred work start time by different modes (currently car and PT implemented). If the person does not have a driver's license or the household does not possess any car, PT is selected. Otherwise, a logit model based on the travel times of the individual commute options is used to compute the probability to use the car. If available cars in the household are not already taken by other household members, the person will make their commute to work with the computed probability by car, otherwise by PT. Other transport options can be included in this request including novel transport services like ride sharing if the corresponding transport mode has been set-up in the MATSim transport model.

In order to create full daily traffic in the transport simulation, the demand segments beyond commute traffic need to be included. These cannot directly be derived from SILO as it does not know about discretionary activities (e.g., shopping or visiting friends). Therefore, a scenario assembler based on the microscopic, trip-based transport demand model MITO (Microscopic Transportation Orches-

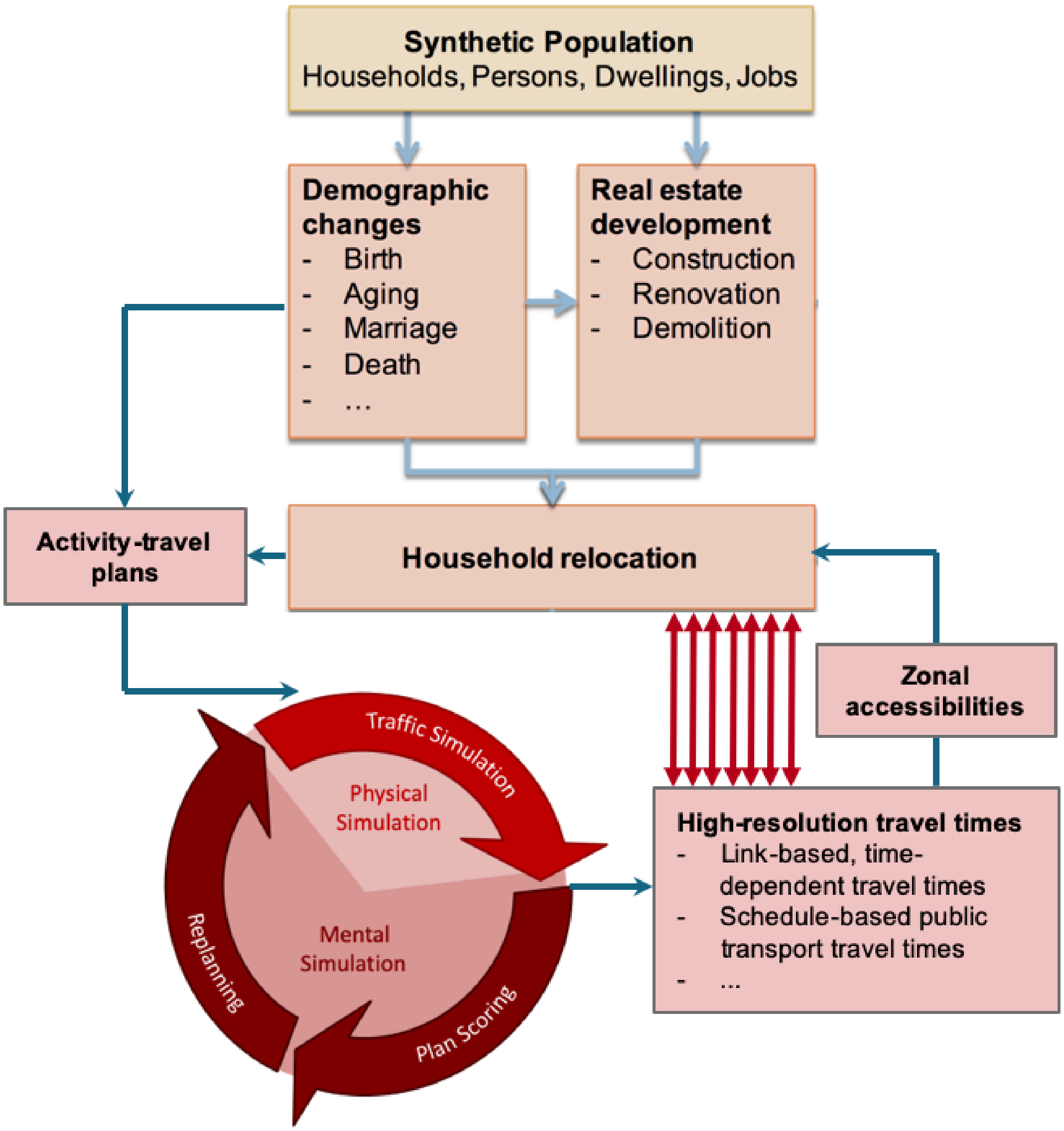


Figure 1: Schematic visualizaton of FABILUT model. Blue arrows denote information whose generation is finished before it is made available to another module. Red arrows denote individualized queries from a module to another component. The requested information is unknown before the requesting module is active.

trator, Moeckel *et al.* 2019) has been implemented. MITO is based on household travel survey data and creates home-based tours and non-home-based trips for each microscopic person of the population residing in the study area including mode and departure time. To simulate this demand in MATSim, a separate MATSim agent has to be created for each tour/trip. Therefore, the application of MATSim in this setup resembles that of a pure dynamic traffic assignment tool with route choice as the only choice dimension active in MATSim (cf. sec. 2.2). While generating realistic travel times for all times-of-day, in this approach the integrity of the individual is not maintained as each person's trips are independently modeled and do not form a consistent daily schedule.

To take full advantage of MATSim's capabilities of modeling complete daily activity-travel patterns, it is plausible to integrate an activity-based demand model (ABM) (cf. sec. 1). Such models are a natural fit to MATSim with its person-centric way of modeling the transport system as they represent activity participation of individuals throughout the whole day (cf. sec. 6).

The output of all the scenario assemblers is a MATSim scenario, which constitutes the central data container holding all components (e.g., the synthetic population of agents with their daily travel plans as well as the transport network) needed for the simulation (Horni *et al.* 2016). The assembling of a scenario and the simulation are initiated automatically by SILO when needed.

2.4 Options to make travel information available in the land-use component

Travel times and cost then emerge from the transport simulation. A fundamental question for the FABILUT integration was how to make this information available to decisions of households modeled in the land-use component of the modeling suite. The following options whose properties are summarized in table 1 are comtemplable:

1. The traditional way of obtaining travel information generated by the transport component is by travel time matrices with the limitations as described in sec. 1.
2. Another option is that SILO receives link-based travel times, i.e., a network with travel time attribution by time-of-day for each link from MATSim. Such a network-based approach has been used in previous attempts to incorporate less aggregated transport indicators in models (e.g., Blanchard and Waddell 2017).
3. Alternatively, SILO can request individual travel information from MATSim.

Options 1 and 2 are "push" variants, since they push the information from MATSim to SILO. Option 3 instead is a "pull" variant, where SILO pulls the information from MATSim when needed. One advantage of this last option is that the routing infrastructure that exists inside MATSim can be re-used. Specifically, this concerns the so-called MATSim trip router, which allows route queries for all configured modes. In consequence, this approach makes any mode configured on the MATSim side immediately available to the SILO side. This is the variant that has been chosen for the present paper. It is explained in detail in the next section.

