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Will urban air mobility fly? The efficiency and distributional impacts of UAM in different urban spatial structures

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ABSTRACT

Recent technological developments open up possibilities for introducing a vast number of novel mobility concepts in urban environments. One of these new concepts is urban air mobility (UAM). It makes use of passenger drones for on-demand transport in urban settings, promising high travel speeds for those willing and able to pay. This research aims to answer the question how benefits from UAM will be distributed, taking into account the spatial dimension and the differential impacts on low- and high-skilled households. We develop a framework that can more generally be used to assess the welfare impacts resulting from the introduction of novel transport modes. The development of an urban spatial computable general equilibrium model building on the polycentric modelling tradition developed by Anas and co-authors allows for an analysis of mutually dependent effects on the land, labour and product markets, triggered by changes on the transport market. Allowing for an endogenous spatial structure through the introduction of agglomeration effects and an amenity-based approach, the framework investigates the relevance of the initial spatial structure for the impact of the introduction of UAM. Incorporating different skill levels of households allows to assess location choice and travel behaviour for households with different characteristics. A numerical simulation of the model shows that the different initial spatial structures impose comparable welfare changes. Variations in UAM features like marginal cost, prices, land demand for infrastructure, vertical travel speed and access and egress times have a (much) more decisive impact on modal choice and welfare effects than the initial urban structure. Simulations show that considering households of different skill levels brings additional insights, as welfare effects of UAM introduction strongly differ between groups and sometimes even go in opposing directions.

JEL-Classification:
R13, R41, C68

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Urban air mobility, spatial equilibrium, welfare effects, agglomeration effects

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1. INTRODUCTION

Rapid urbanization and sustainability challenges are generating huge interest in new transport concepts. Urban economists have enriched urban spatial computable general equilibrium (USCGE) models to depict a large variety of transport and spatial planning related questions. These models are well suited for assessing welfare effects of transport policies and spatial planning within (Bröcker and Mercenier 2011) and between cities (Teulings et al. 2018). There exists a large variety of applications, such as first- and second-best congestion tolling (Palma and Lindsey 2004; Tikoudis et al. 2015), urban sprawl and urban boundaries (Anas and Rhee 2006), speed limits (Nitzsche and Tscharaktschiew 2013), subsidies and taxation on passenger transport in cities (Hirte and Tscharaktschiew 2013b) and the specific modelling of certain cities (Rutherford and Van Nieuwkoop 2011). These models have mainly been used to assess challenges in spatial and transport planning within urban environments. Due to their long-run perspective they have been able to give insight into possible policy options that account for the mutual interactions that exist between transport and, for example, location behaviour of households and firms, and labour market outcomes. This makes the approach particularly attractive for the study of major and long-lasting interventions and changes in transport systems. Yet, current research focusses on existing transport services, whereas little research has been conducted on the introduction of new forms of urban mobility. The introduction of cars and streetcars showed that drastic changes in travel speed due to new transport service offers can change location choices of households within cities, and that these impacts can be different across different income groups if service offers are very expensive in the beginning (Gin and Sonstelie 1992; LeRoy and Sonstelie 1983). Considering the discussion on future forms of transport, it becomes especially relevant to assess how these influence overall welfare in cities. Urban spatial computable general equilibrium models, with their rigorous microeconomic foundations, are particularly well-suited for this. Comparative static analyses in such models, in which for example different policy or technological scenarios are compared, can be readily casted in terms of conventional monetized Marshallian or Hicksian welfare measures, which are direct, endogenously determined, model outcomes that are conceptually equivalent to social surplus measures as used in societal cost-benefit analyses.

Technological advancements open up discussions about autonomous cars in private ownership or shared usage. Closely related is the concept of urban air mobility (UAM), an “emerging concept that envisions a safe, efficient, accessible, and quiet air transportation system for passenger mobility, cargo delivery, and emergency management within or traversing metropolitan areas” (Shaheen et al. 2020). In the context of this paper, UAM solely refers to passenger transport services. Over 200 companies worldwide are currently working on aircraft allowing for this service, aiming at first commercial flights before 2030 (Straubinger et al. 2020b). Due to high travel speeds and high prices the long term impact of this future mode of transport is especially interesting. First, the combination of high prices and high travel speeds demand for a user group with a high willingness to pay for travel time savings (Al Haddad et al. 2020; Straubinger et al. 2020a; Fu et al. 2019), making the assessment of welfare effects on different income groups relevant. Second, the massive increase in travel time could lead to a change in location behaviour of households (Rothfeld et al. 2019b), especially when keeping the existing empirical evidence on rather constant commuting times in mind (Anas 2015).

In order to better grasp these important developments in urban transport systems, we develop a framework for the assessment of welfare enhancing transport mode introduction. In developing an urban spatial computable general equilibrium model, we build on the work of Anas and co-authors (Anas and

Kim 1996). The approach allows to endogenize the transport system and changes to it. Households as well as companies include the impact of transportation into optimisation behaviour which allows to not only assess the direct impact of changes to the transport system but also allows to evaluate the effects on related markets and overall welfare. Welfare measures, both at the level of (groups of) individuals as well as at the aggregate societal level, follow as endogenous outcomes from the equilibria of the model under different scenarios. The nature of the model ensures that the behavioural responses it produces, guided by utility and profit maximization, are consistent with these welfare measures that rely on utilities of households and profits for firms. Furthermore, the nature of the model allows us to easily express welfare measures in monetary terms, following standard practice in societal cost-benefit analysis. That means that for households we determine consumer surplus measures that consistently reflect utility derived not only from transport behaviour in terms of trip distance and mode choice, but also from consumption of other goods, leisure, residential space, and its location. Moreover, the random utility framework applied also allows for idiosyncratic preferences that vary over households, are not directly observable, but are consistently accounted for in welfare assessments through the use of log-sum measures. Also profitability of firm operations (in the long run pushed towards zero under perfect competition), and induced changes in land prices in the city, are considered in these broad welfare measures.

More specifically, we develop an urban spatial computable general equilibrium model of the Anas type, with discrete zones and a polycentric set-up. A core feature of this model is endogenous location choice of households and firms, and by that endogenous transport demand. This gives the opportunity to assess the long-run effects of changes in the transport sector on the land, labour and product markets. Introducing households of different skill levels allows us to investigate the impact on the different population groups. In this paper we aim to answer the question whether the initial spatial structure of a city has an impact on the success and the effects of UAM introduction. The initial spatial structure describes the distribution of high- and low-skilled individuals over space. Existing literature shows that location patterns and resulting segregation effects strongly differ across countries and regions. The standard textbook examples are Paris (EU-type) and Detroit (US-type), where Paris has high-skilled living closer to the city centre whereas in Detroit low-skilled live in the city centre and the high-skilled prefer to live in suburbs. Using an amenity-based approach, as well as adding agglomeration effects, we endogenously model different spatial structures. We add to the existing literature by developing a framework for the assessment of novel transport options that enables urban economists to give policy advice for the introduction of – in this case – UAM, with a special focus on the impact of initial spatial structures and the impact on households with different skill levels.

This research assesses the introduction of UAM, a fast and expensive mode of transport, and evaluates the impact on related markets, on different household types (high- and low-skilled), including changes in location choice. UAM introduction is modelled by adding an additional mode for the households to choose from, as well as by adding additional transport infrastructure, so called vertiports. Comparing the effects in cities with different initial spatial structures (EU- and US-type) allows a differentiated assessment.

We calibrate the model and present model results before and after the introduction of UAM (comparative statics) for different UAM parameters such as marginal (per-kilometre) cost, price, land demand for infrastructure, vertical travel speed and access and egress times. The results of the numerical simulations are compared with regard to different initial spatial structures, but also for different pricing schemes. The performed assessments especially focus on the different impact on low- and high-skilled households. The simulation results show that the initial spatial patterns have a minor impact on UAM's effects, and that local authorities have to carefully monitor UAM introduction in order to ensure a welfare enhancing UAM introduction.

The paper proceeds as follows. Section 2 gives an overview of the existing literature on urban spatial equilibrium models and their predecessors. Section 3 is dedicated to the model basics, describing the relevant assumptions and connections and by that setting up a framework for future work. Section 4 describes the model calibration while section 5 describes simulation results for the benchmark without UAM and for the base scenario of UAM. Section 6 shows the results of a sensitivity analysis with respect to the UAM parameters marginal cost, price, vertical travel speed, access and egress time, and land demand for infrastructure for different city-types, households of different skill levels and location choices. The final section concludes with findings and possibilities for future work.

2. Literature Review

Various approaches exist for transport modelling and assessment. These comprise four-step models (Ortúzar and Willumsen 2011), activity-based approaches (Horni et al. 2016), land-use and transport interaction (LUTI) models (Waddell 2002), urban spatial general equilibrium models (Anas and Kim 1996), and hybrids of these. These models have different aims and purposes.

Urban spatial general equilibrium models like the one developed for this paper conceptualize and endogenize main parts of the economy, like the behaviour of private households, companies and the public sector, on different interrelated markets. This allows to take the market for land, for products and for labour into account in a consistent fashion; for example, a somehow induced increase in hours worked will, through higher incomes, lead to a demand for larger residences, which may increase commutes, and which may reduce labour supply. Accounting for such interrelations is particularly important for studies of phenomena that take longer time periods to fully materialize. All behaviour in these modelling approaches is derived from first principles consistent with utility- and profit maximization, thus allowing for a consistent welfare analysis. As Bröcker and Mercenier (2011) describe, a three-stage decision tree behind the model enables the synthesis of the continuous demand approach from conventional economic equilibrium models and a discrete choice model for location choice. Adjustments to the equilibrium conditions in an urban equilibrium model, enable modelling several changes to the transport sector and regulatory interventions. Notwithstanding some critiques,[4] the widespread application of USCGE models motivates us to further develop them. The possibility to model households' and companies' location choices opens up options to model the housing, labour, and product market that all are interlinked through the transport market.

The basic assumptions behind spatial general equilibrium models follow the findings of Alonso (1964), Muth (1969) and Mills (1972) who unveiled a relationship between transport costs and housing prices. For monocentric cities, equilibrating forces make housing prices decrease with the distance to the city's core. More specifically, the larger the distance to the central business district (CBD), the cheaper is housing. In that way, inhabitants in the outskirts of the city are compensated for higher transport costs

[4] Flôres Junior (2008), for example, argues that urban CGE models often are too aggregate even though they demand a significant amount of data and the required abstractions might lead to artificial settings that are unable to answer the relevant questions.

through lower housing prices. House prices thus adjust such that utility levels are equalized throughout the city, taking away incentives to relocate to other areas. The basic models work with stylized assumptions like monocentricity of cities, forcing all labour demand to concentrate in the CBD. Furthermore, the models assume continuous space, with rent prices decreasing continuously with increasing distance to the CBD, reflecting what is referred to as the bid-rent curve in the literature.

Verhoef (2005) showed that monocentric equilibrium models can be used to assess policy instruments like second-best congestion charges. Brueckner and Franco (2017) applied a similar approach assessing the impact of parking policies by applying a monocentric model.

Using the above mentioned monocentric and abstract equilibrium model, Gin and Sonstelie (1992) and Le Roy and Sonstelie (1983) assess the introduction of streetcars and cars, respectively. They show that distributions of income over space in the US can be explained by the introduction of these disruptive new transport modes. In a monocentric city with two household types, and thus two different income levels, and only one mode of transport, the relationships taken from Alonso (1964), Mills (1972) and Muth (1969) suggest that people with a higher value of time (VOT), correlating with higher income, live closer to the CBD where companies are located. This hypothesis follows from the fact that increasing travel distances lead to longer travel times, which are a heavier burden for high income households than for low income households. Therefore, households with higher incomes are then willing to pay more to live close to the CBD. Glaeser and Kahn (2004) also find evidence for these effects, highlighting that segregation effects are dominant in multimodal cities. When higher income groups would also have a higher demand for residential space, a countervailing power arises: this may attract them towards peripheral locations where land is relatively cheap.

Indeed, some cities show a different distribution of income, with high-income households living farther away from the CBD. LeRoy and Sonstelie (1983) show that especially in the beginning, when costs of a new mode are high, only high-income households are able to make use of the higher travel speeds as they are the only ones who are able to afford it. Thus, maximizing their utility they choose bigger lot sizes at a longer distance from the CBD, where housing is cheaper. Low income households that are not able to use the novel transport mode due to high prices, have to use the existing, slower mode and therefore live closer to the CBD. The concentration of public transport in city centre potentially strengthens this effect.

So, another reason why high-income households may choose to live further away from the CBD is when the effect of their stronger preference for spacious living outweighs the effect of their higher value of time. In the context of UAM this is a relevant finding. Assuming UAM to be a rather expensive yet also fast mode of transport, indicates that the developments found by Le Roy and Sonstelie (1983) might be transferable to our application case.

