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Applications of Quantitative Spatial Models in Spatial and Urban Planning

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Abstract

In the three chapters of this thesis I analyse issues related to spatial and urban planning in the context of the Czech Republic. Besides standard reduced-form methods, I employ quantitative spatial models that are gradually more commonly used in the urban and regional economic research. First, quantitative spatial models allow to circumvent problem of not observing some data, and second, to study second-order general equilibrium adjustment effects that cannot be captured within reduced-form empirical methods.

In the first chapter I estimate agglomeration wage economies across the country. As wage data at a sufficiently detailed geographical level are not available, I have used a quantitative spatial model to infer them from commuting patterns. In the second stage, I then estimated the effect of labour market size and density of employment on wages. Labour-market level wage elasticity of 0.07 is somewhat larger, but comparable with existing literature. Additionally, I show agglomeration economies are rising with level of education achieved.

The second chapter analyses housing construction constraints caused by spatial planning and building permitting processes. First, I show reduced-form evidence indicates that an increase in stringency of these two types of policies decreases new construction. Second, I embed a realistic housing production function into an existing quantitative spatial model framework and calibrate it on data from 1991 to 2011 to predict counterfactual scenarios. Realistic relaxation of policies could increase households' indirect utility by up to 4%.

In the third chapter I investigate effects of noise on open green spaces amenity value in the city of Prague. To control for unobserved quality of greenery I use a quantitative spatial model to back-out their quality using survey data of places used for recreation. The results show noise decreases value of greenery, but only if accessible greenery is spatially concentrated.

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1 Introduction

This thesis contains three core chapters focusing on topics related to urban and spatial planning and employs urban economics methods, in particular quantitative spatial models. All three chapters also do have in common their geographical focus on the Czech Republic. While the first two chapters analyse agglomeration economies and effects of spatial planning regulation on a national level, the third chapter focuses on amenity value of green open spaces in interaction with noise in the capital city of Prague.

This introductory chapter provides wider context for the three following core chapters. First, relationship between urban planning and urban economics is discussed with a particular emphasis on urban economics methods that could enrich practical urban planning. Second, history of urban economic models is briefly introduced with an attention to recent development of quantitative spatial models. Third, the context of ongoing urban and regional development debate in the Czech Republic is shortly presented to frame motivation for selecting the studied topics.

1.1 Urban economics and urban planning

At the first sight it might seem that urban economics and urban planning are somewhat related disciplines as both of them are concerned with how cities work, ultimately both of them sharing the word 'urban' in their names. In fact, differences between the two are staggering. They do differ in terms of their history, objectives, methods used and professional communities.

Urban economics[2] is a rather young field that has formed around the middle of the 20th century and it has its roots in applied microeconomics with its rich mathematical theoretical foundations that are used as a framework for applied econometric analysis of real world data. Most of practitioners in urban economics are within the academic sector and even the professional organisation Urban Economics Association in its stated mission writes the association "... seeks to promote participation and excellence in academic research in urban and regional economics" explicitly targeting academic audience only.

Conversely to that, urban planning has been a long established profession ultimately dating back to the first formation of more complex human settlements which required some form of coordination. Urban planning is both academic and applied discipline, but it seems it remains very practically oriented in both of the two forms. (Bertaud, 2018, p. 2) even calls planning "... a craft learned through practice". It utilises techniques from other fields such as geography, engineering, social sciences and arts. Actual practical planning is then largely dependent on a local institutional context which itself defines what are goals, tools and methods of planning.

[2] Or the "New urban economics" as it is called by Arnott (2011)

Key difference is however in the objectives of the two disciplines. Whereas urban economics is mostly interested in understanding how cities do work, and specifically with respect to planning how they are affected by various planning policies, objectives of urban planning are instead much broader ranging from analysing cities, setting their development goals, designing public policies to achieve these goals and finally evaluating implemented policies. The difference is therefore between analytical-descriptive approach of urban economics and interventional approach of urban planning.

However, it is not true the two disciplines cannot cooperate. Already back at the beginning of 20th century Geddes (1915) defined analysis as an integral part of urban planning. Specifically, he listed physical geography, historical development, position in the city system and social conditions. If we see urban planning nowadays as a circular process starting with an analysis, proceeding to a plan drafting, then to a plan implementation and concluding the process with an evaluation which enriches analyses in the next iteration, natural place where urban economics could step in is at the beginning and at the end in analytical and evaluation phases.