2.5 Querying MATSim's trip router for land-use decisions

To integrate SILO and MATSim microscopically, a new query architecture has been implemented. This query architecture allows agents to solicit individual travel information from and to microlocations in form of x/y coordinates at a specific time-of-day by applying MATSim's trip router. This travel information is individual in that (1) it reflects travel times from a micro location to a micro location in x/y coordinates, (2) it reflects travel times for a specific time-of-day, and (3) it is created taking into account relevant constraints of the individual and its household.

Table 1: Options for integration to make travel information generated by the transport model available to the land-use model.

	Matrix-based provision (cf. sec. 1)	Network-based integration	Router-based integration
Advantages	State of the practice, easy to implement and computationally efficient	High level of detail in provided transport information, high flexibility in interpretation of transport-related information on land-use side	Transport-based information available to the land-use component to the full level of detail, no re-implementation for transport-side functionality required, interfaces sufficient, novel services can be treated under the same interface
Disadvantages	Strong limitations regarding policy scope, fully preemptive provision of pre-computed information, inflexible, limited spatial and temporal resolution, limited representation of demographic detail	Transport-related functionality (already existing in the transport model) needs to be re-implemented in land-use model, high maintenance effort, computationally more demanding, duplicative, problematic for complex modes and services that cannot be described by annotated networks sufficiently well	Computationally more demanding

No origin-destination-based trip information needs to be computed *preemptively* as it is done for the creation of skim matrices. Instead, the query architecture generates individual travel information as it is specifically needed when modeling specific decisions in the land-use model. Novel travel options will just be an additional response under the same interface. Currently, travel times are used for relocation and job search decisions in SILO.

The car travel times and costs are informed by the last executed transport model iteration and emerge from the simulation of the transport system. They are stored by MATSim internally and are accessed via MATSim's trip router. PT (public transport) travel times are computed by applying a PT router based on the region's PT schedule. The router also includes access and egress times as well as transfer times for PT queries.

3 Fabiland: Test scenario for detailed model analysis

A small hypothetical scenario named 'Fabiland' is used for the following analyses. It has been designed to be large and rich enough to represent spatial development in its main facets realistically while keeping it comprehensible in one view and limiting runtimes (about 20 min for 10 simulation years).

Fabiland consists of 25 square zones with a side-length of 5 km, i.e., a size of 25 km^2 each, and a grid road transport network. Every zone is its own region which is feasible here as the number of zones is comparatively low (cf. section 2.1 for the definitions of zones and regions in SILO). Next to the road network, there is a 3-stop PT (public transport) line that connects the central zone and two zones in the northeast of the scenario (cf. fig. 2). Stops are served in both directions in 10-minute intervals.

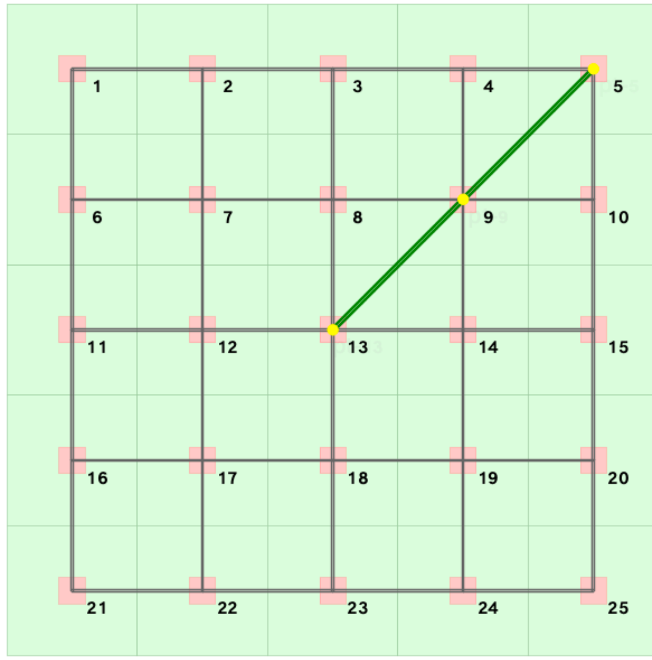


Figure 2: Fabiland scenario (Red squares depict settlement areas, green line represents the PT line with its three stops in yellow).

As depicted in fig. 3, the scenario is populated by altogether 24,000 households of whom 8,160 reside in the central zone. The zone in lower-right corner corresponds to zone 25 in fig. 2. There are six zones with 2,400 households each as shown in fig. 3, while the other zones are only sparsely populated by 80 households each. The scenario has 24,000 jobs, 8,160 of them in the central zone, 2,400 in six zones as shown in fig. 3 and 80 jobs in the remaining zones.

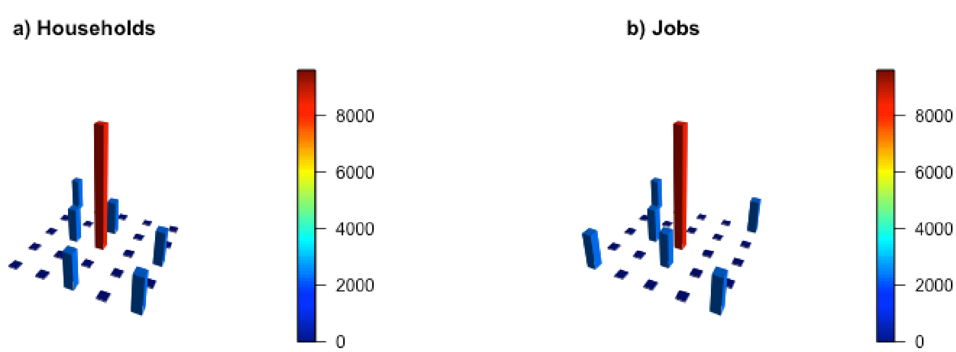


Figure 3: Distribution of households and jobs in Fabiland scenario.

3.1 Base case

Fig. 4 shows the destination zones of all relocations by households over ten simulation years. Households primarily relocate to zones that either have population or jobs. Households without workers (top row) show similar patterns of relocation regardless of their car availability. These households do not depend on low commute travel times and instead focus on general accessibility. For households with workers, by contrast, relocation patterns vary between households without car availability ('PT captives') and households that can commute by car. As the base case only offers PT service in the top right corner of Fabiland, PT-captive households tend to favor the connected zones much more than households that own a car. In addition, zones that have population but few jobs and no PT connection (such as zone 15 on the mid-right) are ignored by PT-captive households. Similarly, PT captives are more likely to move directly to zones with only jobs (such as zone 21 on the bottom left).