Anas and co-authors (Anas and Hiramatsu 2013; Anas and Kim 1996; Anas and Rhee 2006; Anas and Xu 1999) have further enhanced the conventional monocentric model. Allowing for location choice of companies as well as of households, they have opened up the possibility to model a polycentric city. This modelling framework has been used to assess a variety of challenges addressed by transport and urban planning policies. Depending on the relevant research question the methodological basics were either used to construct a strong abstraction of reality (e.g. Anas and Kim 1996) or to develop a city model that encompasses geographical and sociodemographic data of a city to a high level of detail (e.g. Anas and Hiramatsu 2013). In both application cases, the method enables to assess a broad range of policies and mechanisms reaching from agglomeration effects (Anas and Kim 1996), over Pigouvian tolls (Anas and Xu 1999) to the implementation of urban boundaries (Anas and Rhee 2006).

The stylized USCGE model of the Anas type has also been used by other authors to assess transport policies. Hirte and Tscharaktschiew (2013a, 2013b) assessed the impact of income tax deductions of commuting as well as the optimal design of power taxes for electric vehicle introduction. Introducing speed limits, Nitzsche and Tscharktschiew (2013) find that policies which are unrelated to the spatial shape of the city lead to inefficiencies, while local speed limits might well be welfare enhancing. Straubinger et al. (2018) compared on-street and off-street parking in a USCGE model showing that the welfare gains due to the elimination of cruising for parking and additional capacity on the road are surpassed by the losses due to the additional expenses for the new parking infrastructure.

USCGE models of this type thus appear to be a promising approach when discussing the impact of transport and land-use policies also on related markets. Literature shows that abstract models without detailed data on the specific city already provide insights into likely effects of changes. As briefly discussed above, the effects of differences in income between different households might be of relevance also for UAM. Introducing a second household type to the model, and by that distinguishing between low- and high-skilled workers, can give additional insight to location choice within the city (Brueckner et al. 1999). Adding amenities to the different city zones, they explain differences in spatial income distribution in the US and Europe and guide us towards possible model adaptations for our research focus. In the following we build upon their stylized differentiation between EU and US-type cities. We assume high skilled to live close to the centre in EU-type cities and we assume them to live in suburbs further away from the centre in the US-type cities. The opposite holds for low-skilled households.

3. The Equilibrium Model

The framework for the assessment of introducing a novel transport mode that we define in this research follows the models developed by Anas and co-authors (Anas and Hiramatsu 2013; Anas and Rhee 2006; Anas and Xu 1999). We consider a closed city in which population is exogenously given. The city's area is divided into three discrete zones. Locations within one zone are considered to be equal with regard to travel times, housing prices, etc. Despite assuming a linear city, we thus do not treat space as continuous, but only define locations according to their respective zone. In the following we refer to the middle zone as the CBD and see the other two zones as suburban zones that are located at each side of the central zone. We do this despite the fact that within the model companies are able to choose their location, thus the model allows for polycentric setups. The term CBD is hence used for easier identification of the different zones. The size of all zones is equal for ease of comparison, but this is of course not an essential assumption. The model is a strongly stylized abstraction of reality and does, for example, not incorporate the real transport network of a specific city. In contrast it assumes all road traffic to take place on one linear road going from one end of the linear city to the other so that all trips crossing the city pass through the CBD. The model therefore does capture the important empirical phenomena that traffic is busier in the central part of the city than in the suburbs, and that urban trips can stay within zones or travel between zones, in all possible directions, hence allowing us to study also the question of which sub-markets are more likely to be served by the new mode. Due to free location choice of households and companies, transport is endogenous within the model, and includes commuting trips as well as shopping trips of households.

Utility-maximizing households, profit-maximizing firms and the public sector are represented in the model. The first two are free to choose their optimal location in any zone throughout the city, which is one of the core features of the model, as company location choice allows for employment centres to exist outside the city centre.

The three actors (households, companies and the public sector) are closely linked through their activities on the markets for labour, land and products. The interrelations between the different markets are the core of all USCGE models, as it enables to understand and model that a change on any market – be it in price or quantity – has an effect on all other markets. The equilibrium model as we use it here, thus, does not assume economies to move from one equilibrium to another in short time. This model rather aims at showing the long-term effects that changes in one part of the system can have on all other parts of the system.

Introducing a second household type allows to assess the impact of a novel mode of transport on different parts of society. Applying an amenity-based approach allows us to model different city types, with different initial spatial distributions of income classes over space and by that generating different city types (US- and EU-type). Adding agglomeration effects makes production in the proximity of other companies more efficient, and attracts companies to the production sites of other companies, as long as the resulting increase in land rents does not more than offset these benefits.

3.1. Households

As described above, the developed framework encompasses three groups of main actors, namely private households (high- and low-skilled), companies and the public sector. We want to start with a closer description of the private households inhabiting the city. Each household maximizes its utility by optimally allocating its given time endowment to leisure and working, and its earned money to the consumption of goods and housing. The household is also free to choose its place of residence, its work location and its commuting mode. These choices also feed into the utility maximization problem. The specificities of the underlying equations and assumptions are described in more detail in the following.
We assume that low- and high-skilled households have the same preferences, and only differ in their preferences for certain zones; and of course in their exogenous skill levels, and consequently in the resulting (endogenous) income. We drop the index for low- and high-skilled in the following for the sake of readability.

Households will differ in the home and work location they choose, where i describes the zone they live in and j describes the zone they work in; as well as in their mode choice for commuting, where m declares the chosen mode. Goods are produced in each region k and are differentiated, and hence form imperfect substitutes characterized by the zones of production. We can thus, distinguish households according to their skill-level, home location, work-location and commuting mode. The households maximize their utility by consuming housing, products from all zones k and leisure time. Additionally, the household gains intrinsic utility from using a certain mode (asc_m), which we use as a positive alternative specific constant (hence *asc*) for cars to also enable mode choice calibration, and from ($amenities_i$) from living in a certain zone i. Amenities in our context serve as a container term for a broad range of aspects governing relative preferences over more central versus peripheral living, possibly going beyond classical definitions of amenities. Indeed, it may reflect any perceived advantage that a household could derive from living in a certain zone insofar as not explicitly described by spatial variation in other variables in the model.

Household Utility

Following most of the above mentioned literature, households have Cobb-Douglas preferences, with a constant elasticity of substitution (CES) sub-function expressing their love for variety regarding the products produced in the city's different zones. The households maximize their utility by consuming a certain lot size q_{ijm}, a certain number of bundles of products from all zones k Z_{ijkm}, and leisure time l_{ijm}; with σ, φ and ω in the utility function (1) below being the respective expenditure share parameters:

$$U_{ijm} = \sigma \ln\left(\sum_{k=1}^{K} Z_{ijkm}^{\eta}\right)^{1/\eta} + \varphi \ln q_{ijm} + \omega \ln l_{ijm} + \ln amenities_i + \ln asc_m \quad (1)$$

where $\sigma + \varphi + \omega = 1$, and $\frac{1}{1-\eta}$ is the elasticity of substitution between the varieties of products (with $\{-\infty < \eta < 1\}$). If $\eta \to 0$ the CES preferences reduce to a Cobb-Douglas relationship, while with $\eta \to \infty$ the formulation converges to a Leontief subutility-function.

The systematic utility U_{ijm} feeds into the overall utility function of the household:

$$\widetilde{U}_{ijm} = U_{ijm} + \varepsilon_{ijm}. \quad (2)$$

The households' utility $\widetilde{U}_{ijm}$ is influenced by an idiosyncratic stochastic term ε_{ijm}, which assigns a random utility to a certain housing/workplace/commuting mode pair *ijm* for the specific household and adds it to the systematic utility U_{ijm}. This idiosyncratic term reflects unobserved preferences for certain *ijm* pairs, resulting from, for example, an emotional attachment to a particular zone. It will be assumed that these terms follow a certain distribution, and the implied utility from this term is accounted for in the welfare assessments.

Location and mode choice

As mentioned above, households not only maximize their utility by optimally allocating resources, but also by choosing their work and home location as well as their commuting mode. This decision is modelled by applying discrete choice theory.

We assume a nested structure behind households' choices for location and mode, where home and workplace location choice takes place in the upper nest and mode choice happens in the lower nest. We assume that independence of irrelevant alternatives (IIA)[5] holds within one nest, but does not hold across different nests. The level of correlation between the different nests is indicated by λ_{mode}. Following McFadden (1978) and Train (2009) we use $1 - \lambda_{mode}$ as an approximation for the correlation. $\lambda_{mode} = 1$ indicates complete independence and leads the nested logit to collapse into a standard logit formulation.

[5] The independence of irrelevant alternatives refers to ratios of probabilities being independent of the attributes or existence of other alternatives (Train 2009). Relaxing the IIA assumption through a nested logit model, allows to reflect relationships between choice options.

For more discussions on the mechanisms behind this relationship, see Anas and Kim (1996, p. 239) and Train (2009).

Following Train (2009) and other literature in the field of nested logit models we understand the two choice levels as similar to the relationships in conventional multinomial logit models (MNL), where the "upper level MNL" (choice of i and *j*) uses the expected utility Γ_{ij} of the respective nests *ij*. Adding a scaling parameter λ_{idio} to model the importance of idiosyncratic preferences we can thus write:

$$\Psi_{ijm} = \frac{e^{\frac{\lambda_{idio} * inU_{ijm}}{\lambda_{mode}}}}{\sum_m e^{\frac{\lambda_{idio} * inU_{ijm}}{\lambda_{mode}}}} \cdot \frac{e^{\Gamma_{ij}}}{\sum_{ij} e^{\Gamma_{ij}}} \tag{3}$$

with the expected utility of nest *ij* being:

$$\Gamma_{ij} = \lambda_{mode} \ln \sum_m e^{\frac{\lambda_{idio} * inU_{ijm}}{\lambda_{mode}}} \ . \tag{4}$$

Due to the non-constant marginal utilities of income over household types *ijm* we will also make use of this relationship to later calculate welfare effects. Expected utility over all household types per skill level will be calculated, following the standard entropy term approach for MNL described by e.g. Koster et al. (2018), adapted to the nested structure:

$$expected\ utility = \sum_{ij} \left(\frac{e^{\Gamma_{ij}}}{\sum_{ij} e^{\Gamma_{ij}}} \Gamma_{ij} \,/ \lambda_{idio} \right) - \left(\frac{1}{\lambda_{idio}} \right) \sum_{ij} \left(\frac{e^{\Gamma_{ij}}}{\sum_{ij} e^{\Gamma_{ij}}} \ln \left(\frac{e^{\Gamma_{ij}}}{\sum_{ij} e^{\Gamma_{ij}}} \right) \right) . \tag{5}$$

As utility is ordinal, this utility measure will not give sufficient insight into welfare effects of UAM introduction over all households within the city. Thus the so-called equivalent variation between scenarios will be calculated for each nest and skill type. This is a Hicksian monetary measure for welfare changes: it expresses the utility change when going from the one to the other equilibrium as the equivalent change in income that the household would require in the original equilibrium, and with the original prices, to have the same gain in utility. The expression of utility changes in monetary equivalents is an approach that also underlies classical cost-benefit analysis, although the Marshallian surplus measures typically used in applied work have the disadvantage, compared to the Hicksian measure that we use, that with multiple simultaneous price changes – as we will typically observe in general equilibrium models – the measure may not be uniquely defined, but may instead depend on the assumed order of price changes. Hence our preference for the Hicksian measure in our analysis. This welfare measure thus has the great advantage that it is fully consistent with the utility functions that govern behavioural responses in the model; it is expressed in monetary terms and therewith directly comparable with monetized investment costs; and it is, in contrast to Marshallian benefit measures, uniquely defined when there are multiple simultaneous price changes, a common feature in general equilibrium models.

Monetary and Time Budget

Households essentially gain utility through the consumption of goods, housing and leisure time. Yet, the consumption of all three is not unrestricted. We assume each household to have a fixed time endowment.

This time can either be used to earn money, that again can be spent on housing and products, or as leisure time. The monetary budget, thus implicitly is part of the time budget. In the following we describe how these two budgets are connected and how we formulated the constraint for utility maximization.