At the beginning, urban economics could provide general framework of how neighbourhoods, cities and city systems work and how they are interlinked. Such a framework could be accompanied with analyses from many other disciplines relevant for planning. Eventually, mechanisms how cities work should be understood in the first place before policies intended to regulate them are implemented. Otherwise even well intended policies might trigger a sequence of unintended consequences. Second, measuring effects of actual policies is typically not straight-forward, but urban economics, relying heavily on econometrics and causal inference, provides a tool kit of rigorous techniques to to tackle this to evaluate policies that have been already implemented and to estimate what true effects of these policies are.

Calling for cooperation

Although use of urban economics tools in analytical and evaluation stages of urban planning might seem natural, it is actually rather rare. This has been noticed by both planners and urban economists.

For instance Bertaud (2018), a planner arguing for the necessity to understand how markets shape cities, admits planners distort markets with their regulations despite knowing little about how markets actually work and they rarely invite economists to cooperate. Although being a planner himself, he recognizes importance of understanding underlying economic forces shaping cities to propose policies which would efficiently deliver what they were designed for.

One attempt to bridge the gap between the two disciplines was publication of The Oxford Handbook of Urban Economics and Planning (Brooks et al.,

2011) bringing together scholars from the both fields with intention to inform mutually an audience from the two disciplines about an up-to-date research in this interdisciplinary environment. Although the collection is very informative for researchers in academia, it is hard to say whether it had or will have an impact on practical urban planning.

There are voices calling for tighter cooperation between planners and urban economists also from the economists' side. For instance, Jan Bruckner has expressed this opinion during the Land Use session at the Urban Economics Association meeting in Washington, DC, in 2022 arguing similarly as Bertaud (2018) that involvement of urban economists in urban planning would improve policy making.

While there might exist demand on planners' side for more urban economics insights in planning, the question is whether current development of urban economics as a research field reflects it. Henry Overman raised this as a question when addressing the keynote speaker Gilles Duranton during his lecture at the European Meeting of Urban Economics Association in 2023 in Milan. In particular, he seemed to express a worry that recent development of urban economics has diverted from policy relevant topics rather toward topics more appealing to the academic research community.

It could be however also said urban economics has made a significant progress over the past two decades to bring theory closer to observed real world data with introduction of quantitative (general equilibrium) spatial models as it has been shown in Ahlfeldt et al. (2015) and now building on this already canonical model. One factor which has limited wider adoption of urban economics models in planning until these days has been over-simplification of reality in these models. Their abstract comparative statics results have not provided sufficient guidance for real world planning operating on a very local level and within much more complex network of stakeholders typically omitted in economic models. (Brooks, 2011, p. 16) writes: "Planners would benefit from economists focusing more on models that are more realistic reflections of the situations where they operate". As it will be discussed later, the new class of quantitative spatial models is well suited to do so. First, these models are able to model cities or regions on a very detailed level. Second, they allow to extend the framework to take into account various stakeholders or policies, and third, they allow to run general equilibrium counterfactuals to test expected outcomes of various policy regimes.

Persistent regulation under perpetual change

Urban planning regulation should be scrutinized from time to time to assess whether it still leads to fulfilment of its intended goals. Zoning, density caps and other forms of regulation are often times long lasting and motivation behind their original imposition could be more or less forgotten or economic conditions change to such an extent the regulation does not achieve any more what it was designed for.

Bertaud (2018) illustrates it with an example of minimum size of apartments and maximum number of units within a block in New York City. Condition of apartments there at the end of 19th century was inadequate and called for some action: "... the late nineteenth century [New York] tenement building suffered from many problems. The rooms were cramped; they provided little light and air; and buildings lacked running water. A privy would be provided in the back, but it was shared by many, many people" (Barr, 2016, p. 128).

The Tenement House Act has been passed in 1879 requiring minimum size of an apartment at 26.7 square metres. Original intention was to face overcrowding as family sizes at that time were large and more spacious apartments were thought to resolve the issue[3]. Over time the minimum size of an apartment in NYC has grown up to 37.2 square metres in 1987 despite significant changes in households' structure, size and resulting demand for housing. Bertaud (2018) mentions there were 38% of households formed of individuals or unrelated persons in 2015 leading to substantial demand for smaller housing units. Indeed, when construction of some units ranging in size from 24 to 33 square metres was exceptionally allowed, they became huge success confirming there was pent-up demand for small, but well located units.