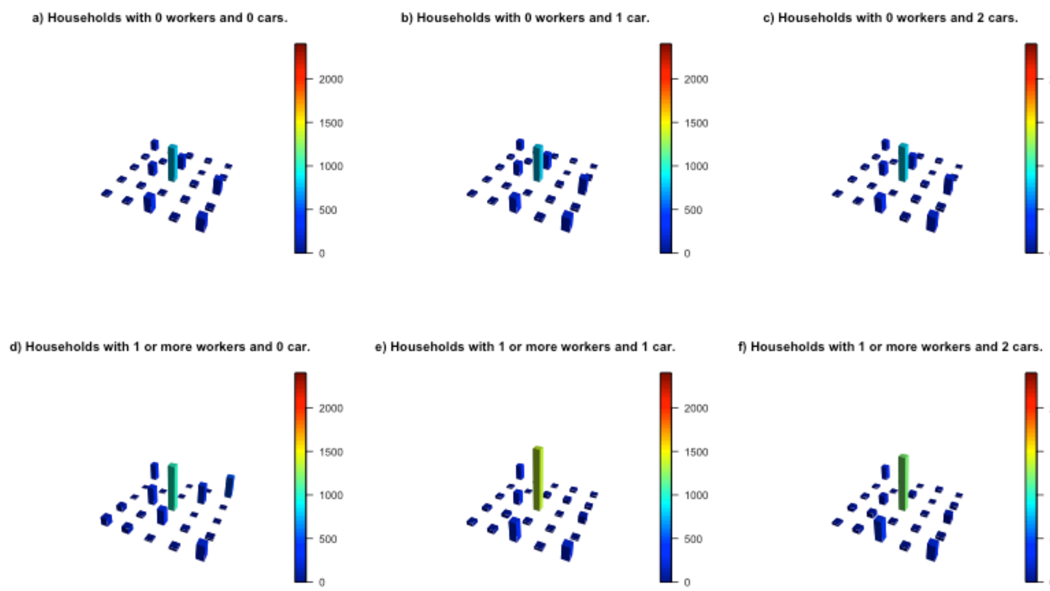
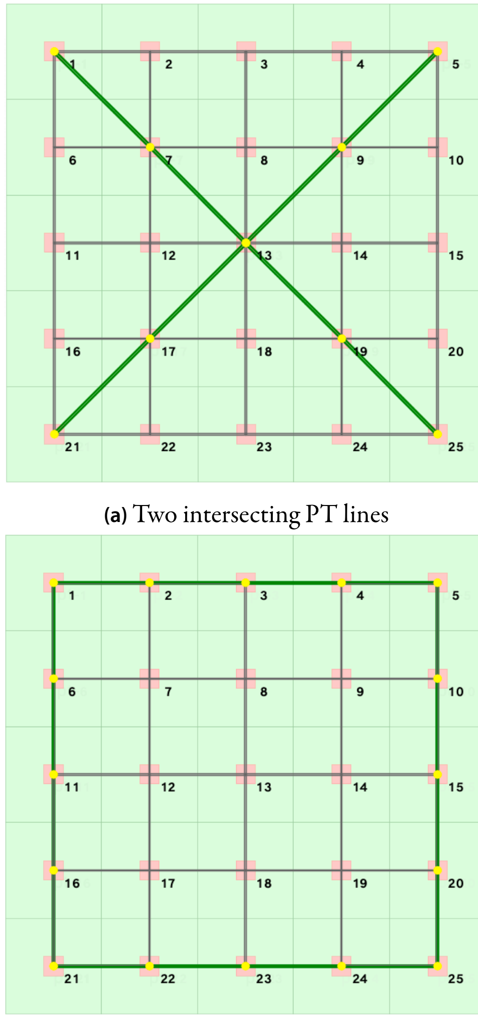


Figure 4: Household relocations over ten years in base case.

3.2 Public transport service improvement

In the following, two different improvements of the PT system are implemented, both extending the base case PT network. First, the existing PT line is extended and supplemented with a second line that intersects the existing line in the center (cf. fig. 5(a)). Second, as an alternative, a ring line along the circumference of the scenario is implemented (cf. fig. 5(b)). Fig. 11 (in the appendix) shows the household relocations over ten years in the case with two intersecting PT lines. Fig. 12 (in the appendix) shows the household relocations over ten years in the case with one ring-shaped PT line.

As interventions into the public transport system are to be analyzed, PT captives (household without a car) are of particular interest. Fig. 6 shows the destinations of relocations of PT-captive households over ten simulation years in the base scenario and the two PT improvement scenarios. The short



(a) Two intersecting PT lines

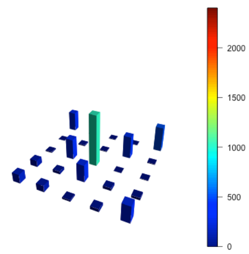
(b) One PT line ring

Figure 5: Improvements in the public transport system

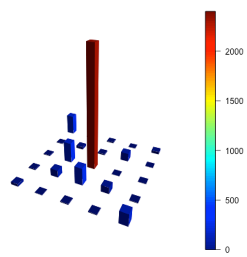
PT line (cf. fig. 6(a) = fig. 4d) that connects the center with the northeastern corner (cf. fig. 2) encourages households to either move directly to the zones with jobs or to zones on that PT line. In the case with two crossing lines (cf. fig. 5(a)), PT-captive households prefer the center (cf. fig. 6(b)), which offers many jobs itself and is also very well connected to other places with jobs. If PT is provided as a ring line along the circumference (cf. fig. 5(b)) PT-captive households mainly move to zones with jobs (cf. fig. 6(c)). In sum,

1. PT-captive workers depend on a job, and if the job cannot be reached by PT, they move their residence close to the job.
2. If, however, the job can be reached by PT, they prefer, between the possible residence locations that also have good access to PT, a residence that has a high accessibility of other amenities.

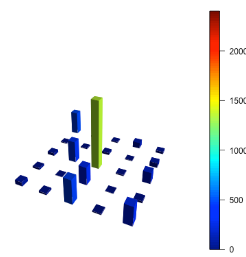
In line with theory, the model states that if it is intended to encourage people to take residence close to jobs, these places also need to have non-job amenities in sufficient quality and quantity.



(a) Base case (One short PT line)



(b) Two intersecting PT lines



(c) One PT line ring

Figure 6: Relocations of PT-captive households over ten simulation year in different PT scenarios

3.3 Combination of public transport improvement with land-use variations

We now consider the impact of two land-use-oriented modifications on the effect of the aforementioned PT improvements:

First, we analyze the effect of zoning restrictions (Schwanen *et al.* 2004). For this, we compare the previous spatial layout where dwellings are only located (and can only be constructed) in the centers of the zones (red-shaded squares in figs. 2, 5(a), and 5(b)) with a case without any zoning restrictions, i.e., dwellings are dispersed throughout the full space of the zones. The latter case may be labeled as 'urban sprawl.'

Second, we analyze the impact of so-called 'superblocks', an urban planning strategy that aims to promote sustainable mobility by reducing car traffic on streets except some remaining main roads which surround large traffic-calmed areas called 'superblocks' (Mueller *et al.* 2020). A straightforward way to model this policy in MATSim is by switching on an explicit consideration of access and egress. If explicit access/egress routing is *de*activated, there is no extra travel cost that represents the effort to reach a car. One can imagine small driveways that allow quick car access from the main road to the dwelling with no (significant) travel effort. If, by contrast, access/egress routing is explicitly considered, people need to walk from their dwelling to the nearest main road as depicted in fig. 2. By this, it is assumed that there are no driveways and only the main roads, which make up a rather coarse network (cf. figs. 2, 5(a), and 5(b)), can be traversed by cars. The distance to these roads determines the walk time that people need to reach the main roads from the car-free neighborhood by foot.