We assume working hours ($Hwork$) per day to be fixed, and expect the number of working days ($Dwork_{ij}$) per year to be endogenously chosen by the households. Hirte and Tscharaktschiew (2015) discuss the advantages and disadvantages of this way of modelling labour supply (in contrast to exogenous numbers of working days and endogenous working hours). They find that effects of transport policies are stronger when working days are endogenous, as households can react to changes in the transport sector by changing their annual amount of commuting trips. In some cases measures even appear to have opposing impact.[6]

Every household has a fixed amount of hours per year that it does not spend sleeping. We consider this as the maximum available hours and call them time endowment *TE*. *TE* is spent working, commuting (t_com_{ijm}), travelling for shopping purposes (t_shop_{ik}) and leisure time. It is important to mention that we only allow for mode choice for commuting trips, which is described in equation (3). Shopping trips all are done by car.

$$TE = Hwork * Dwork_{ijm} + Dwork_{ijm} * 2 * t\_com_{ijm} + l_{ijm} + \sum_{k=1}^{K} Z_{ijkm} * 2 * t\_shop_{ik}. \tag{6}$$

The households allocate the available time in the most efficient way. For analytical reasons we assume the full income to be the amount of money the household can earn if *TE* is only used for working (including commuting) under a given home / work location pair and using a certain mode *ijm*. Equation (6) can thus be transformed to:

$$Dwork\_max_{ijm} = \frac{TE}{Hwork + 2 * t_{com_{ijm}}}, \tag{7}$$

where $Dwork\_max_{ijm}$ denotes the maximum number of working days if all available time is dedicated to working. The full labour income ($Full\_Inc\_lab_{ijm}$) then equals:

$$Full\_Inc\_lab_{ijm} = Dwork\_max_{ijm} * Hwork * w_j(1 - \tau^l) - Dwork\_max_{ijm} * 2 * c\_com_{ijm}. \tag{8}$$

This equation describes a situation in which all of TE, which is not needed for the trip to work, is dedicated to working. This time is valued by the net income (total wage minus labour tax (τ^l) minus the costs for commuting. Some rearrangements yield:

$$Full\_Inc\_lab_{ijm} = TE \frac{Hwork * (1 - \tau^l) * w_j - 2 * c\_com_{ijm}}{Hwork + 2 * t\_com_{ijm}}. \tag{9}$$

[6] Hirte and Tscharaktschiew (2015) show that labour supply modelling only has a minor impact on commuting behaviour and congestion, while differences in welfare effects and other economic variables do occur. Welfare effects are less sensitive to changes in labour supply modelling when planning policies are analysed than they are when looking at economic instruments like congestion tolls.

This finding is in line with e.g. Verhoef (2005), who shows that the consumption of an additional time unit of leisure leads to a reduction in working time of $\frac{1}{Hwork+2*t\_com_{ijm}}$. The net reward for one time unit working is $Hwork * (1-\tau^{l}) * w_j - 2 * c\_com_{ijm}$. The household thus, as it were, buys back leisure time until the shadow price (VOT) equals:

$$VOT_{ijm} = \frac{Hwork*(1-\tau^{l})*w_j-2*c\_com_{ijm}}{Hwork+2*t\_com_{ijm}}. \tag{10}$$

In addition to income from labour, the household earns money by owning land, for which it receives rents (R) (see below), and by receiving a lump-sum redistribution (τ^{ls}) from the government. More specifically, we assume that the city's inhabitants own the entire city's area. We thus assume all rents – for company sites, housing and transport infrastructure – to flow back to the households, primarily to avoid welfare from leaking away from our general equilibrium analysis in the form of rent payments to absent landlords. To indicate different levels of asset ownership for the different skill types we assume the skill levels productivity (μ for low-skilled households and $1-\mu$ for high-skilled households) to define the rent distribution this leads to the full income:

$$Full\_Inc_{ijm} = R + \tau^{ls} + TE * VOT_{ijm}. \tag{11}$$

This relationship allows us to formulate the following constraint under which the households maximize their utility (1):

$$R + \tau^{ls} + TE * VOT_{ijm} = \sum_{k=1}^{I} \pi_{ijkm} Z_{ijkm} + r_i q_{ijm} + l_{ijm} * VOT_{ijm}. \tag{12}$$

The left-hand side of the equation denotes the full income as described in equation (11) and the right-hand side of the equation describes the expenditure for the consumption of housing, products and leisure time. We hereby value housing by rent prices r_i, products by π_{ijkm} which includes not only the price of the good (p_k) but also monetary (c_shop_{ik}) and time (t_shop_{ik}) costs a household faces when travelling to the zone *k* of production to buy the product. As indicated above we do not allow for mode choice here. Thus a differentiation by mode is not necessary for (c_shop_{ik}) and (t_shop_{ik}):

$$\pi_{ijkm} = p_k + 2 * c_{shop_{ik}} + 2 * t_{shop_{ik}} * VOT_{ijm}. \tag{13}$$

Equation (12) also makes use of the discussion in context with equation (10) showing that leisure time is "bought" by the household at its opportunity costs that equal the VOT (see also equation (16)).

In contrast to most other models of the Anas type, we thus only have one constraint. Anas and Kim (1996) as well as Hirte and Tscharaktschiew (2013a) distinguish between a monetary budget and a time budget each household has. The two constraints are linked by the labour supply of the household. Spending more time on working leads to a higher monetary budget, while spending less time on working leaves more time for other activities, yet leads to less labour income. We unite these two constraints as discussed above, forming equation (12).

Optimal Demand

Bringing together all of the above described relationships allows to formulate the optimal demand for housing, leisure and products for households according to their home and work zone as well as their commuting mode.

Maximizing utility (equation (1)) under this constraint (equation (12)) leads to Marshallian demand functions for products

(14), housing (15) and leisure time (16). Working with Marshallian demand functions we follow the approach of Rutherford and Van Nieuwkoop (2011), whereas most other researchers work with first order conditions derived from a Lagrangian approach. In our model set-up with only one constraint this is the straightforward approach.

$$Z_{ijkm} = \frac{\sigma * Full\_Inc_{ijm} * \pi_{ijkm}^{\frac{1}{\eta-1}}}{\sum_{k=1}^{I} \pi_{ijkm}^{\frac{\eta}{\eta-1}}}. \quad (14)$$

$$q_{ijm} = \frac{\varphi * Full\_Inc_{ijm}}{r_i}. \quad (15)$$

$$l_{ijm} = \frac{\omega * Full\_Inc_{ijm}}{VOT_{ijm}}. \quad (16)$$

3.2. Companies

The second group of agents are companies. We assume them to be linked to the private households in several ways. First of all they demand labour, for which they pay the equilibrium wage. Besides labour, the companies require land for production. The products produced by the companies are then again sold to the households. As described above, the model assumes all land to be owned by households. The companies, thus, pay rent to the households.

As our model describes a polycentric city, we consider not only households, but also companies to be unconstrained in their location choice within the city. As a result, there are companies in all zones of the city. We assume the products in the different zones to be imperfect substitutes. The consumers' love for variety leads to consumption of products from all zones (equation (1)).

Production Function

The model's companies are assumed to produce products out of land and low- and high-skilled labour. We assume a CES production technology. Assuming a CES production function with a CES sub-nest for the different types of labour implies constant elasticity of substitution between land and labour and a different, yet constant elasticity of substitution between the two types of labour (high- and low-skilled).

$$X_k = E_k \left(\delta * land_k^o + (1-\delta) * \left[\left(\mu * labor_{low}{}_k^s + (1-\mu) * labor_{high}{}_k^s \right)^{\frac{1}{s}} \right]^o \right)^{\frac{1}{o}} \quad (17)$$

In equation (17), the elasticity of substitution between land and labour is $\frac{1}{1-o}$, the elasticity of substitution between low-skilled labour and high-skilled labour) is $\frac{1}{1-s}$, and E_k is the efficiency parameter of production.

Agglomeration Effects

Empirics show that companies benefit from positive productivity effects when clustering close to each other. This is an important determinant of spatial structures, which is why we include agglomeration effects in the model.

Following Combes et al. (2010), we use the efficiency parameter to model agglomeration externalities. Using the employment density in the own zone, and assuming an elasticity of 0.06, we follow the early literature on agglomeration effects (Melo et al. 2009; Rosenthal and Strange 2004):

$$\ln E_j = 0.06 * \ln\left(\frac{\sum_{i,m}\left(\Psi_{low_{ijm}} * N_{low} + \Psi_{high_{ijm}} * N_{high}\right)}{A_j}\right). \tag{18}$$

Optimizing Production

The companies aim at an optimal usage of resources and at minimizing costs. Using the above described production technology (equation (17)), they, thus minimize input costs and determine optimal input demand.

Equation (17) is the constraint for the cost function that describes the costs for production in dependency of the companies' land and labour demand:

$$land_k * r_k + labor_{low_k} * w_{low_k} + labor_{high_k} * w_{high_k}. \tag{19}$$

Companies take wages and rents as given. Minimizing equation (19) under the constraint (equation (17)) the companies' optimal land and labour demand is:

$$labor_{low_k}^{*} = \frac{X_k}{E_k}\left(\delta\left(\frac{r_k}{\mathrm{w_{low_k}}}\right)^{\frac{o}{o-1}}\left(\frac{1-\delta}{\delta}\right)^{\frac{o}{o-1}} * (\mu)^{\frac{o}{o-1}}\left[\mu + (1-\mu)\left(\frac{\mu}{1-\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{high_k}}}{\mathrm{w_{low_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o^2-os}{os-s}} + (1-\delta) * \left[\mu + (1-\mu)\left(\frac{\mu}{1-\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{high_k}}}{\mathrm{w_{low_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o}{s}}\right)^{\frac{-1}{o}}. \tag{20}$$

$$labor_{high_k}^* = \frac{X_k}{E_k}\left(\delta\left(\frac{r_k}{\mathrm{w_{high_k}}}\right)^{\frac{o}{o-1}}\left(\frac{1-\delta}{\delta}\right)^{\frac{o}{o-1}}(1-\mu)^{\frac{o}{o-1}}\right. \tag{21}$$

$$* \left[(1-\mu)+\mu\left(\frac{1-\mu}{\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{low_k}}}{\mathrm{w_{high_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o^2-os}{os-s}}$$

$$\left. + (1-\delta) * \left[(1-\mu)+\mu\left(\frac{1-\mu}{\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{low_k}}}{\mathrm{w_{high_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o}{s}}\right)^{\frac{-1}{o}}$$

$$land_k^* = \frac{X_k}{E_k}\left\{\delta + (1-\delta) * \left(\mu\left((\mu)^{\frac{1}{o-1}}\left(\frac{r_k}{\mathrm{w_{low_k}}}\right)^{\frac{1}{o-1}}\left(\frac{1-\delta}{\delta}\right)^{\frac{1}{o-1}}\right.\right.\right. \tag{22}$$

$$\left. * \left[\mu + (1-\mu)\left(\frac{\mu}{1-\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{high_k}}}{\mathrm{w_{low_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o-os}{os-s}}\right)^{-s}$$

$$+ (1-\mu) * \left((1-\mu)^{\frac{1}{o-1}}\left(\frac{r_k}{\mathrm{w_{high_k}}}\right)^{\frac{1}{o-1}}\left(\frac{1-\delta}{\delta}\right)^{\frac{1}{o-1}}\right.$$

$$\left.\left.\left. * \left[(1-\mu)+\mu\left(\frac{1-\mu}{\mu}\right)^{\frac{s}{s-1}}\left(\frac{\mathrm{w_{low_k}}}{\mathrm{w_{high_k}}}\right)^{\frac{s}{s-1}}\right]^{\frac{o-os}{os-s}}\right)^{-s}\right)^{\frac{o}{s}}\right\}^{\frac{-1}{o}}$$

The objective function (19) is minimized at the point where average costs equal marginal costs. Assuming free market entry we expect prices to equal marginal cost, satisfying the first-best optimality condition.

3.3. Modelling the Transport Sector

Trips are endogenous in our model and are determined by work and home location choice of the household as well as its preferences for products. The model considers travel time and monetary travel costs for commuting as well as for shopping trips. We assume that commuting takes place during peak hours while shopping trips are made during off-peak times. This assumptions leads to congested trips for commuting and uncongested travel for shopping. At this stage, the model only includes congestion for road transport whereas the vertiports, which are likely to be capacity restricting in the UAM network, are assumed to have unlimited capacities; we elaborate on possible effects of this limitation in the conclusion of the paper. For road congestion, the model uses a static congestion modelling approach. The BPR (Bureau of Public Roads) congestion function (Small and Verhoef 2007) is applied.

The transport sector is an essential part of the model we set up to create a framework for the assessment of novel transport modes. In this version of the model, we limit the transport alternatives to two modes. Starting with private cars and UAM, as we want to analyse the effects of UAM introduction in comparison to the closest substitute. With regard to the granularity of our model, and its set up with discrete zones for household and company location, we assume car transport to be the suitable benchmark transport mode.

Mode choice is only possible for commuting trips, and is part of the endogenous classification of household types *ijm*. Mode choice is part of the overarching discrete choice set described in equation (3), and takes place in the upper nest. The household gets to choose which mode m to use in location pair nest ij.