Another type of frequently used regulation is a minimum distance between individual buildings or their technical standards. Motivation for such regulation could be driven by fire protection considerations: "Building code requirements arose from the perception that given close proximity, an easily combustible building endangered neighbouring properties" (Tabb and Sawers, 1984, p. 380).

Crowding and high densities were addressed by another policies also on the building-level. As Engels (2009)[1845] has noted, provision of direct sunlight or ventilation in densely developed 19th century districts was poor: "These streets [in Edinburgh] are often so narrow that a person can step from the window of one house into that of its opposite neighbour ... the light can scarcely penetrate into the court or alley that lies between" (p. 48).

While the original idea of requiring some minimal standard for streets' width or buildings' set backs seems reasonable, the regulation in some instances has evolved into absurd and hardly justifiable form. For instance, new residential buildings built in the Czech Republic have to comply with following requirement regarding direct sunlight: On the 1st March, at least one room has to receive direct sunlight of the width at least 200mm entering through a window at an angle no less than 25 degrees with respect to the window plane for at least 90 minutes (According to the binding standard CSN EN 17037, Kanka, 2022).

[3]However, as Barr (2016) points out, restricting new supply of small units ultimately led to price growth of existing small units, rather harming than helping targeted households

Minimal distance between buildings in the UK is a rather simple rule, but it is said to have a quite peculiar origin. "The 21-metre rule is, according to the Stirling prize-winning architect Annalie Riches, a bizarre hangover from 1902, originally intended to protect the modesty of Edwardian women. The urban designers Raymond Unwin and Barry Parker walked apart in a field until they could no longer see each other's nipples through their shirts. The two men measured the distance between them to be 70ft (21 metres), and this became the distance that is still used today, 120 years later, to dictate how far apart many British homes should be built" (Harper, 2022). Whereas this requirement could had been appropriate for a given neighbourhood design in a given time period, it does not seem likely it would fit all urban and suburban contexts or would persist unchanged over time.

Planning on a city-wide level has become widespread during the 20th century. In the US, the so called Euclidean (functional) zoning [4] became common practice in the late 1920's and later. Objectives of these plans were to protect property values by excluding nuisances from residential areas, as well as to promote public health and morals (Wolf, 2008).

Although the modernist movement in Europe came out with similar proposals to functionally zone cities and generally increase environmental quality of residential neighbourhoods, modernists' approach to city planning was instead driven by artistic beliefs and intuition instead of by economic reasoning (see Le Corbusier and Eardley, 1973). While arguments behind zoning in the US and in Europe did differ, the planning instrument of zoning was answer to problems of the industrial city of the late 19th century. Whereas economic circumstances have changed since then, zoning remained.

Even proposals by Alexander et al. (1977), who are otherwise very critical about modernists' planning, are in some respects not economically sound. For instance they call the post-war US urbanisation bringing population from rural areas to cities as 'forced migration'. They do not take into account changes in the economy and instead they call for a policy response either in a form of subsidies for firms in smaller towns, zoning and city growth boundaries or provision of public services.

Development in the UK was specific with its early adoption of city growth boundaries in a form of designated green belt areas. After experiencing massive suburbanisation in the first decades of the 20th century, planners started considering policies to contain urban growth and proposed creating undevelopable belts around large cities (Hall and Tewdwr-Jones, 2020) which started to be implemented between 1930's and 1950's (Mace et al., 2016). Their purpose has been "... to check the unrestricted sprawl of large built-up areas; to prevent neighbouring towns from merging into one another; to assist in safeguarding the countryside from encroachment to preserve the setting and

[4] Named after the case law Euclid vs. Ambler in which the US Supreme court upheld the zoning plan enacted by the city of Euclid. For more information see Wolf (2008).

special character of historic towns; and to assist in urban regeneration, by encouraging the recycling of derelict and other urban land" (Barker, 2006, p. 158). At the beginning of the 2000s, UK green belts covered 12.9% of overall land, roughly 50% more than actually developed land with is share of 8.3% (Barker, 2006). Similar to examples of regulation discussed earlier, green belts were designed long ago to address problems prevalent at time of their design. However, the economy has significantly changed since then and it should be assessed whether these policies are still welfare improving.