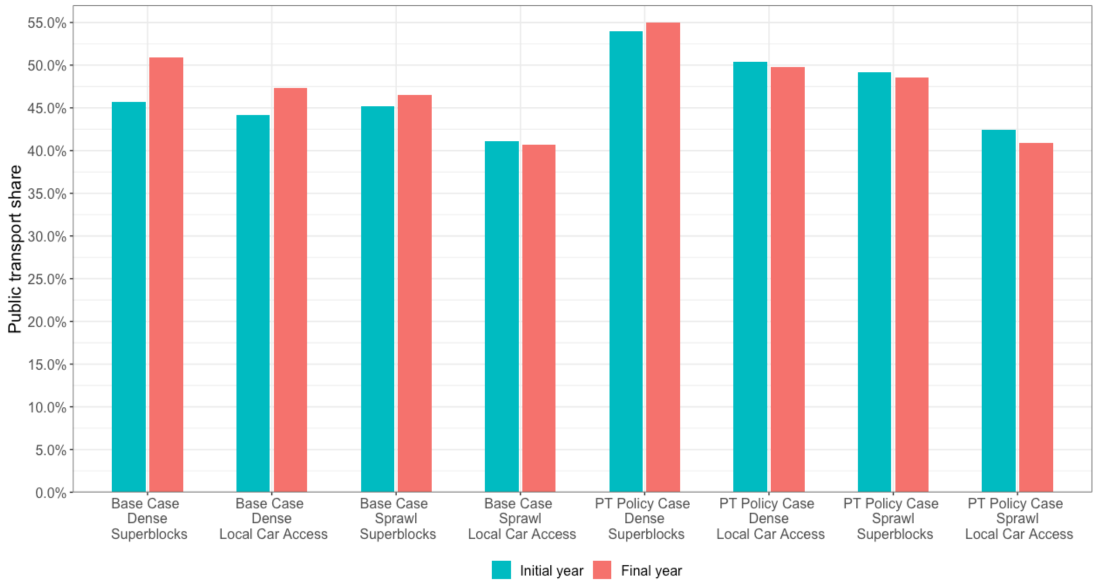


Figure 7: Public transport shares in different analysis cases.

In the following, we compare the PT shares (cf. fig. 7) of (1) the base case (cf. fig. 2) vs. the PT improvement case with two intersecting lines (cf. fig. 5(a)) in combination with (2) a 'dense' (zoning restrictions) vs. a 'sprawled' settlement structure and (3) direct vs. reduced local car access ('superblocks'), yielding eight analysis cases altogether as shown in fig. 7. First, it can be noted that in all cases where local car access is restricted ('superblocks'), the PT mode share increases by roughly 5 percentage points compared to the corresponding case with unrestricted local car access.

Comparing initial and final years of the ten-year simulations (cf. column pairs for each case in fig. 7), the results also show that PT shares are rather stable over ten years (variations by not much more than one percentage point). Interestingly, the cases with a poor PT supply ('base case') and 'dense' settlement layout are exceptions. In these cases, PT captives can improve their situation significantly by moving to one of the few locations with a decent PT supply. This reaffirms the observation from fig. 6(a), which showed that PT captives tend to relocate to locations on the PT line. In the corresponding cases with sprawl, dwellings are so strongly spatially dispersed that PT-captive households have a low chance of finding a spot in close vicinity to a PT stop where they can actually improve.

An improved PT system does not necessarily lead to higher PT shares. In the case with sprawl and ubiquitous car access (rightmost pair of columns in fig. 7), even a substantial PT improvement does not lead to a recognizably changed PT use. Instead, the PT share is merely by one percentage point higher compared to the corresponding PT 'base case' (4th pair of colums in fig. 7). This is in line with other studies that observe that PT as a pull measure alone often has little effect (Kaddoura *et al.* 2019; Rienstra *et al.* 1999). In the case with a 'dense' settlement structure and limited car access ('superblocks'), the PT share increases by about four percentage points when the PT supply is improved. The same effect in a similar magnitude is found by Simmonds and Coombe (2000). This reaction is in line with previous findings that a sensible combination of pull and push measures brings about a much stronger user reaction than the pull measure (improved PT service) alone (Broaddus *et al.* 2009; Creutzig *et al.*

2012). As exemplified here, the model allows to include push measures from the land-use sphere and the transport sphere equally.

4 Munich: Real-world scenario for policy analysis

A frequent critique of ILUT models and other large-scale models has been that many such models have not reached the state of being operational for real-world scenarios (cf. sec. 1). Addressing this critique has been a development paradigm for the FABILUT suite where it was intended to reach operationality quickly. While its components MATSim (some 50 applicable transport models worldwide) and SILO (seven operational scenarios) have proven its applicability to real-world scenarios, the SILO model for the Munich metropolitan area is the first real-world scenario that uses the new microscopic FABILUT model integration.

4.1 Real-world study area

Besides Munich with $1.48m$ inhabitants, the study area (cf. fig. 8) also includes the four core cities of Augsburg ($296k$), Ingolstadt ($137k$), Landshut ($73k$) and Rosenheim ($63k$). Higher costs of living in Munich have triggered households whose members work in Munich to live in other main cities in the region and commute every day (Moeckel and Nagel 2016). The region is strongly integrated with high commuter flows among the five core cities and the surrounding municipalities. The study area delineation is defined such that it includes all municipalities from where 25% or more of the working population commute to one of the five core cities. This 25% threshold was chosen to include all major commute flows while also keeping the study area size computationally feasible (Kuehnel *et al.* 2020).

The zone system was developed with a quad-tree-based automated zone system generator that iteratively creates smaller raster cells in densely populated areas and larger raster cells in rural areas, while respecting administrative boundaries (Molloy and Moeckel 2017). The synthetic population for this zone system (Moreno and Moeckel 2018) was created based on iterative proportional updating (Konduri *et al.* 2016) and consists of $4.5m$ inhabitants in $2.2m$ households living in roughly the same amount of dwellings. Dwelling coordinates have been allocated to actual residential building objects as classified by OSM (OpenStreetMap 2020). The transport network consists of 499,435 links and has been created based on OSM as well (Zilske *et al.* 2011). The public transport schedule is converted (Poletti *et al.* 2017) from a GTFS dataset (Brosi 2019).

To simulate the travel of microscopically modeled household members, the 'Simple Commute Mode Choice Scenario Assembler' (described in sec. 2.3) is used. By this, commute trips are simulated by an appropriate mode in terms of personal mode availability and the utility to use a mode based on expected travel times of all principally available modes. Collectively, all simulated agents produce a realistic representation of the commute travel patterns, which emerge from the transport simulation. To save runtimes, a sample of 5% of persons modeled in the land-use component of the model are selected to be simulated in the transport simulation (cf. sec. 2.2).