As described in equation (10), the value of time depends on time and money required for commuting trips: $VOT_{ijm} = \frac{Hwork*(1-\tau^l)*w_j-2*c\_com_{ijm}}{Hwork+2*t\_com_{ijm}}$. Expecting UAM to be a rather expensive mode of transport we run into problems for scenarios where $Hwork * (1-\tau^l) * w_j < 2 * c\_com_{ijm}$ as the VOT then has negative values which leads to an infinite demand for leisure. We therefore exclude *ijm* combinations from the choice set that have daily commuting costs that are higher than the daily net wage. A logit choice model would still assign positive choice probabilities to such combinations due to the unbounded distribution of the stochastic term, but when commuting brings no intrinsic utility – i.e., other than enabling working – it seems justified to exclude such choices from the equilibrium choice set.

3.4. Public Sector

Besides private households and companies, the model includes a public sector. The public sector in the model is an overarching entity that covers the relevant public institutions for the assessment of welfare changes due to novel transport modes.

The public sector finances transport infrastructure (depending on the share of land dedicated to infrastructure in each zone *i*) and generates income from labour tax τ^l. Additional revenue stems from transport. For car transport, money flows originate from a gasoline tax and, if applied, congestion tolls. For UAM we assume the equivalent of revenues from marginal cost pricing to flow out of the city to import the technology. Phrased differently, the marginal (per kilometre) cost are the cost involved in obtaining the mode. Revenues or losses from pricing schemes above or below marginal cost pricing are assumed to flow back to the public sector As we assume the public sector to be non-profit, additional revenues are redistributed lump sum to all households (τ^{ls}).

$$\begin{aligned}\sum_{i,j,m}\left(\Psi_{ijm} * N * \tau^l * w_j * Dwork_{ijm} * Hwork\right) \\ + \sum_{i,j,m}\left(\Psi_{ijm} * N * Dwork_{ijm} * 2 * (c\_com_{ijm} - c\_com\_ex_{ijm})\right) \\ = \mathrm{N} * \tau^{ls} + \sum_{i}\left(Share\_Infra_i * A_{i,j} * r_i\right).\end{aligned} \tag{23}$$

3.5. Equilibrium Conditions

The clearance of all markets generates an equilibrium and thus allows to solve the model. Following Walras' law, we therefore need four equilibrium conditions. The first describes the zero-profit condition for the companies. The remaining three require market clearance on the markets for products (24), labour (26) and land (27).

The Market for Products

Market clearance on the market for products is achieved when the production in zone k (X_k) equals demand for goods produced in zone k (including exports from zone k):

$$X_k = \sum\nolimits_{i,j} (\Psi_{i,j} * Z_{i,j,k} * N) + Export_k. \tag{24}$$

Exports

The sum of all exports equals the monetary value flowing out of the city. Money leaving the city stems from pecuniary transport costs for shopping and commuting (excluding, of course, taxes paid to the public sector): ($c\_com\_ex_{ijm}, c\_shop\_ex_{ik}$). We assign the share of exports per zone $Export_j$ according to the employment shares:[7]

$$\begin{aligned} Export_j * p_j = & \sum\nolimits_{i} (\Psi_{ijm} * N * Dwork_{ijm} * 2 * c\_com\_ex_{ijm}) \\ & + \sum\nolimits_{i,k} (\Psi_{ijm} * N * Z_{ijkm} * 2 * c\_shop\_ex_{ik}) \end{aligned} \tag{25}$$

The Labour Market

The third equilibrium condition requires labour demand (left side of equation (26)) and supply (right hand side of equation (26)) in one zone to be in equilibrium:

$$labor_j = \sum\nolimits_{i} (\Psi_{i,j} * N * Hwork * Dwork_{ij}). \tag{26}$$

The Land Market

The land market is cleared if area A_i in zone i is fully taken up by infrastructure (roads and vertiports in our setting), companies ($land_i$) and households:

$$A_i = \sum\nolimits_{i} (\Psi_{i,j} * q_{i,j} * N) + land_i + (Share\_Roads_i + Share\_Vertiports_i) * A_i. \tag{27}$$

4. Model Calibration

As previously discussed urban spatial equilibrium models of the Anas type are often rather abstract and mainly aim at giving insights on a more general level than specifically modelling all details of a certain region or city. Despite the model and the numerical simulation being a strong abstraction of reality we

[7] This short-cut assumption is made for several reasons. The purpose of this model is to discuss effects of transport system changes arising within the city. Outside demand is therefore not explicitly modelled. Besides transportation services no other exports and imports are taking place. As the world price equals the producer price of a good and this price differs for different company locations, exports have to be assigned to a certain zone.

calibrate the model to somewhat resemble a medium sized German city[8]. This means that the model does not encompass households or companies with specific characteristics or captures the specific design of the transport system in a city. Instead, it rather uses average values on income, wages, rents, population density, etc. to grasp the expected overall effects of a change in the transport system. Table 1 gives insight into chosen parameter values and wherever possible shows sources used for the calibration.

Parameters will not be changed for the different city types (EU- and US-type) as we want to emphasize the impact of different spatial settings and want to have an isolated discussion on that; i.e., keeping "all else equal". Changing all other parameters as well would only complicate the comparison.

These parameters form an input to the simulations. Parameters related to the city's population or to car transport follow values used in the literature. The number of households modelled takes into account that the model does not cover all of the city's area but only a section or "slice" of it, allowing us to use a one-dimensional spatial setting. The time endowment TE accounts for all hours per year that the respective household does not spend sleeping, and is set to 6,000 hours. The expenditure shares of the Cobb-Douglas utility function are calibrated in a way to match expenditure for housing and consumption of empirical values given in Table 2. The expenditure share for leisure time gives additional possibilities for calibration.

Parameters o and s in the production function determine the substitutability of land to labour, and high- and low- skilled labour, respectively. Exponents close to zero approximate Cobb-Douglas relationships, large negative values indicate a lower substitutability, and positive values give high substitutability. We assume land and labour to be less close substitutes than low- and high-skilled labour. The remaining parameters (δ and μ) in the production function are proxies for expenditure shares, allowing us to differentiate the importance of land, low-skilled and high-skilled labour for production. 10% of land inside the study area is assumed to be used for road infrastructure. Costs for car travel are assumed to be at 0.25€ per kilometre plus additional costs for gasoline.

[8] Parameters as e.g. expenditure shares, urban density and working hours per day are thus chosen in a way to then result in variables as e.g. wage levels, rents or working days per year to also reflecting empirical values for German cities. The exact values of the parameters and variables are described in the following tables.

Table 1. Calibrated parameter values

Symbol	**Description**	**Model value**	**Literature value / comment**	**Source**
N	Total number of households	180,000	Adapted to depict section of the city	
N_{low}	Total number of low-skilled households	90,000	Split up half and half	
N_{high}	Total number of high-skilled households	90,000		
TE	Total time endowment (hours per year)	6,000	=365*16.45	Statistisches Jahrbuch Deutschland (2019)
σ	Share parameter utility function product k	0.5	0.41	Tscharaktschiew and Hirte (2010) / Statistisches Jahrbuch Deutschland (2019)
φ	Share parameter utility function land	0.2	0.22	Tscharaktschiew and Hirte (2010) / Statistisches Jahrbuch Deutschland (2019)
ω	Share parameter utility function leisure	0.3	0.37	Tscharaktschiew and Hirte (2010) / Statistisches Jahrbuch Deutschland (2019)
η	Parameter utility function products	0.8	0.6	Tscharaktschiew and Hirte (2010)
$Hwork$	Working hours per day	8	8	Eurostat (2004)
δ	Parameter production land	0.2	0.2	Tscharaktschiew and Hirte (2010)
μ	Parameter production low-skilled labour	0.4		
o	Parameter production relation land to labour	−1.5		
s	Parameter labour substitution	−0.1		
$Amenities(i)$	Amenities per household type and zone	1 – 1.05		
$A(i)$	Land area in zone i (km^2)	65		
$Share_{Roads}(i)$	Exogenous share of land allocated to roads	20%	17% Munich	Statistisches Amt der Landeshauptstadt München (2017)
p_t	Costs per vehicle and kilometre	0.25€/km	0.25€/km	Straubinger et al. (2018)
p_{gas_prod}	Gasoline producer price per litre	0.50€/l	0.50€/l	Statista (2020b)
p_{gas_tax}	Gasoline tax per litre	0.95€/l	0.90€/l	Statista (2020b)
p_{gas}	Gasoline price total	1.45€/l	1.45€/l	Statista (2020b)

Table 2 shows results for the calibrated benchmark and contrasts them with empirical values for the respective numbers. These numbers give insight into how well the model meets empirical values.

Table 2. Simulation results calibrated against empirical values

Description	Model value	Literature value	Source
Working days per year	170 – 270	175–222	Statista (2019) (avg. weekly working hours * 46 weeks)
Average commuting distance	10 – 15km	10.5km	Institut für Arbeitsmarkt- und Berufsforschung (2018)
Population density	930/km²	1,000km²	Statistisches Jahrbuch Deutschland (2019)
Average rent per month	6.60 – 7.50€/m²	6.72€/m² – 17€/m²	Statistisches Jahrbuch Deutschland (2019; Statista (2020a)
Average area per household	330 – 510m²	97m²	Statistisches Jahrbuch Deutschland (2019)
Average labour income	28,000 – 42,000€/year		
Average overall income	100,000 – 150,000€/year	53,688€/year	Statistisches Jahrbuch Deutschland (2019)
Expenditure transport excluding savings	7%	16%	Statistisches Jahrbuch Deutschland (2019)
Expenditure housing excluding savings	29%	38%	Statistisches Jahrbuch Deutschland (2019)
Expenditure products excluding savings	64%	46%	Statistisches Jahrbuch Deutschland (2019)
Average wage	20 – 32€/h	27.75€/h	Statistisches Jahrbuch Deutschland (2019)

Comparing model results and empirical values for Germany shows that the exogenously chosen parameters produce reasonable values for endogenous variables in the simulated base equilibrium. One striking exception is the average land demand per household, which we compare to average apartment sizes in Germany. As indicated above, the model is rather stylistic and does not include all aspects of urban land use like gardens, parks, schools, and other sectors that demand land. Due to the way land ownership is modelled, all rents flow back to the households, affecting also land demand. Land rents per square meter are also relatively low. The model results give rents in the magnitude of rural areas. Urban areas have higher rents per square meter. Yet, the described model does not include recreational areas, agricultural land inside the city and land for public institutions. In Munich housing and company premises for example only occupy approximately 35% of the land in the city (Statistisches Amt der Landeshauptstadt München 2011). This indicates that rents in our calibration would get close to what can be seen in Munich if the rented area is around one third of the total area in a zone. We do not include public space into the model as the trade-off between public land as a public good and private land as a private good would introduce a multitude of additional distortions and complications into the model.

The other values, in contrast, match quite well. The average number of work days per year from the model varies in the range we also get when looking at empirical values. Average commuting distance is at the lower end of empirical values, which makes sense, as the model only covers commuting inside the city and we thus lose long-distance commutes. Comparing commuting distances in different model zones to empirical values for different parts of cities (Bundesministerium des Innern, für Bau und Heimat 2020) give similar values. Population density is a bit below empirical values, which is in line with lower rents and can also be traced back to the initial number of households and the initial size of the areas. The average of low- and high-skilled wages from the model is also very close to what the empirics for 2019 in Germany give.

For the UAM parameters, like travel speed access and egress times, cost, prices and land for vertiports, it is hard to foresee what values are realistic. The model will therefore be used to assess a broad range of values for these parameters, to then give indications on their relevance to and impact on welfare. The following table (Table 3) contrasts the parameter values chosen for simulation with values from existing studies.

Table 3. UAM parameters

	Description	**Base scenario values (Range of parameter values)**	**Values from existing studies**	**Source**
$Share_{Vertiports}(i)$	Exogenous share of land allocated to vertiports	0.2% (0.0% – 1.0%)	Non-existent, additional information provided below	
$access_{time}$	Time required for access and take-off as well as for landing and egress (added twice to the total travel time)	0.1h (0.0h – 0.2h)	0.08h – 0.25h	Ploetner et al. (2020)
$cruise_{speed}$	Horizontal travel speed UAM (in the UAM base case)	150km/h (50 km/h – 300km/h)	150km/h 100km/h 320km/h	Ploetner et al. (2020) Volocopter, VC200 Joby, S4
$price_{UAM}$	Price for UAM consisting of a kilometre dependent fee and a base fee	0.80€/km + 0€ base fare (0.40€/km + 0€ – 0.00€/km + 30€)	1.75€/km – 5.00€/km 1.80€/km	Ploetner et al. (2020); Porsche Consulting (2018)
mc_{UAM}	Marginal cost of UAM provision	0.80€/km (0.20€/km – 2.40€/km)	1.75€/km – 5.00€/km 1.80€/km	Ploetner et al. (2020); Porsche Consulting (2018)

For vertiport land demand we assume a need for 0.2% of the land in the study area. This value is based on resulting UAM demand per zone and peak, a headway of three minutes, 1.3[9] passengers per vehicles, a peak duration of 180 minutes and an area of 625m² per landing pad[10] (including additional space to taxi and park the UAM vehicle).