The aim of this section was to present several examples of regulation instruments designed in the past which were however not challenged since then despite major changes happening in economy. Positive welfare effect of some of these regulation policies is controversial at best. The core of the problem is related to understanding of planning, and physical planning in particular. Especially the continental tradition of urban planning was mostly concerned about the most durable aspects of cities, such as streets' and public spaces' layouts[5]. These aspects of cities could be indeed thought eternal and once designed they need not be questioned. However, the tools of planning have changed significantly over the course of the twentieth century, changing from designing public spaces and developable plots to large-scale functional zoning, definition of developable land and regulation of maximum developable densities. From an economics perspective, the variables shaping land use dynamically change over time and if land use is subject to some regulation, the regulation should respond to changes in economy (As Bertaud (2018) argues). However, the question is whether planners do acknowledge this distinct nature of the new tools they have adopted when comparing them to the older tools used before.

1.2 Urban economics models

Quantitative spatial models are a tool with which we can tackle some pervasive problems in analysing urban and regional economies for the purpose of analysis, design and evaluation of public policies. Problems these models can tackle are lack of sufficiently detailed observed data, if variables of interest are observable at all, and then ability to predict effects of policies including general equilibrium adjustments of economy. This class of models could be seen as a recent next step in building economic theory of city structure and city systems and interactions within them.

Urban models development

As the first forerunner of spatial economics and urban economics models is considered Johann-Heinrich von Thünen who formulated the theory of the

[5] Well documented for instance in Sitte (1979)[1889] with recommendations how to design new city districts.

agricultural land use dependent on a land rent, which is itself a function of a distance to the market. He assumed commodity prices being set on the market, with commodities having different transportation costs relative to their value. This leads to formation of concentric land use rings with products costly to transport being cultivated close to the market city and products cheapest to transport cultivated furthest away from the market. Also the outer boundary of the market city influence is defined at the distance where labour and capital costs of producing crops plus its transport costs to the market equal crops' market price so the resulting land rent is zero. Anywhere further away land rent would be negative and therefore it does not pay off to cultivate it there. Thünen's insights are genuine, as he departed from classical English economic theory which assumed that compensating differentials are driven by soil quality. Instead, Thünen assumed soil of uniform quality and compensating differentials being driven by proximity of land to the local market (Ponsard, 1983). In exactly the same way were designed the first urban economics models of internal city structure at the beginning of 1960's.

The key contribution to the urban economics literature and establishing the field was formulation of the monocentric city model and its further refinement by Alonso (1964), Mills (1967, 1972) and Muth (1969). The whole framework has been summarised by Brueckner (1987) who I follow in the following brief introduction.

The monocentric city model (in its more elaborate version) is a within-city general equilibrium model featuring workers and real estate developers. By assumption, all jobs are concentrated in the city centre where all workers commute at commuting costs which are a function of distance from workers' residences to the city centre (also called central business district, or CBD). Within this setting, decreasing density, decreasing housing prices and decreasing land prices endogenously arise in the model. By assumption, all workers have the same preferences and the same income from employment. To maintain equilibrium, all workers have to be indifferent of how far from the CBD they live. From that follows, as commuting is costly, housing and land prices have to decline with distance from the CBD to compensate for longer commutes. Distance of the urban fringe from the CBD also results endogenously from the model. All land is assumed to have some value given by its agricultural productivity. However, if land in a given location is close enough to the CBD, its value in urban use is higher and it is developed. This is analogous result to the one in Thünen. Land itself in Mills (1967, 1972) and Muth (1969) is an intermediate input along with capital in developers' production function producing housing units. Whereas price of capital is constant across city, price of land grows towards the CBD and developers would substitute it with more capital (meaning they would build taller buildings) as distance to the CBD decreases.

The monocentric city model was later numerously extended, but with respect to the topic of this thesis it worth to mention inclusion of spatial planning regulation. Fujita (1989) has shown in a closed city model that imposing a city growth boundary when demand for housing grows leads to higher land and real estate prices, as well as to decrease of welfare under a condition the unregulated case is in a competitive equilibrium without market failures.