4.2 Policy studies

The following five policy scenarios are implemented to apply the FABILUT model in a real-world scenario study and to gain insights in terms of the potential of the developed modeling suite:

1. A base case scenario

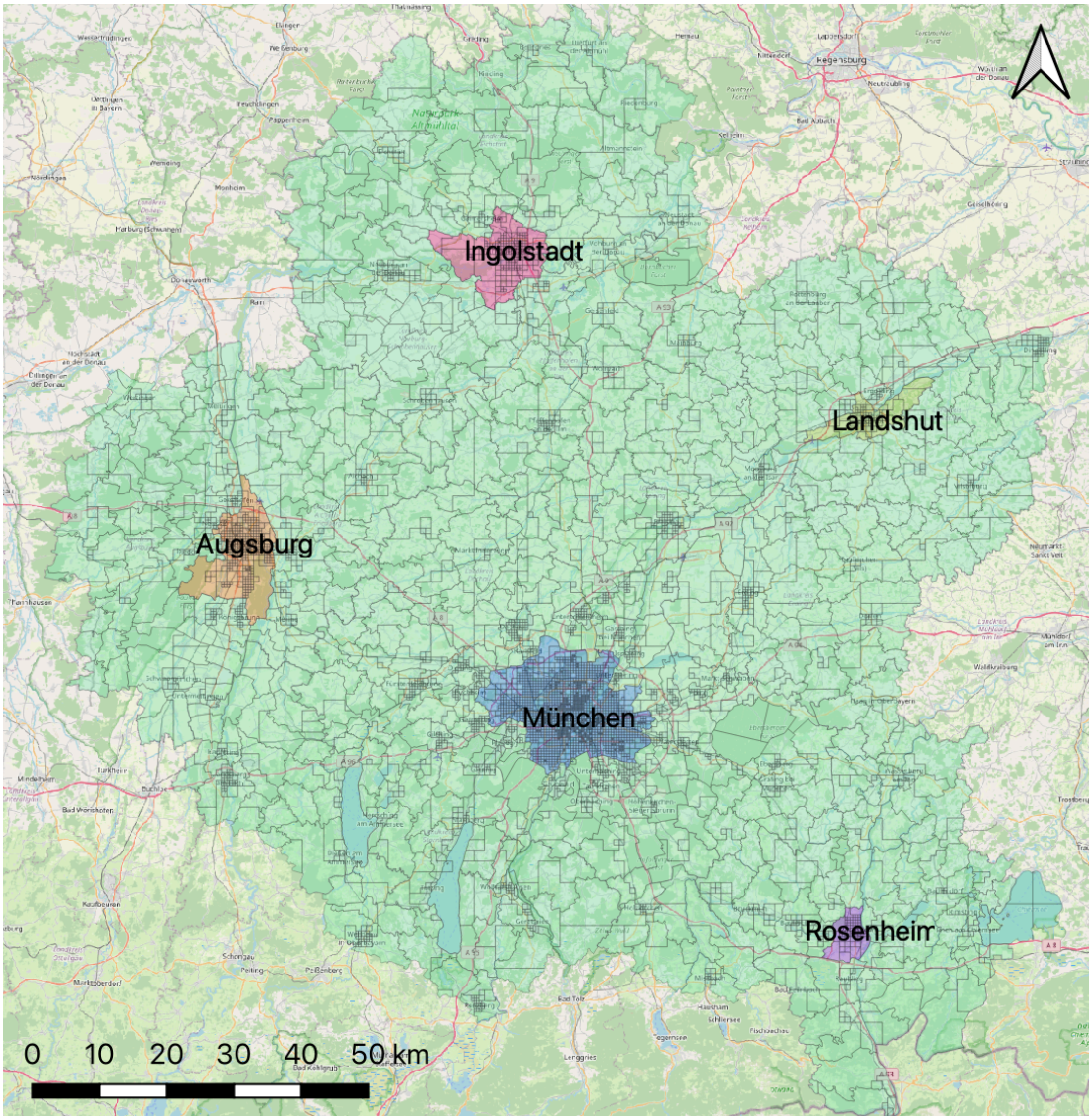


Figure 8: Munich (München) region real-world study area including the four surrounding core cities Augsburg, Ingolstadt, Landshut and Rosenheim (Background map: © OpenStreetMap contributors).

2. A Hyperloop (a passenger transport system in an evacuated tube with very high speed) connection between Munich and each of the other four core cities Augsburg, Rosenheim, Landshut and Ingolstadt.
3. Development of new housing is only allowed within Munich's city limits.
4. Development of new housing is only allowed within the five core cities Munich, Augsburg, Rosenheim, Landshut and Ingolstadt.
5. Core city development of scenario 4 combined with the Hyperloop of scenario 2.

The scenarios are chosen deliberately extreme to produce strong and clearly visible reactions. Similar to sec. 3, population groups are analyzed separately. Fig. 9 shows the percent difference in number of households in the different cities and scenarios. PT (public transport) captives are shown at the bottom row and all other households in the top row.

In the Hyperloop scenario (scenario 2, yellow bars in fig. 9) the numbers of households with cars do hardly change, whereas significant changes can be seen for the PT-captive households, the largest in Ingolstadt, Rosenheim and Landshut, where the numbers of PT-captive households increase by 16% to 22%. While the Hyperloop leads to a lower population increase in Munich compared to the base scenario, the number of PT-captive households slightly increases by 2%.

In the scenarios that only permit development in the core cities, with (scenario 5, pink bars) and without the Hyperloop (scenario 4, blue bars), households with cars move to the core cities. PT-captive households concentrate even more in the core cities outside of Munich with the Hyperloop connection in place (scenario 5, pink bars) than without.

Notably, Ingolstadt shows much higher percentage increases than the other core cities. This has largely to do with the fact that Ingolstadt is located more remotely from Munich than the other three core cities (cf. fig. 8). As no new houses are allowed outside the core cities in these two deliberately very restrictive policy scenarios, new households and relocating households have to find residence in the core cities. As the 'catchment area' around Ingolstadt is larger than those of other core cities, Ingolstadt is the closest settlement opportunity for a comparatively high number of households. At the same time, Ingolstadt is one of the smaller core cities such that the influx of new households produces a particularly high *relative* increase.

Lastly, PT-captive households are less flexible in their housing choice when development is concentrated to Munich only (scenario 3, green bars). As expected, all areas but Munich lose households with cars (who tend to be more affluent) compared to the base scenario. Some PT captives, on the other hand, cannot afford to live in Munich anymore and move to less accessible places like Ingolstadt and Landshut, reversing the trend of more affluent households to some degree.

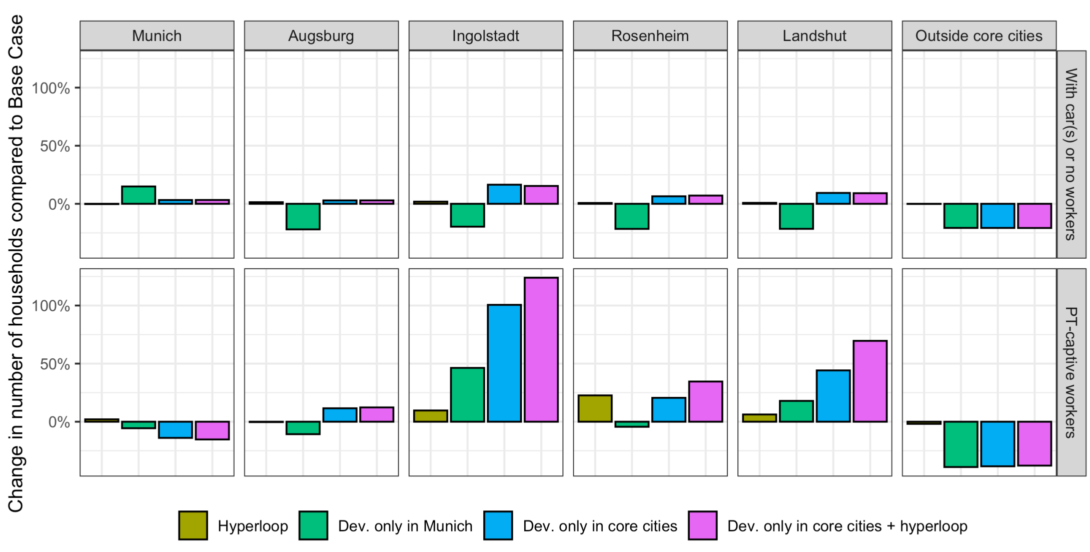


Figure 9: Percentage change in number of households in defined areas across the different scenarios compared to the base case, segmented into PT captives and households with car availability.