Access and egress times are relevant to the total travel time of UAM. We assume the given value to be added before and after the flight, thus accounting for access and egress as well as boarding and deboarding. This is a strong simplification when e.g. comparing this model to the agent-based approach developed by Rothfeld and co-authors (Rothfeld et al. 2018; Rothfeld et al. 2019a; Balac et al. 2019), who explicitly model access and egress times to vertiports. Yet, for the given purpose this is a reasonable simplification.

The parameter values for travel speeds in UAM aim at covering stated cruise speeds of several vehicle configuration from multi-copter to lift+cruise concepts (Shamiyeh et al. 2017).

As the above table reveals, the marginal cost and prices for UAM are relatively low. Yet, these rather low values were chosen deliberately. First, the aim of this paper is to understand the impact UAM can have

[9] An average seat load factor of 1.3 for UAM was chosen as: (1) Nearly 75% of all vehicle concepts that currently being developed have one or two seats; (2) We envisage empty flights for vehicle relocation to be necessary. This also takes capacity from the vertiports. Counting them in decreases the average number of passengers per flight.

[10] This includes additional space to taxi and park the UAM vehicle and for passengers to wait for boarding. We build upon the FATO area currently required for existing helicopters (minimum 10x10m with additional 5m for safety).

on cities. High prices, above or at the level of taxi prices, might be realistic at the beginning; yet, as e.g. Ploetner et al. (2020) show, modal shares of UAM can then be expected to very low. With rather low modal shares of UAM the expected impacts on location choice and related markets is expected to be minor. Of course, during sensitivity analysis higher prices and cost have also been analysed, yet the base scenario for UAM assumes a positive future for UAM. The second reason for choosing 0.80€/km in the UAM base scenario is more a methodological point. As described in section 3.3 the model encounters issues for UAM prices that lead to $Hwork * (1 - \tau^l) * w_j < 2 * c\_com_{ijm}$ as the VOT then has negative values which leads to an infinite demand for leisure. We exclude home-work location pairs that encounter this problem (where the monetary cost of commuting exceeds the daily wage) from the choice set. Yet, we aimed at simulating a base-case that does not force us to manually exclude choices but wanted a base scenario that is in line with discrete choice theory.

5. The Numerical Simulation

The results of the numerical simulation are presented in two steps:

(1) Results for the two different city types are described. We assume one city to have high-skilled households having a stronger preference for the city centre. For the sake of brevity we call this an EU-type city, following e.g. Brueckner et al. (1999) who see amenities as a driver for this. Cities where high-skilled live further away from the city's core and low-skilled closer to the CBD will be referred to as US cities. The model obviously does not include all factors defining these structures, yet it allows first insights into the relevance of initial spatial structures for UAM introduction – and we find these easy-to-remember labels for the two spatial structures.

(2) We introduce UAM to both of these spatial structures and assess the consequences, paying special attention to the difference in effects between the two city set-ups.

The results of sensitivity checks where the UAM parameters price, marginal cost, travel speed, access and egress times and required land for vertiports are varied, are presented in the later Section 6.

5.1. The Benchmark for different spatial settings

We first present the base equilibria for the EU and US type cities, with car as the only transport option.

Location Choice

Figure 1 to Figure 4 show the numerical results[11] for location choice in the different city types (EU and US) and for the different household types (low- and high-skilled). Every bar resembles the number of households living in the respective zone, the different colour shadings indicate the zone the households commute to. For all settings, the home zone is also the most attractive work zone, as the households try to minimize generalized transport costs. Increasing commuting distance decreases the attractiveness of a work location, but idiosyncratic utility may of course justify this choice nevertheless. Differences between the two spatial settings (US and EU) can clearly be seen. While only 24% of low-skilled live in the city centre in the EU case, it is more than 46% in the US case. The effect of amenities leads to more low-skilled living in the suburbs in the EU case, and vice versa for the US case.

[11] In most of the figures that will follow, only one suburb is displayed. Due to the symmetric city set-up, this suffices.

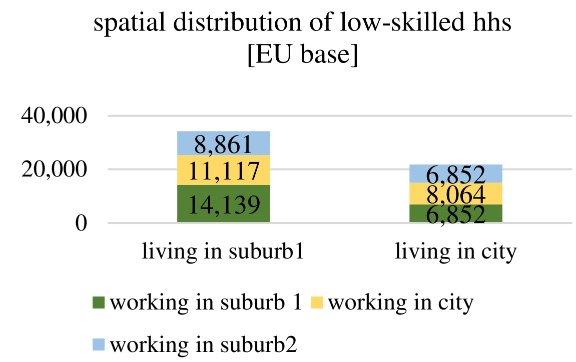

Figure 1: Spatial distribution of low-skilled hhs [EU base]

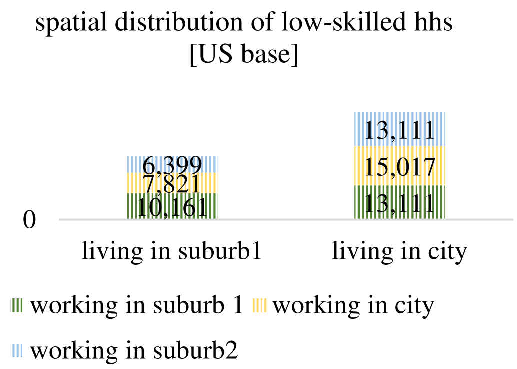

Figure 2: Spatial distribution of low-skilled hhs [US base]

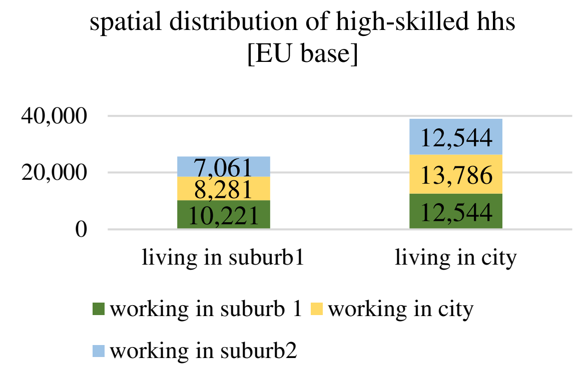

Figure 3: Spatial distribution of high-skilled hhs [EU base]

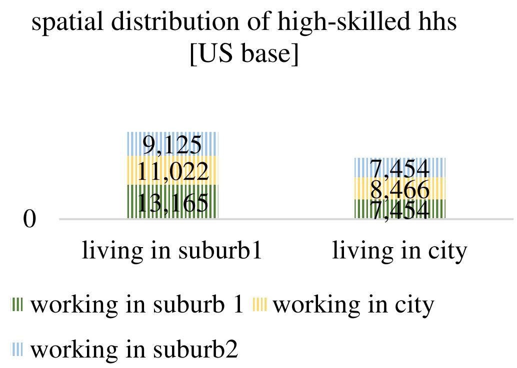

Figure 4: Spatial distribution of high-skilled hhs [US base]

For the high-skilled households (Figure 3 and Figure 4) the numbers show opposite effects with more high-skilled living in the city centre in the EU case (43%) and 26% of the high-skilled living in the city centre in the US case.

Related markets

As classic contributions by Alonso (1964), Muth (1969) and Mills (1972) already explain, one can expect rents to decrease with increasing distance to the city centre. This relationship can also be seen in both spatial settings of this model. Yet, Figure 5 shows that prices develop differently for the different spatial settings. While rents decrease by 10.5% from the city center to the suburbs in the EU setting, they only decrease by 6.5% in the US setting, where the households with a higher willingness to pay live in the suburbs.

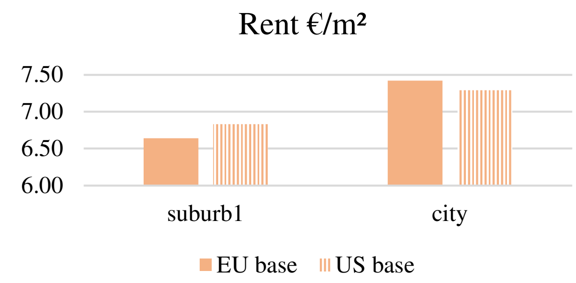

Figure 5: Rent [€/m²] for both spatial settings without UAM

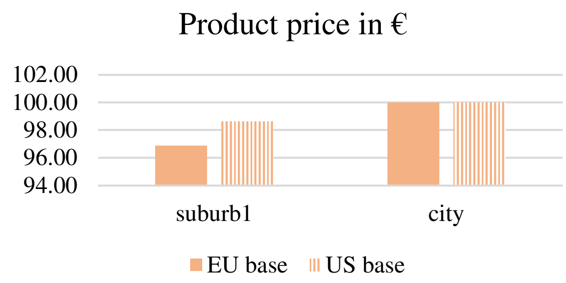

Figure 6: Product price [€] for both spatial settings without UAM (city price is numeraire)

Looking at the prices for products (Figure 6), shows that even here differences are found for the different spatial settings. For both cases, the price in the city is normalized at 100€. The zero-profit assumption helps interpret these results. In both the EU and the US case, production is cheaper in the suburbs, which leads to lower prices for goods. Yet, the stronger drop in suburban rents in the EU city also leads to lower prices.

Hourly wages for both spatial settings also differ. In general, US-type cities have higher wages for high- and low-skilled, where the only exception are wages of low-skilled in the CBD. At a first glance one might derive that workers in a US-type city are more productive than in the EU city. Yet, it has to be kept in mind that price levels also differ and the figures shown in Figure 7 and Figure 8 represent nominal wages.

For both spatial settings wages in the suburbs are higher compared to the city. Again the zero profit assumption for firms guides towards the interpretation. Hourly wages purely reflect the marginal productivity of the respective worker. The lower land rents make firms use more land per unit of labour in the suburbs, which raises the marginal productivity of labour, and hence the wage.

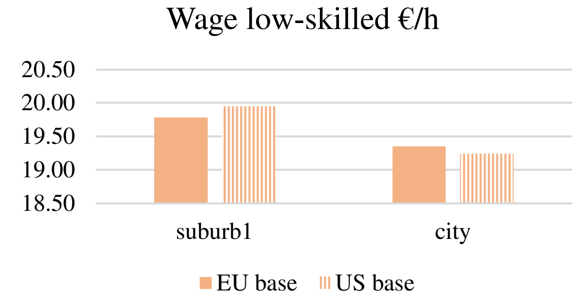

Figure 7: Wage [€/h] low-skilled workers for both spatial settings without UAM

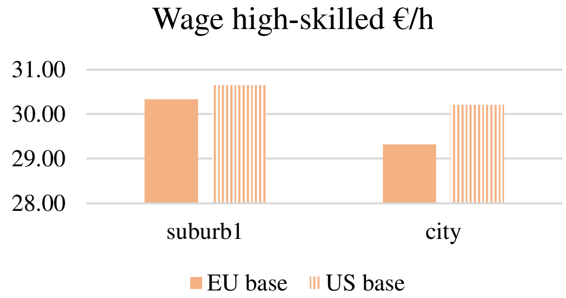

Figure 8: Wage [€/h] high-skilled workers for both spatial settings without UAM

In both spatial settings, the companies take the largest share of land per zone. Interestingly, land demand of companies is higher in the suburbs in the EU case, while it is the other way around in the US case. Land demand of high- and low-skilled follows the location patterns described above. High-skilled households always demand more land than the low-skilled in all zones. The only exception is the city centre in the US case, where in absolute values all low-skilled households living in that zone demand more land than the high-skilled living there.

5.2. Introducing UAM

After now having obtained a feeling for what the differences are in the initial setting, the next step is to look into changes after UAM introduction. The simulations at hand are (1) the scenarios with no UAM that have already been discussed in the preceding section, which are compared to (2) the UAM base case of the respective spatial setting. The pricing strategy in the UAM base case assumes marginal cost pricing. UAM users therefore have to pay 0.80€ per kilometre travelled and do not face base fares that have to be paid per trip. Besides that, UAM vehicles are assumed to travel at 150 km/h average speed and passengers to require six minutes access time and six minutes egress time. Land demand for vertiports and UAM related infrastructure is assumed to add up to 0.2% of area in each zone. At this point it is important to emphasize again that mode choice is based on overall expected utility, and not on generalized transport costs only. The choice parameters were chosen to fit location and mode choice to the best of the authors' knowledge. As UAM is a so far non-existent mode, a profound mode choice model is hard to specify (Fu et al. 2019).