Bertaud and Brueckner (2005) instead analyse effects of imposing uniform maximum height regulation in a closed city model. As the height is in a standard model endogenously decreasing from the city centre, the regulation is binding only in the inner part of a city. The result are higher real estate and property prices everywhere and larger city footprint. Because utility of workers is equalized across city and in both regulated and unregulated cities marginal workers at the city fringe pay the same housing rent equal to the construction costs of housing units, the only difference between the two scenarios is length of commuting. Longer commute in the regulated scenario therefore reveal lower utility compared to the unregulated case.

However, both Fujita (1989) and Bertaud and Brueckner (2005) are within-city models which do not assume adjustment of city population when utility in a city changes due to a change in spatial planning regulation. In their models population is perfectly immobile and fixed in place. On the other hand, if population is perfectly mobile and the size of a city is marginal relative to the outer economy, any change in utility in a city would be immediately equalized by immigration or outmigration to equalize utility across space. Therefore regulation in one city would have no effect on utility of workers whatsoever, unless a change in regulation is done everywhere. As the real world population is imperfectly mobile, somewhere in between of perfect mobility and perfect immobility, implications of comparative statics for utility and rents in Fujita (1989) and Bertaud and Brueckner (2005) are upper bounds, ultimately depending on population mobility.

The key assumption in the monocentric city model is the assumption of all jobs being located in the CBD. This core assumption has been relaxed by Lucas and Rossi-Hansberg (2002) who let job locations arise endogenously in their model of a symmetric circular city[6]. They assume a city embedded in a larger economy with exogenously given reservation utility level. Identical workers have preferences over consumption good and residential land. Firms produce consumption good with labour and land input and local productivity is a function of proximity to other jobs and exponentially decreases with distance. A Cost of commuting is assumed to be a time cost which decreases amount of labour supplied to firms. Their results support multiple possible equilibrium land uses. If costs of commuting are high, employment will lo-

[6]Earlier attempts of relaxing the assumption of exogenously given employment locations include Fujita and Ogawa (1982) who modelled a linear city with endogenous employment locations.

cate close to workers' residences. As commuting costs decrease, workplaces will start to cluster to gain advantage from agglomeration economies. In the extreme, very low commuting costs would lead to the monocentric city model with employment concentrated in the city centre. Agglomeration productivity decay parameter affects the equilibrium land use as well. The faster agglomeration economies dissipate across space, the more densely firms cluster together.

Different stream of literature has looked at the system of cities rather than internal structure of one city. Henderson (1974) developed a model of optimal city size that is endogenously determined by centripetal agglomeration productivity force and centrifugal congestion force. Cities in his model are located on a featureless plane and populated by identical workers. Important for predictions of the model, he assumes two options how capital is owned, either by an absentee owner, or by workers. He derives that a sufficient condition for workers' utility to be concave with respect to city size is share of land in production (the congestion force) has to be larger than agglomeration productivity elasticity. When number of cities in the economy is very large, equilibrium city size in case of workers owning capital will be such that utility from labour and capital is maximised. However, in case of absentee atomistic capital owners, workers do prefer to locate in smaller cities and resulting equilibrium will not be Pareto efficient.

Whereas Henderson (1974) has shown in his model how agglomeration of economic activity could endogenously arise in a featureless space such that equilibrium city size would be neither autarchy, nor concentration of all activity in a single point, but somewhere in between, Roback (1982) instead studied system of cities with heterogeneity in exogenous productive and residential amenities. She assumed perfectly mobile firms and identical workers who in equilibrium have to produce goods at the same costs and achieve the same level of utility. In a wage-rent space, firms can competitively operate either at high wages and low rents or vice versa. If local city provides higher productive amenities, firms increase productivity and at the fixed level of rents could pay higher wages. On the other side, workers are indifferent if higher rents are offset by higher wages. If a city has higher residential amenities, then workers at the fixed level of wages are willing to pay higher rents because they have access to desirable amenities. This leads to endogenous formation of wage-rents equilibria across cities in the economy. Roback (1982) concludes the effect of amenities is not fully capitalised into land values as part of the effect is captured by wage differentials.