As pointed out ins sec. 2.1, work start times are explicitly modeled. Fig. 10 combines segmentations of the population by work start time and by car availability and compares relocation destinations for these different population groups in the base case. It can be seen in the top row (cf. figs. 10a) and b)) that there are no significant differences in relocation choices between households with workers that start their work during PT service hours and those that start during off hours for households with car availability. As shown in the lower row cf. figs. 10c) and d)), PT-captive households move by higher shares to Munich. Workers who start their job in the night (midnight to 4 a.m., cf. fig. 10d)) are again more likely to move to Munich and significantly less likely to move to places outside the five core cities. This is plausible as these households rely on PT and the PT supply during the night is worse in more rural areas, while Munich offers at least a basic night service.

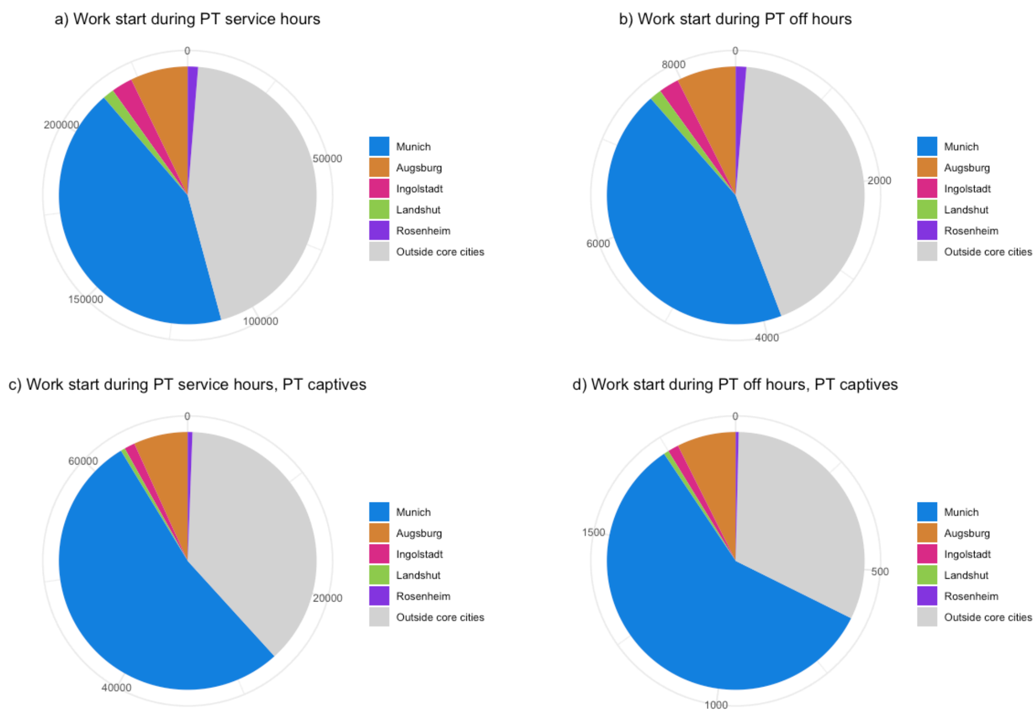


Figure 10: Household relocations by area of destination, by intended work start time and by car availability in base case.

The differences between PT captives and non-captives are striking. The model assumes that households without enough cars need to react by moving residency, but evidently they could as well procure additional cars, assuming they can afford them. This makes targeted policies a challenge. Only improving public transit has not enough effect given the effort (Hyperloop case, scenario 2). Restricting development to core cities has considerable effect, but increases housing prices in those core cities while at the same time forcing less affluent PT captives to move to those core cities. Finally, with models or data that do not differentiate between captives and non-captives, the reactions of the non-captives would overwhelm the reactions of the captives, making it impossible to reach a comprehensive assessment of such policies, especially in terms of equity.

5 Discussion

Spatial resolution Most spatial models use zones to organize space. The layout of the zoning system affects model results, in particular for larger zones. This has been described as the modifiable areal unit problem (MAUP) by Openshaw (1977). A possible approach to mitigate MAUP effects is to use smaller zones or small raster cells to reduce spatial bias (Spiekermann and Wegener 2000). While this reduces MAUP effects, it increases computational effort. The number of entries in zone-to-zone (or cell-to-cell) travel time matrices, for instance, grows as n^2 when the number of zones n increases. Therefore, these matrices can become very large, which makes them difficult to create, to store and to read. At the same time, an increasing number of place-to-place relations increases the share of relations that are calculated and stored, but never used (Kuehnel *et al.* 2020). In highly-resolved spatial layouts this can even be true for the majority of relations.

Because of FABILUT's query architecture the decisions modeled in the SILO land-use component of the integrated model can depend on individualized travel information which is specifically generated for the specific x/y coordinates and specific time-of-day based on the routers of the MATSim transport model when needed (cf. sec. 2.5). Obviously, MAUP does not come into play if such individual (=non-aggregated) information is used (Fotheringham *et al.* 1989). In the Fabiland test scenario (cf. sec. 3), we were able to model various spatial distributions of (new) dwellings *within* the zones, which resulted in different travel behavior. This would not have been possible in a pure zone-based model.

In a parallel study (Kuehnel *et al.* 2020), quantifying aggregation errors related to spatial and temporal aggregation using the Munich scenario, we found that the effects of spatial aggregation are highly relevant in terms of introducing inaccuracies into PT travel times. As PT networks are thinner than car networks, the access/egress to/from the next PT stop has a great impact on overall travel times. Especially in rural zones, which also tend to be larger zones with a low PT system density, the correct actual distance to the next stop can make a huge difference.

Temporal resolution Traditional spatial models do not only aggregate spatially, but also temporally. Often, only one zone-to-zone travel time matrix for one time-of-day is used and regarded representative for the whole day. Obviously, this does not capture the temporal variability of travel times over the course of the day, (e.g., because of changes in congestion patterns.

As SILO models work start times explicitly (cf. sec. 2.1), it is sensible to use this information for a corresponding travel information request. These details are neglected if a single matrix is used. For PT travel information, the time-of-day plays a particularly important role as service frequencies typically differ by time-of-day, while at some times-of-day services may not run at all. In the Munich study (cf. sec. 4), we were able to identify diverging relocation patterns of workers who start work in day hours and night hours.