Mode Choice

Table 4 shows mode choice results for the described approach. The numbers to the left show modal split on the basis of trips, while the right-hand side numbers show modal split on the basis of kilometre travelled within in the city. In the base UAM case the novel transport mode is sufficiently attractive to already attract a share of up to 16% of high-skilled households' trips and 12% of low-skilled households' trips. Differences between the different city-types are minimal, while there are quite some drastic differences between the numbers on the trip basis and on the kilometre basis.

Table 4: Modal Split of UAM

	[% of all trips]		**[% of all km]**	
	EU	**US**	**EU**	**US**
Low skilled	11.8	11.8	6.3	6.7
High skilled	16.1	16.2	12.3	12.8

These numbers hint at a relatively unexpected development. As shares decrease when going from trip basis to kilometre basis, one can derive that households tend to travel shorter distances with UAM: longer commutes, for which UAM could be expected to be relatively attractive, have less UAM demand than shorter commuting trips. Comparing shorter to longer commutes, the difference in generalized cost changes is in the advantage of UAM, but nevertheless the expected utility conditional on UAM decreases compared to car. This results directly from the non-constant marginal utilities of income and time, and because UAM is so much more expensive. Its relative loss, due to the non-constant marginal utility in money income, dominates its relative gain due to the non-constant marginal utility of (leisure) time. This remains even after accounting for re-optimization of the full consumption bundle after mode choice has been made.

Surprisingly, this effect is even stronger for low-skilled, as can be seen from the decrease in difference between high- and low-skilled households' mode choice. Yet again, when looking closer at the numbers the effect does make sense. The shorter the distance travelled the lower the willingness to pay for travel time savings has to be. E.g. relatively speaking low-skilled have a bigger interest in short trips for UAM.

Related Markets

When introducing UAM into the model two points are adapted: (1) Households get to choose between car and UAM for their commutes, and (2) additional infrastructure is needed for take-off and landing of the UAM vehicles, thus approximately 0.2% of land per zone is assumed to be used for UAM infrastructure that will also be refinanced through taxes by the public sector. This additional land demand is modest and therefore is expected to only have a negligible impact on rents in all zones over both spatial setting. Figure 9 shows that this assumption is confirmed in the numerical results. As in the preceding section, uni-coloured bars represent EU-type cities while verticals stripes indicate results for the US. The light orange bar visualizes results for the non-UAM case in this sub-section. The dark blue bars depict numbers for the UAM base case. This colour code will be used wherever applicable in the following.
For the price of products (Figure 10) only minor changes can be seen. As the price in the city is the numéraire, of course, there is no change, for the price in the EU-suburbs we see marginal drops of less than 0.1%.

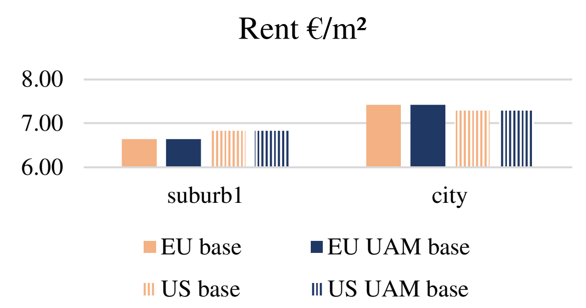

Figure 9: Rent [€/m²] for both spatial settings with and without UAM

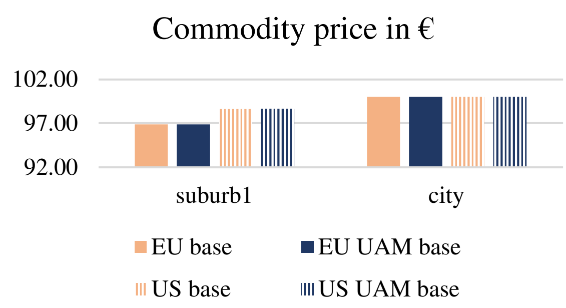

Figure 10: Commodity price [€] for both spatial settings with and without UAM (city price is numeraire)

Wages increase slightly or stay stable after UAM introduction (Figure 11 and Figure 12). Increases in wages can be seen in work locations further away from the majority of households. In the EU-setting wages thus slightly increase for low-skilled in the city centre and for high-skilled in the suburbs. For the US setting the opposite is true. This development is provoked by a decrease in labour demand due to higher commuting cost.

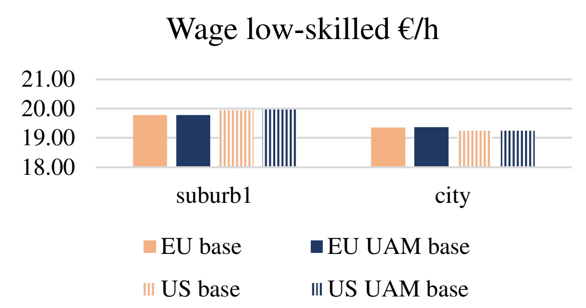

Figure 11: Wage [€/h] low-skilled workers for both spatial settings with and without UAM

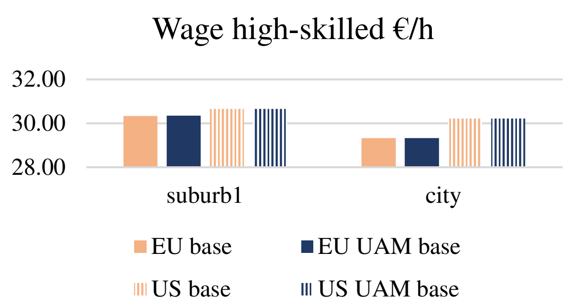

Figure 12: Wage [€/h] high-skilled workers for both spatial settings with and without UAM

As seen above the introduction of UAM does induce changes not only on the transport sector but also on related markets. In this context it is important to also assess changes in expected utility of the households with different skill level and location choice, hoping to also find indications whether some city types might benefit or suffer more from UAM becoming available than others.

The Impact on Welfare

Welfare changes are assessed using equivalent variation (EV) per home-work location pair. The measure allows to monetarize changes in expected utility (Equation (5)) through UAM introduction. The values given for EV in Figure 13 to Figure 16 show money a household of that skill type and home-work location pair would need to be paid to achieve the expected utility level that would be reached after UAM introduction for that same home-work location pair, expressed per year in €. Figure 13 and Figure 14 show results for EU-type cities. The different colours indicate different work locations of the households. Figure 15 and Figure 16 give the respective results for the US-city.

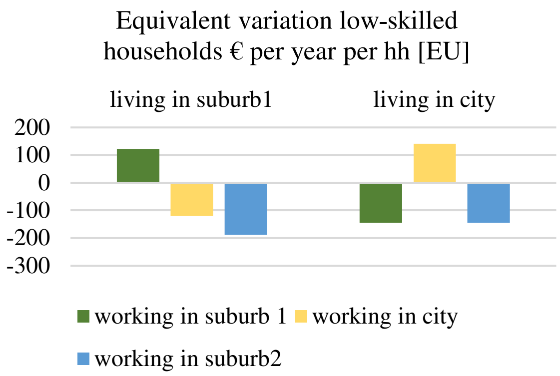

Figure 13: Equivalent variation low skilled [€/year/household] EU; comparing non UAM case with UAM case

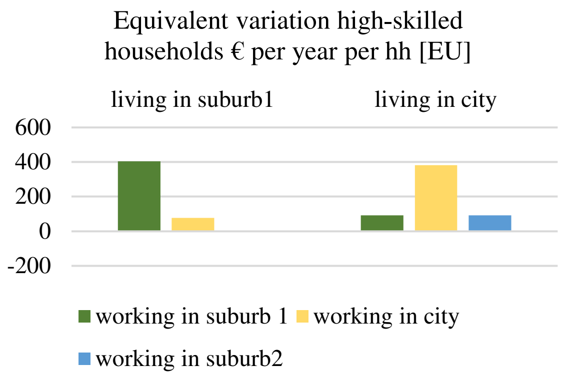

Figure 14: Equivalent variation high skilled [€/year/household] EU; comparing non UAM case with UAM case

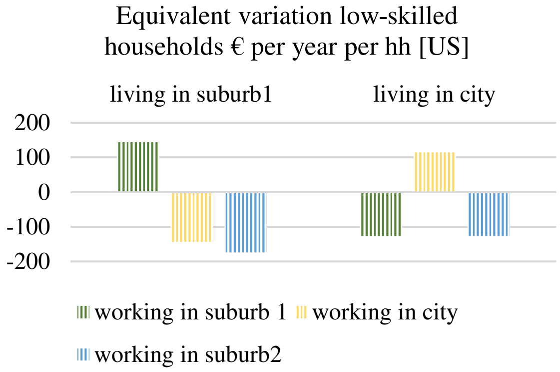

Figure 15: Equivalent variation low skilled [€/year/household] US; comparing non UAM case with UAM case

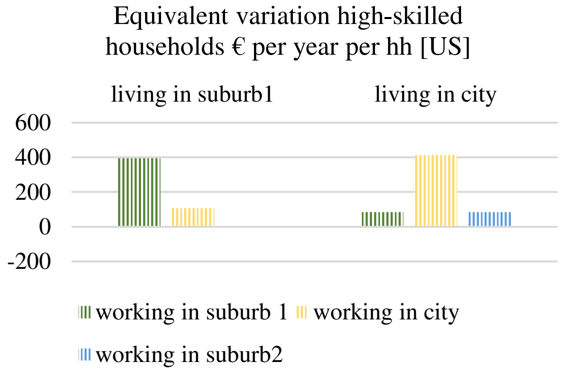

Figure 16: Equivalent variation high skilled [€/year/household] US; comparing non UAM case with UAM case

The effects of UAM introduction strongly differ between the two skill levels and home-work location pairs. The effects go in the same directions for the two initial spatial structures. Low-skilled households only benefit from UAM introduction if they use it on short routes, which again is due to the mode choice modelling. With commuting becoming more expensive the respective household has a decreasing value of time (equation (10)), which leads to less labour supply and less monetary income that can be spent on housing and products. This effect is more significant, the higher kilometre-dependent prices are, and therefore decreases modal shares on longer trips and brings modal split on a kilometre basis down. High-skilled benefit more from UAM introduction when commuting trips are short. When crossing the city for the commute high-skilled households face negligible welfare losses (less than 0.01% of annual income). On average, welfare losses for low-skilled in the EU and US setting account for 0.04% of annual income. High-skilled have an average benefit of 0.13% of annual income.

The sum of welfare losses over low- (first bar) and high-skilled (middle bar) as well as the sum over both (right bar) show that the US-type city's benefits are 0.4% higher (Figure 17). Welfare gains of high-skilled are 5 to 5.5 times higher than welfare losses of low-skilled.

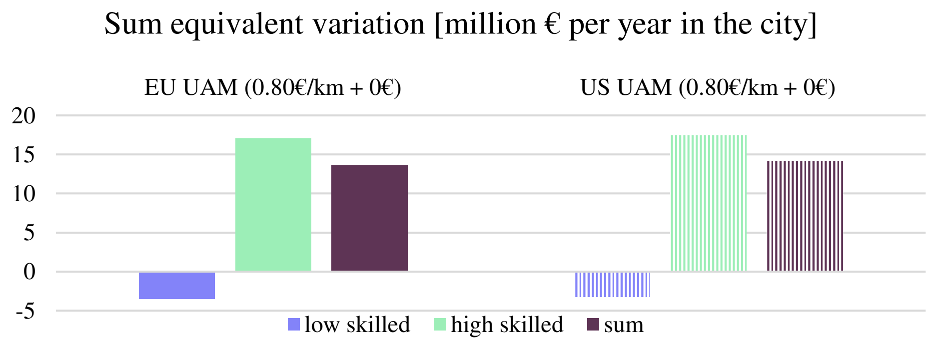

Figure 17: EV sums (per skill type and total) [million €/year]

6. Sensitivity Analysis

As mentioned above, there is still a high level of uncertainty regarding the system parameters of UAM. Varying the different parameters (prices, marginal cost, travel speed, access and egress times, required land) allows to assess the impact of each of the parameters, and how these impact the different household types (low- and high-skilled) and whether impacts differ over initial spatial structures of cities. In the following we will therefore discuss the results of a sensitivity analysis. Table 3 gives an overview over the upper and lower boundary values of the sensitivity analysis.

6.1. Mode Choice

To better understand the overall impact of the parameter variations, it is helpful to understand the impact on mode choice. Figure 18 gives, for each sensitivity analysis, the maximum arc elasticity, that relates the change in parameter to the change in modal split of UAM, when compared to the base scenario for UAM. The full set of results can be found in Appendix B.

The impacts of the different parameters substantially differ. Changes in prices and changes in marginal cost, that tantamount to increases in prices have rather strong impact. Changes in travel time induced through either changes in cruise speed or in access and egress time, in contrast have a smaller impact on modal choice in the way we model it here. Changes in land demand for UAM ground infrastructure in contrast have a negligible impact on mode choice.