The latest major methodological progress in urban economics models was an introduction of quantitative spatial models that are described in more detail in the following section. These models essentially integrate all features of previous urban economic models. They reproduce observed urban gradients, allow for endogenous concentration of economic activity and housing and take into account exogenous productive and residential amenities that do differ across space. On top of that, they could be extended to cover broader space and rationalize city systems.

Quantitative spatial models

Quantitative spatial models used in urban setting rapidly gained popularity since publication of the path-breaking article 'The economics of density: Evidence from the Berlin Wall' (Ahlfeldt et al., 2015). According to the Google scholar, as of April 2023, the article has been cited already almost 900 times with the number of citations increasing gradually every year.

Unlike older urban models treating space as a single continuous variable (Brueckner, 1987) or in two continuous dimensions (Lucas and Rossi-Hansberg, 2002), quantitative spatial models are based on discrete locations that easily brings them to the real world heterogeneous geography and observed data. Redding and Rossi-Hansberg (2017) argue earlier models with continuous space or few discrete locations cannot be easily translated into empirical specifications and as a result past empirical research was predominantly done in reduced-form. Inability to estimate structural parameters invariant to policy changes made these models subject to Lucas' critique. Lucas (1976) analysed the problem when reduced-form estimates are used for predicting responses to policy shocks. Such predictions are however likely biased, as these estimates do not take into account agents' optimization and adjustments to new economic conditions caused by the policy shock. As quantitative spatial models explicitly model agents' behaviour and rely on structural parameters invariant to policy shocks, they can be used to simulate counterfactual scenarios taking into account general equilibrium adjustments in the economy.

Earlier urban economics models focused either on the internal city structure, or the system of cities without any internal structure. These two approaches are mimicked by quantitative spatial models. Some do focus on a single city embedded within the wider economy allowing for city-region migration (for instance Ahlfeldt et al., 2015; Heblich et al., 2020), or are isolated from the rest of the economy not allowing for migration (for example Zárate, 2022). In these models individual locations are city blocks or some other small local units which are all connected by workers' commutes.

Another applications are on regional or metropolitan level, where individual units are states, metropolitan areas or commuting zones so they are self-contained economies in terms of places of residences and places of work and assuming there is no between-locations commuting. In these models individual locations are integrated through migration (such as in Diamond (2016); Bryan and Morten (2019)) which is of main interest, although other markets, such as goods trade, could be studied in these models as well.

Model in Monte et al. (2018) integrates both single-city and regional approaches. Its spatial units are US counties which are integrated by workers' commuting and goods trade[7]. They also include migration in a form of imperfect mobility as workers do have idiosyncratic preferences for workplaces and places of residence and therefore they inelastically respond with migration to changes of utility across space.

The framework of these models also allows their extension to incorporate additional markets or policies that could be of interest to planners. Redding (2023) lists ten such extensions. Among them are for instance heterogeneity of groups of workers, presence of purely local goods, multiple traded goods with non-zero trade costs, inclusion of zoning regulation or local development programs, or endogenous congestion.

Quantitative spatial models could be also very useful in contexts where key data are missing, such as data on wages or rents. Sturm et al. (2023) show in a case of Dhaka how they can fully specify the model using only mobile phone location data, travel times from Google and satellite-based data of building heights. Using the model, they estimate property prices and to show applicability of the model they run counterfactuals with decreased commuting costs and increased building density. It worth to point out all the three datasets used to calibrate the model are nowadays technically available for the whole world so the analysis could be reproduced for any city.

Data limitations are not only the developing countries' problem. For instance wages are notoriously not available at fine geographical level in the Czech Republic which limits urban research otherwise common in other countries. When discussing why there have not been any attempts of employing quantitative modelling techniques in spatial planning in the Czech Republic, Vorel (2015) indeed names missing detailed data as the biggest problem.

1.3 Applications in the context of the Czech Republic

The aim of this thesis is twofold. First, to address topics in urban economics related to spatial and urban planning that haven't been studied so far or for which literature is limited, and second, to show how tools of urban economic analysis could be employed in urban planning specifically focusing on the case of the Czech Republic where economic reasoning in urban planning and its evaluation is still scarce. This section is therefore intended to provide more detailed context on why the three chapters in this thesis are related to and relevant for the Czech spatial planning.