A remedy to such temporal resolution issue can be using multiple skim matrices for various time slices. While this helps to reduce the effects of temporal aggregation, it linearly increases computational effort, eventually cancelling out the advantages that aggregate approaches have in terms of this aspect.

The aforementioned quantitative study (Kuehnel *et al.* 2020) shows that for car travel times, the impact of temporal aggregation is higher than the impact of spatial aggregation. Many people start their job at untypical times-of-day and commute opposite to the main direction of travel. Thus, their travel times are underestimated in cases with no distinction by time-of-day as it is mostly the case when using travel time matrices. Contrary to car travel times, the PT travel times seems to be less affected by temporal aggregation than by spatial aggregation.

Relevance of network density While temporal resolution errors can be fully addressed by using individualized travel information requests, a variant of a spatial inaccuracy effect can still exist in the setup based on x/y microlocations. This has to do with network densities and could in analogy to the MAUP (modifiable areal unit problem) be described as a 'modifiable network density problem'. Like a changed zonal system may affect results in zone-based approaches, a change in network density – which determines whether or not smaller roads are included – may affect modeling results as the accuracy of routing decreases with less realistic networks (Chang *et al.* 2002). Also, in coarser networks there are fewer route alternatives for congested route segments (Kuehnel *et al.* 2020), potentially distorting congestion patterns. If network access and egress is explicitly modeled, a coarse network will introduce significant bias in overall travel time and cost computations.

Demographic detail and integrity of modeled entities Traditional approaches based on a provision of pre-calculated travel time matrices do not distinguish individuals. With new demand-oriented and, thus, more individualized policies as well as diversifying user characteristics (lifestyles, work schedules, preferences), there is inevitably a stronger focus on the individual decision-maker.

An example of such an individual constraint can be the availability of a car. A principally existing household car will still not be available to a member of the household if another member is already using it for another trip. In FABILUT, the coordination of the use of the household car is explicitly modeled such that a household member to whom the use of the car is more beneficial takes it with a higher probability (cf. sec. 2.5), leading to a corresponding limitation of mode choice options for the other household members.

In FABILUT, MATSim's trip router, which can respect attributes of the trip-making individual in computing the cost of a trip, is available to the submodules of SILO. Therefore other properties and constraints (e.g., age, gender, disability status, etc.) of the individual can be respected in modeling people's choices in land-use and transport decisions. For instance, mobility-impaired people typically perceive the same trip by PT much different from people with a higher degree of mobility. Access and egress as well as transfers may be evaluated differently.

Travel behavior may also differ with regard to income and willingness-to-pay. In terms of tolls, for instance, chosen routes may vary among users with different VTTSs (value of travel time savings) as they regard routes with different monetary cost/time ratios optimal. Capturing such differences in aggregate form is not straightforward as generalized link costs (consisting of both monetary cost and time) would differ among different users. It is more straightforward to allow the individual to query a route from their start to their target location, taking into account their given time, monetary and other personal constraints in the cost function of the applied routing algorithm. This is only straightforward to do in a disaggregate setting.

The ban of certain types of Diesel cars from particularly polluted road segments in many German cities affects households very differently depending on their individual car ownership. To model impacts of such measures in a behaviorally sound way, household-based attributes (type of owned car), household-based decisions (which household member takes the car), and transport information (which specific routes can be taken with the given car) need to be taken into account. FABILUT allows the agent to directly apply MATSim's trip router, which respects which links the agent is allowed to traverse taking into account individual properties, (e.g., the type of vehicle that would be used for the considered trip.

Analysis of policies and technological advancement This tight integration also increases the scope of feasible policy analyses. The higher spatial and temporal resolution improves the analysis capabilities of policies that focus on local impacts (e.g., PT-oriented development) or time-specific impacts (e.g., dynamic tolls), while higher demographic resolution allows to represent decision processes better.

In particular for novel policies and new combinations of policies for which there is no empirical knowledge, and thus no information how to calibrate models that describe such processes in more aggregate terms, a person-centric approach like FABILUT is favorable as the system-wide effects do not have to be known, but emerge for the representation of individual decision processes that the model mimics (e.g., specific vehicle restrictions as described in the previous section).

New technologies like electric car and fuel cells and new services like ride sharing or car sharing are gaining popularity. Fully automated vehicles might become available for daily use. In MATSim, such advancements and the travel options they provide to users have been be simulated (e.g., Bischoff *et al.* 2017). With FABILUT's tight coupling, their effects in a land-use/transport context can be analyzed without additional integration work as any new travel option is simply an additional response to travel information requests from a given land-use decision in SILO. So, the tight integration allows to assess such advancements as they become available on the transport simulation also in terms of their repercussions in the land-use system.

Analysis of environmental impacts A high spatial resolution is a key property of an urban model to allow for analyses of environmental aspects (Kuehnel *et al.* 2020; Spiekermann and Wegener 2008). Noise, for instance, varies on a microscopic scale, especially when the shielding by buildings is taken into account (Kuehnel *et al.* 2021).

In SILO's latest version, each dwelling and job is geo-referenced to a microscopic coordinate which makes the model suitable for fine-grained environmental assessments like noise impact analyses (Kuehnel *et al.* 2021). MATSim is fully coordinate-based and possesses extensions to model noise (Kaddoura *et al.* 2017) and emissions (Kickhöfer and Kern 2015). As the individual traveler is a consistent entity with knowledge of previous trips, (e.g., emissions can be computed directly by the physically correct formulas (e.g., incl. engine temperature, which depends on previous driving (cf. sec. 2.2) and do not have to rely on aggregate approximation.

While based on this functionality environmental impacts can be modeled as an effect of transport and land-use activity, an ILUT model like FABILUT also allows to analyze environmental circumstances as an effect on spatial decisions like household relocation choice. Kuehnel *et al.* (2021) present a proof of concept for a feedback loop between transport-related noise emissions and land-use. Spiekermann and Wegener (2018) mention this has not been done before.

Flexibility and usability Models should be extendable to be able to incorporate new and specialized research questions (Moeckel 2018). FABILUT is flexible as the interaction between FABILUT's core components SILO and MATSim can be adjusted to react to data availability (cf. scenario assemblers in sec. 2.3). Also, SILO and MATSim themselves are modular. MATSim uses modern dependency injection technology (Guice) to plug together simulation components as required for a particular analysis case while ensuring consistency. It is steadily extended and applied to model advancements in the transport system like demand-responsive transport services (e.g., Bischoff *et al.* 2017). By tightly coupling SILO and MATSim, FABILUT enables the transport-specific analysis capabilities of new features to be directly applied in a wider land-use context.

Modern code dependency management tools (Apache Maven) are used to allow using the latest code version of MATSim in SILO, if desired. No manual action is required to bring in updated functionality of newer MATSim versions as this is taken care of by automatic code deployment.

As pointed out in sec. 1, ILUT models traditionally have been aggregate in nature mainly because of limitations in computing power. As this constraint has been eased due to technological advancement, some models have become more disaggregated (Miller 2018). More disaggregation is generally regarded more computationally expensive, leading to longer runtimes (Wegener and Spiekermann 2009). The practical experience with some more disaggregate models seems to agree with this assertion.