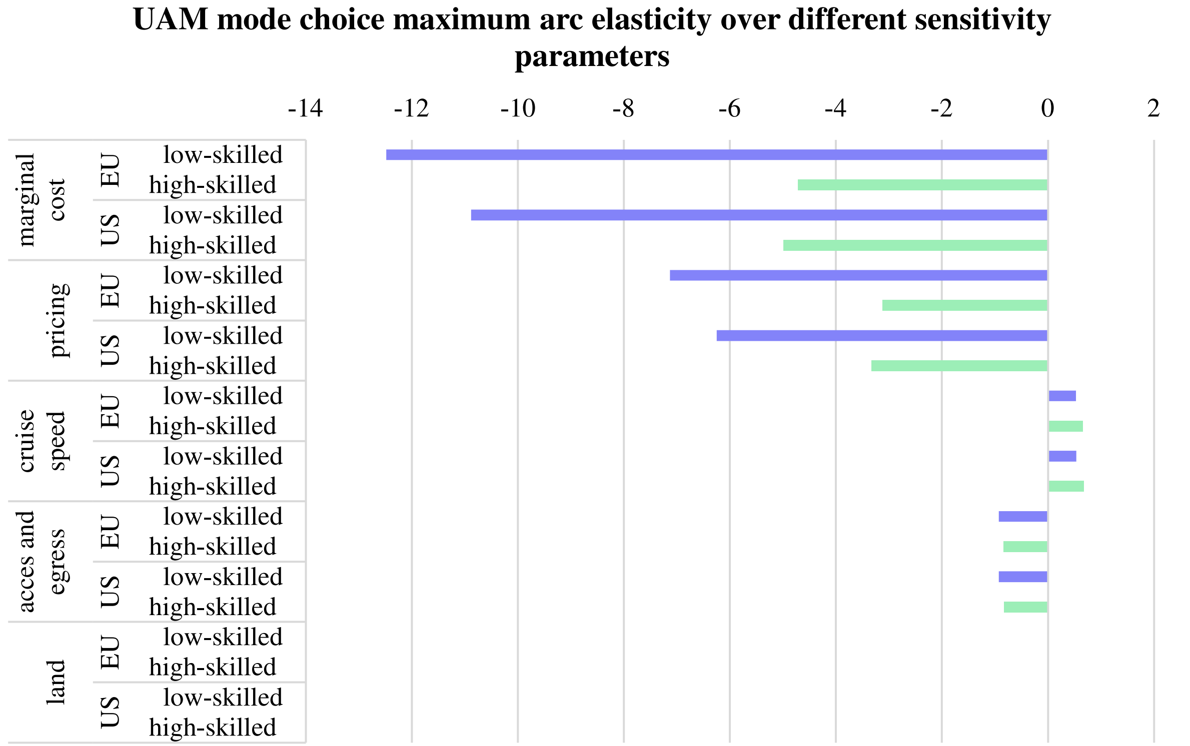

Figure 18: UAM mode choice maximum arc elasticity over different sensitivity parameters

Differences between the two city types are marginal. The main difference can be seen for marginal cost and pricing. When usage fees decrease, low skilled in the EU-setting seem to respond more strongly, while the opposite is true for high skilled.

6.2. Welfare Impact

To express the welfare changes we again use equivalent variation. As described above this measure gives the amount of money a household in the non-UAM benchmark would need to be paid, to be as well off as after UAM introduction. Figure 19 again relates the magnitude of changes in UAM parameters to magnitude of changes in EV. Thus, again arc elasticities are displayed, this time per skill level, city type and varied parameter in percent. The full set of results again can be found in the Appendix (C-G). As an important side note, we want to highlight that the UAM base scenario produces a welfare loss for low skilled and welfare gains for high-skilled due to UAM introduction. The sum of effects for both skill types is positive.

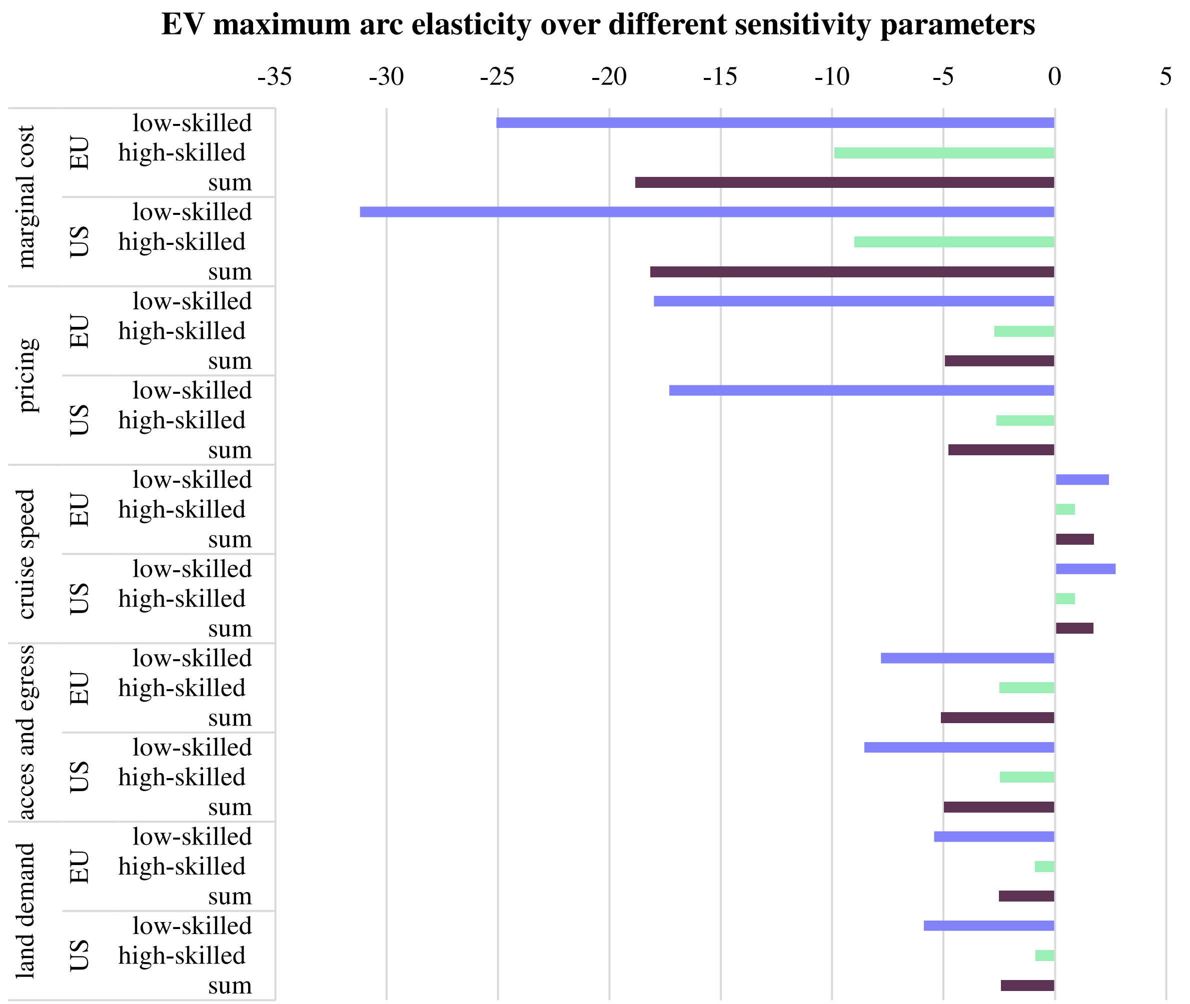

Figure 19: EV maximum arc elasticity over different sensitivity parameters

Compared to the mode choice effects, welfare changes are significantly more volatile over the different parameter settings tested, yet, the general direction of effects are similar to what can be seen for modal choice. In general low-skilled households' welfare is more severely impacted by changes than high skilled. Changes in cruise speed in general have the smallest impact. Decreasing access and egress times in contrast induces relatively high welfare gains, also for low skilled.

While mode choice was nearly unaffected by changes in land demand for vertiports, welfare impacts are stronger. This is an interesting finding, especially as the model assumes that land rents (that increase with vertiport land demand) flow back to the households. Yet, the overall effects on related markets overdraw the positive impact that increasing land rents have, and lead to overall welfare losses if UAM requires too much ground infrastructure. This suggests a need for a more detailed assessment of vertiports, their design, and throughput capacity.

The direction of effects does not differ over the two city types; yet, as the results show, slight differences occur.

When closer assessing the results for various pricing schemes, one can see that welfare results strongly differ over different skill types and pricing schemes. The strong negative impact for some pricing schemes can be explained from economic principles. Assuming marginal cost pricing for UAM means that we already assume a close to optimal pricing scheme. As road congestion is not priced, the scenario with marginal cost pricing for UAM reflects a second-best option. When deviating from marginal cost pricing also for UAM this adds an additional market distortion. In our model, when prices are below marginal cost the public sector makes losses. We assume the government to refinance these losses through the lump-sum tax. This implicitly implies subsidies for UAM that mainly benefit high-skilled, as their modal share for UAM is significantly higher.

7. Discussions and Next steps

The aim of this paper is to assess the impact of UAM introduction on low-and high-skilled households' welfare in cities with different initial spatial structures. For this purpose we develop an assessment framework based on micro-economic foundations, that allows to not only assess the impact of a novel mode of transport on the transport sector itself, but also to evaluate the impact on related markets. Applying an urban spatial general equilibrium model, we aimed at showing the welfare impact of UAM introduction on high- and low-skilled households. Assuming that fast travel speeds and high usage fees mainly attract high-skilled households, it was important to distinguish between household types in this assessment. Empirics show that around the globe the spatial distribution of households of different skill-levels vary. As UAM suggests to be more attractive for high-income households, the hypothesis was that the spatial distribution of income groups over space might have a noticeable impact on aggregate (overall) welfare effects. As USCGE models allow to also depict location choice, and have already been used to asses land-use and transport policies, applying these seemed a promising approach.

We were able to show that the amenity-based approach allowed to construct two types of cities. The so-called US-type city has low-skilled households living close to the city centre, while the EU-type cities has them living further away from the city centre. Subsequently, UAM was introduced into these cities. A comparative statics analysis, comparing the benchmark situation without UAM and the base scenario with UAM, showed that the proposed model is suitable for the assessment. In the base scenario with UAM, high-income households achieved welfare gains due to UAM introduction, while low-skilled households faces welfare losses.

Interestingly, the results show that the direction and magnitude of welfare effects do not differ between the two city-types. Minor differences on an individual level can be seen. Yet, aggregating the results shows that the differences in location choice of high- and low-skilled households over the city for both city types does have at least a minor impact on overall effects.

As UAM is not yet in place and development is still ongoing, it is hard to foresee the values for the system parameters. Therefore, a sensitivity analysis for the UAM system was performed, including changes in prices, marginal cost, vertical travel speeds, access and egress times as well as land demand for infrastructure. The results reveal that varying these parameters results in significantly different mode choice values and overall welfare effects.

Changes in marginal cost or pricing schemes had the biggest impact on mode choice and welfare. Deviations from marginal cost pricing had large negative welfare effects, mainly also due to the fact that they indirectly create subsidies for UAM and thus distort mode choice.

The impact of changes in travel time, induced either by changes in cruise speed or access and egress time, only had a minor impact on mode choice results as well as welfare effects. As the study area is relatively small, and thus travel distances are rather short, the impact of cruise speed is only minor. Yet, seeing that also changes in access and egress time do not significantly change welfare effects allows to assume that omitting congestion at vertiports might be an acceptable model simplification for now. Yet, we want to highlight that this is an important limitation of this research. Congestion for cars was modelled by applying the BPR congestion function that gives delays along routes in accordance with their capacity and demand. So for car transport congestion takes place en-route while for UAM, we would not expect to see delays en-route. Firstly this is a safety risk, and one would assume VTOL vehicles to not get take-off clearance if congestion in the air would arise. Second, we assume vertiports to be the bottleneck and not airspace. Thus, the modelling approach for congestion on roads and for UAM will differ significantly. Surprisingly, land used for UAM ground infrastructure has a significant impact on welfare while this is not true for mode choice. Literature often sees low infrastructure demand as one of the main advantages for UAM. These results shows that, as long as there is a need for infrastructure it is important to also keep negative impacts resulting from related markets in mind. So when designing vertiports and estimating possible required throughput a thorough trade-off between negative impacts of larger ground infrastructure and larger vertiports due to higher throughput are inevitable.