[7] In the trade literature there are models following Eaton and Kortum (2002), from which contemporary quantitative spatial models departed, considering goods flows only and omitting migration and commuting. Conversely, urban and regional models do not assume population is fixed in place and therefore population mobility should be captured in these models

Agglomeration economies

In general, understanding of agglomeration economies in the Czech Republic is rather poor and lack of it is obvious in media, public debate, policy making, legislative process and subsequent court decisions. Up to date there is not to my knowledge a single article analysing agglomeration economies in the Czech Republic. This is very likely caused by the fact that information about wages are not collected for analytical and research purposes on sufficiently detailed level[8]. The two following examples illustrate it quite well: the first one focuses on a national strategy regarding spatial development and actual policies proposed by members of government, and the second one describes court proceedings regarding lawfulness of spatial variation in wages.

The EU has been for long concerned with imbalanced regional development and increasing core-periphery divide. Recently, the key principles of the EU approach to spatial policies have been formulated in the European Spatial Development Perspective (ESDP) with the central concepts of polycentricity and decentralized concentration. The later planning approach comes from the Dutch planning which aim was to avoid over-concentration and congestion in large cities by designing clusters of employment centres surrounded by residential areas tightly linked by transport infrastructure (Hall and Tewdwr-Jones, 2020).

However, polycentricity might have very different implications depending on geographical scale. For instance on the EU level, it might imply to redistribute activity from global cities such as Paris or Brussels to other places in the EU, but the same concept could be also applied on national level as spreading economic activity from national capitals to regional centres, or it could be similarly understood even on regional level (Hall and Tewdwr-Jones, 2020). When polycentricity is combined with decentralized concentration on local level, it still implies some form of employment and services concentration. This can reflect reality of structural transition of European economies toward higher proportion of jobs in services and in sectors which benefit more from agglomeration economies[9]. At the same time the framework recognizes option of more dispersed population, either due to the existing dispersed settlement structure, or due to preference for lower density single-family housing. In overall, the framework is quite flexible and ultimately depends on interpretation.

Principles of regional policy implementation in the Czech Republic could be found in the spatial policy umbrella document of the Regional Development Strategy of the Czech Republic 2021+ (Ministry of Regional Development CZ, 2019). The strategy defines three-tier level of cities: Three metropolitan areas (the three largest cities - Prague, Brno and Ostrava), about ten agglom-

[8] Publicly available data are aggregated to 13 regions plus the capital city of Prague. Even microdata for research purposes seem to be provided on regional level only.

[9] For discussion of agglomeration economies by industries see for instance Cheshire et al. (2014)

erations (typically slightly bellow 100 thousand inhabitants) and dozens of regional centres of a higher order (typically with at least 15 thousand inhabitants and twice large catchment areas). In the analytical part, the Strategy concludes rural areas, peripheries and very small settlements are depopulating and ageing, while Prague and Brno are the only long-term growth regions. In particular, the Strategy identifies as a problem that particularly young and skilled workers leave regional centres for higher-order centres. Regarding the regional centres, the Strategy calls for maintaining polycentric character of the Czech settlement and strengthening of regional centres and refers to Mulíček and Sýkora (2011), who argue the desirable form of future spatial development should be polycentric to relieve congestion and allow more balanced development. Nonetheless, they admit the development in the Czech Republic has been rather the opposite, as a number of commuting centres has decrease between 1991 and 2001 and size of commuting areas of the largest cities increased, substituting local centres with more distant and larger ones on regional level.

Both the Strategy and Mulíček and Sýkora (2011) however fail to properly define what level of geographical scale they do have in mind when proposing polycentric development and they also fail to distinguish between at least two types of regional centres: ones located in close proximity to larger cities that have become integrated into labour markets of the large cities, and remaining centres out of reach of the large cities that could indeed become stronger anchors of their local labour markets.

In the proposal part, the Strategy sets a global objective for rural hinterlands to have stabilized population, but it is unclear at what levels the population should stabilise, whether the current population is the intended desirable level, or depopulation is expected to continue and population would stabilise in longer-term horizon. However, the document seems to suggest the current population is already below desirable level. Among more detailed measures it proposes for instance improvement of regional accessibility that could centralise and strengthen regional centres as local employment hubs, or in general to improve local services and amenities. The strategy is however silent about underlying causes of outmigration which is likely low competitiveness of jobs in these remote areas when compared to larger cities.