While appropriate runtimes may be defined differently by different users, we argue that the runtimes and the computational requirements of the FABILUT modeling suite for typical scenarios are reasonable. The FABILUT model for the Munich metropolitan area with a population of $4.5m$ completes a model run with 40 simulation years in about two days. The router-based queries of about 200,000 households which consider moving in a given year consume about 40 min. For comparison, the creation of a car travel time matrix for the Munich study area based on 4.7k zones took 4 to 7 min for one time-of-day period. The creation of a matrix for public transport took about 1 min for one time-of-day period (Kuehnel *et al.* 2020). To distinguish more times of day, multiple matrix computations would be necessary. It appears that the computational effort that FABILUT's query architecture requires is reasonable for the high levels of spatial and temporal resolution and individualization that this type of integration provides.

6 Conclusion and Outlook

An important novelty of FABILUT is that not only land use and transport (SILO and MATSim) are simulated at the agent level, but also the connection between the two components is microscopic. No travel information is pre-computed (as typically done in existing models that use matrices to provide travel information to the land-use component), but indivisualized travel times are generated *on request* once needed for a specific household decision. A newly developed query architecture ensures that travel information can be retrieved for land-use decisions from MATSim by the full level of detail based on a previous MATSim simulation. Based on this query architecture, the FABILUT suite allows to assess the impact of new transport systems and services, as any new system or service will just be an additional response under the same interface between SILO and MATSim. As such, the integrated land-use/transport modeling capabilities grow automatically with MATSim's increasing transport modeling capabilities.

The next development step for the FABILUT modeling suite will be the inclusion of an activity-based travel demand model (ABM). Recently, the ABM actiTopp (Hilgert *et al.* 2017) has been integrated with MATSim and applied to derive the demand for transport for the creation of a simulation model for the Zurich region (Ziemke *et al.* 2021). Like SILO and MATSim, actiTopp is implemented in Java and open-source. While actiTopp is less comprehensive than other ABMs, it has comparatively low input specification requirements, which can be derived directly from SILO to a large extent. The inclusion of an activity-based travel demand model will further expand analysis capabilities. The current allocation of household vehicles among household members can be improved by coordinating who can use which vehicle over the course of the day.

Currently, accessibilities are computed at the zonal level in SILO. As an alternative, they can be computed in MATSim directly using existing functionality (Ziemke *et al.* 2017). These microscopic accessibilities will further reduce the impact of the zone system on model results (Kuehnel *et al.* 2020).

In this study, different policies were defined, implemented and analyzed and it was found that the model reacts in plausible ways that are in line with earlier findings and theory. In the future, it is intended to apply the model to different types of scenarios, e.g., study areas with polycentric and monocentric urban structures or regions with shrinking population. The issue of parking is also of interest as it is an important mediator between transport (e.g., commuting by car) and land use (e.g., availability of parking spaces close to home and work).

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Appendix

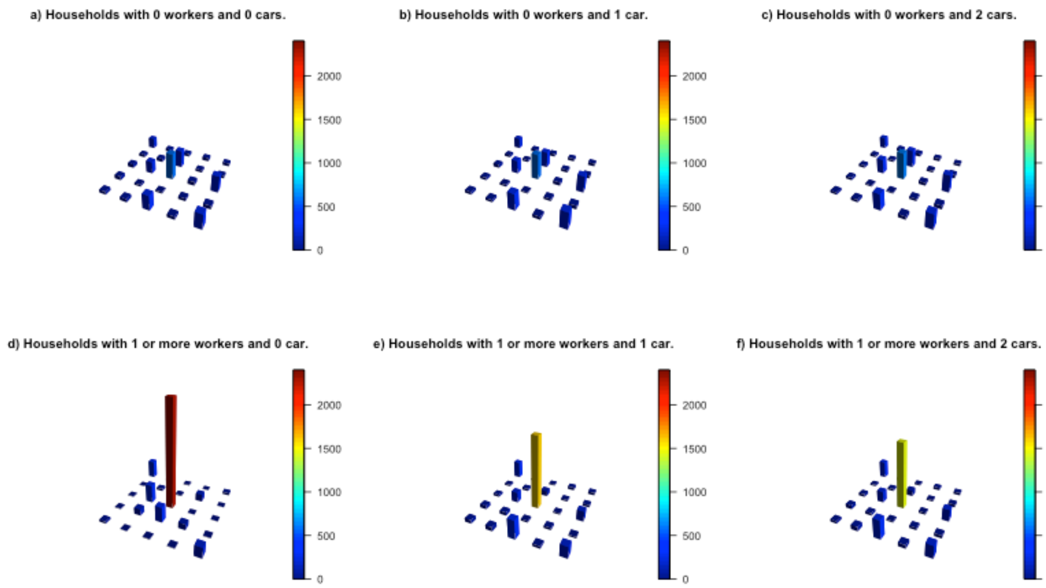

Figure 11: Household relocations over ten years in policy scenario with two intersecting PT lines.

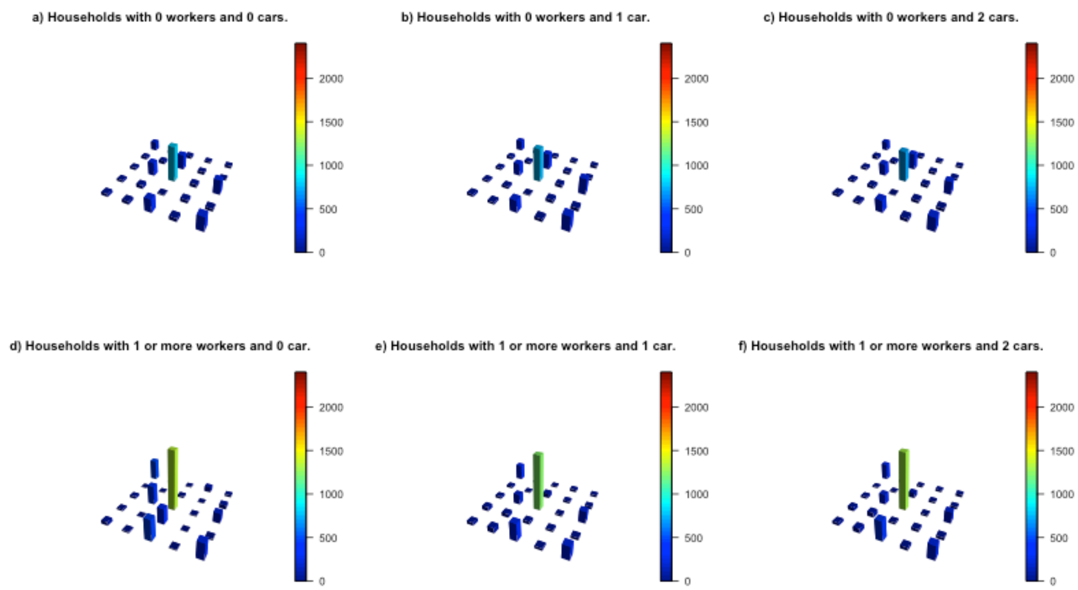

Figure 12: Household relocations over ten years in policy scenario with one ring PT line.