Despite the broad range of effects that USCGE models can incorporate, there still are several limitations to this model. For now, amenities, allowing to model US- and EU-type cities were included as exogenous container terms. When allowing for endogenous amenities and involve external effects, the magnitude of effects might differ. It is therefore necessary to expand this research and find ways to endogenously model location choice of households and companies. An additional interesting way forward is to assess the impact of asymmetric cities and polycentric set-ups. Additionally, welfare within this paper does not incorporate negative effects of UAM often put forward by literature (Reiche et al. 2018; Shaheen and Cohen 2019; Straubinger et al. 2020b). Negative aspects and barriers like noise, visual pollution or social acceptance are not covered. Yet, these aspects open up additional interesting questions. A possibility would be to include environmental effects and noise emissions of UAM into the analysis.

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APPENDIX

A. Symbol directory

$\widetilde{U}_{ijm}$	Utility of household type *ijm*
A_i	Land supply in zone *i* [m²]
$Dwork\_max_{ijm}$	Maximum possible number of work days if all time is used for working for household *ijm*
$Dwork_{ijm}$	Number of working days of household type *ijm*
$Full\_Inc\_lab_{ijm}$	Maximum possible income from labour of household type *ijm*
$Full\_Inc_{ijm}$	Maximum possible income of household type *ijm*
$Share\_Roads_i$	Share of land assigned to roads in zone *i*
$Share\_Vertiports_i$	Share of land assigned to vertiports in zone *i*
U_{ijm}	Systematic utility of household type *ijm*
VOT_{ijm}	Value of time of household type *ijm*
X_k	Output of firms produced in zone *k*
Z_{ijkm}	Products shopped in zone *k* by household type *ijm*
$c\_com\_ex_{ijm}$	Monetary costs of commuting from *i* to *j* in mode *m* flowing out of the city
c_com_{ijm}	Monetary costs of commuting from *i* to *j* in mode *m*
$c\_shop\_ex_{ik}$	Monetary costs for travelling from *i* to shopping location *k* flowing out of the city
c_shop_{ik}	Monetary costs for travelling from *i* to shopping location *k*
inU_{ijm}	Indirect utility of household type *ijm*
$labor\_high_j$	Demand for high-skilled workers of companies in zone *j*
$labor\_low_j$	Demand for low-skilled workers of companies in zone *j*
$land_i$	Land demand of companies in zone *i*
l_{ijm}	Leisure time household type *ijm*
q_{ijm}	Land demand household type *ijm*
r_i	Land rent in zone *i*
t_com_{ijm}	Time required for commuting from *i* to *j* with mode *m*
t_shop_{ik}	Time required for travelling from *i* to shopping location *k*
w_high_j	Wage of high-skilled workers in zone *j*
w_low_j	Wage of low-skilled workers in zone *j*
Γ_{ij}	Expected utility for nest *ij*
Ψ_{ijm}	Choice probability for home work location pair *ij* and usage of mode *m*
ε_{ijm}	Idiosyncratic utility household type *ijm*
λ_{idio}	Measure for the importance of systematic utility and idiosyncratic preferences
λ_{mode}	Measure for correlation between nests
π_{ijm}	Price of products including travel costs of household type *ijm* (consumer price)
τ^{gas}	Gasoline tax revenues
τ^{ls}	Lump-sum tax
τ^{w}	Labour tax
$agglo$	Parameter to calibrate the size of agglomeration effects
CBD	Central business district
CES	Constant elasticity of substitution
EV	Equivalent variation
$Hwork$	Number of working hours per day

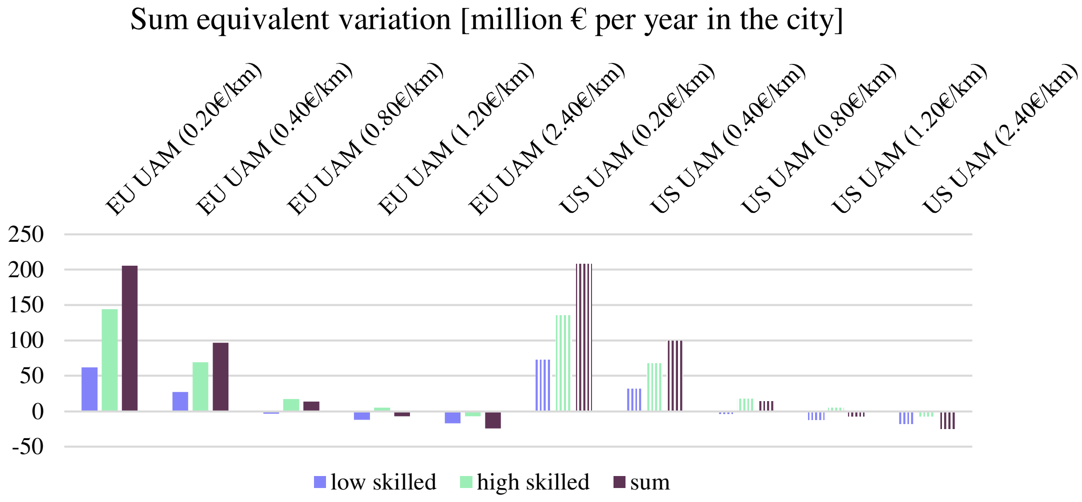
i	Zone in which the household lives
j	Zone in which the household works
k	Zone in which the household shops
m	Mode the household type uses for commuting purposes
MNL	Multinomial logit model
N	Number of households in the city
R	Income from land rents per households
TE	Total time endowment
UAM	Urban air mobility
USCGE	Urban spatial computable general equilibrium model
σ	Expenditure share products
φ	Expenditure share housing
ω	Expenditure share leisure time
o	Measure for substitutability between land and labour
s	Measure for substitutability between low and high-skilled labour
δ	Share parameter of the productivity function (land)
η	Factor accounting for the love for variety regarding products
μ	Share parameter of the productivity function (low-skilled labour)

B. *Modal Split of UAM [% of km] in the Sensitivity Analysis*

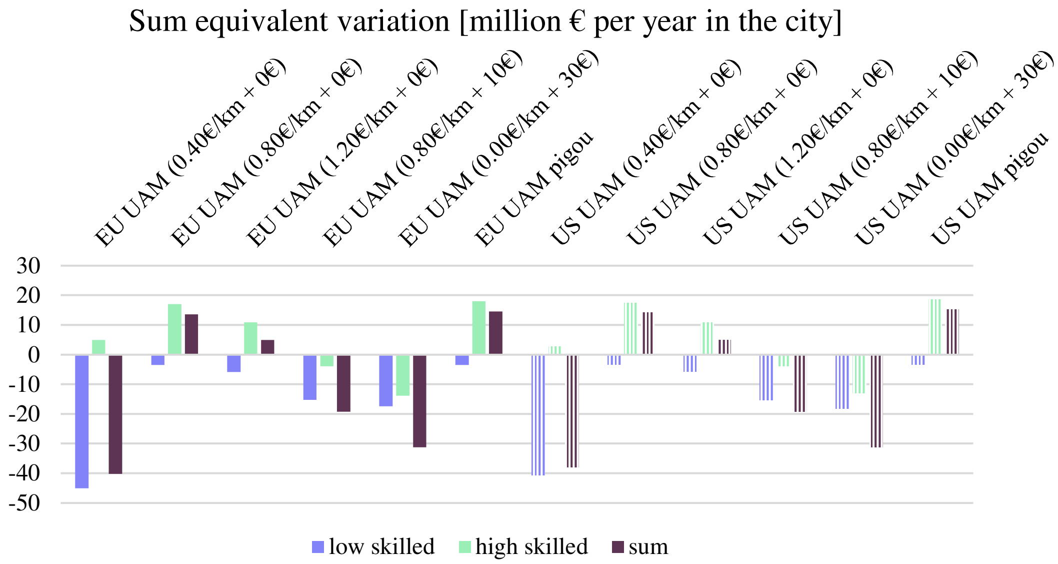
	Low-skilled		High-skilled	
	EU	US	EU	US
Marginal Cost Variation				
0.20€/km	64.77	61.38	55.88	58.15
0.40€/km	35.91	43.56	37.91	39.38
0.80€/km	6.25	6.70	12.31	12.25
1.20€/km	2.15	2.28	4.58	4.44
2.40€/km	0.54	0.55	1.07	1.06
Price Variation				
0.40€/km + 0€	35.97	34.61	37.99	39.47
0.80€/km + 0€	6.25	6.70	12.31	12.25
1.20€/km + 0€	2.16	2.28	4.59	4.44
0.80€/km 10€	0.25	0.29	1.90	1.96
0.00€/km + 30€	0.15	0.13	1.25	1.54
Cruise Speed Variation				
50km/h	4.04	4.30	6.90	6.72
100km/	5.55	5.94	10.54	10.42
150km/h	6.25	6.70	12.31	12.25
200km/h	6.64	7.13	13.34	13.32
300km/h	7.08	7.60	14.48	14.52

Access and Egress Time Variation				
0.00h	12.02	12.90	22.71	22.46
0.05h	8.68	9.31	16.81	16.68
0.10h	6.25	6.70	12.31	12.25
0.15h	4.54	4.84	9.00	8.99
0.20h	3.30	3.53	6.62	6.63

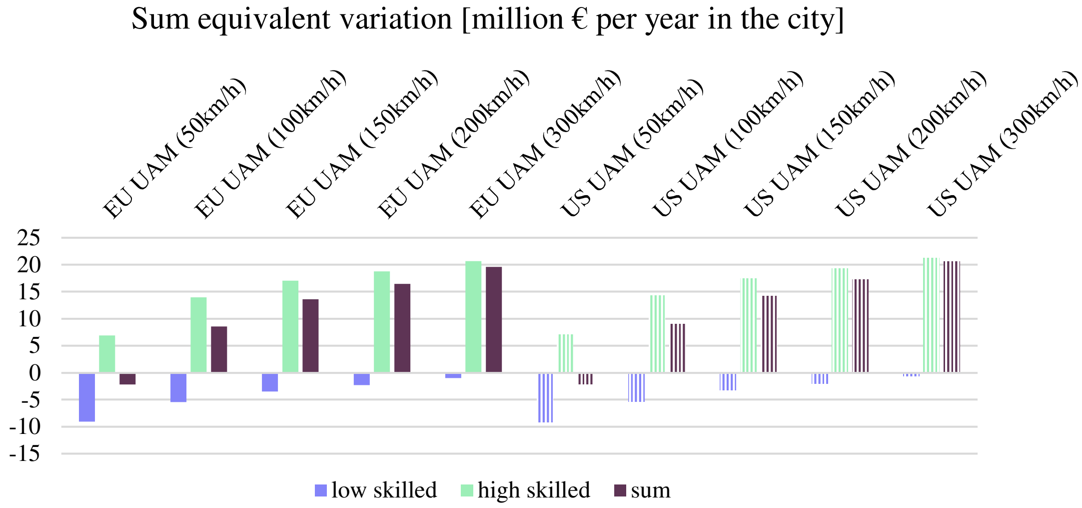
C. EV sums (per skill type and total) [million €/year] for varying marginal cost



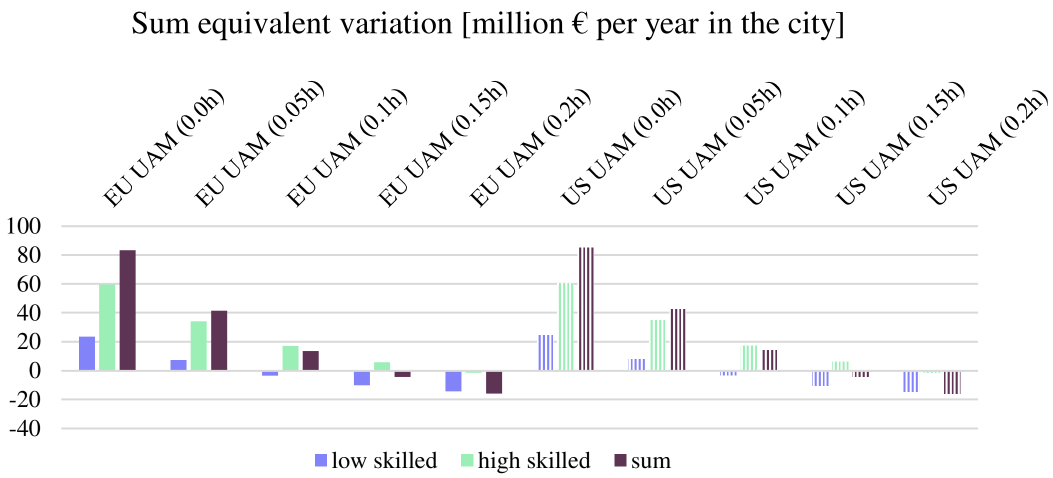
D. EV sums (per skill type and total) [million €/year] for varying prcing schemes



E. EV sums (per skill type and total) [million €/year] for varying cruising speeds



F. EV sums (per skill type and total) [million €/year] for varying access and egress times



G. EV sums (per skill type and total) [million €/year] for varying vertiport land demand