Despite the Strategy lists urbanisation as a Megatrend to be monitored and taken into account, it immediately claims the process of "urbanisation in its pure form has not manifested in the Czech Republic for a long time" (Ministry of Regional Development CZ, 2019, p. 30), in other words that the process of urbanization has been completed. In a stark difference, OECD (2020) says the share of urbanisation in the Czech Republic is low, as the country is actually fifth least urbanised out of all the OECD countries.

Common story regarding past and expected depopulation of remote rural areas is lack of qualified labour force (Slach and Ženka, 2021). Instead, the question whether more knowledge-intensive firms in rural areas could compete with comparable firms in denser urban markets would address the core of the problem, but such a question is raised neither in media, public debate nor in policy documents.

Explicit aim to stop depopulation of small settlements is seen from the statement of the former Minister of Agriculture Marian Jurečka (later Minister of Social Affairs as of the end of 2022), who wanted to provide subsidised loans up to approximately 80,000 EUR for entrepreneurs and decrease monthly social security payments for employees by 20 EUR in municipalities with less than 500 inhabitants. He especially mentioned that vulnerable municipalities are the small ones which are far away from larger cities (Šefrová, 2016).

Presented evidence has shown inability to reflect structural change of the Czech economy undergoing growth of service based industries coupled with urbanisation trends. Insufficient reflection of the structural transition could be however seen even at the city level as the case of Prague shows. Despite the largest Czech city has shifted massively toward service and knowledge-intensive industries, the new proposal of zoning plan still allocates significant portions of land for manufacturing and justifies it simply by the need of such employment (Prague Institute of Planning and Development, 2014). Contrary to that, the need to rethink employment policies for small and large cities is expressed in Bacolod et al. (2009) who document stronger agglomeration economies for cognitive-intensive occupations and call rather for support of knowledge-intensive sectors in large cities.

The second example presents how Czech legislation and court decisions neglect economic heterogeneity of different regions, partly driven by agglomeration economies.

In 2021, the Constitutional court of the Czech Republic[10] upheld earlier decision of the Supreme court and lower-level courts that wage differentials for the same position across the country are unlawful and it confirmed the earlier court decisions were not unconstitutional (Usneseni Ustavniho soudu [Resolution of the Constitutional Court], 2021, Rozhodnuti Nejvyssiho soudu [Judgement of the Supreme Court], 2020).

In the particular case, the plaintiff, a driver employed by the Czech Post in Olomouc, one of regional major cities, sued the Czech Post in 2016 for a compensation of approximately 4,000 EUR as his wage was lower than a wage for the same position in the same salary band offered in the capital city of Prague. The plaintiff built the case on an evidence that the base wage and

[10] "The Constitutional Court is the judicial body responsible for the protection of constitutionality" (Article 83 of the Constitution of the Czech Republic). By the definition the role of the Constitutional court is not to serve as a Court of Appeal as it is not part of the system of courts. Instead, it assesses whether rights granted by the Constitution were not breached during court trials and in their decisions (Usneseni Ustavniho soudu [Resolution of the Constitutional Court], 2021).

individual performance premium for the same position were 17.6% and 17.7% respectively higher in Prague compared to other regions. The plaintiff claimed this violated the principle of equal treatment and reward.

The claim in particular referred to the section 110, article (1) of the Czech Labour Code that "for the same work or for work of the same value belongs the same wage, pay or reward to all employees of an employer" (Parliament of the Czech Republic, 2006, section 110, article (1), Labour Code, translated by the author). Further, in the article (2) the Code specifies that work of the same value is a work of comparable complexity, responsibility, exertion, being done in comparable working conditions, with comparable efficiency and comparable results.

The defendant, Czech Post, provided two arguments why the wage differed. First, despite the same position, the work in Prague is more difficult and responsible due to multiple reasons. Second, the defendant argued the higher wage in Prague reflects higher costs of living and a necessity to stay competitive on the market.

From an economics perspective, the argument partly looks like a reversed causality: The post claimed wages should be higher, because living costs are higher. Standard argument would be the wages are higher because marginal product of a worker is higher and higher wages then drive living costs up. Assuming however a simple model with tradable and non-tradable sectors, where the former has increasing returns to scale and the later does not, the non-tradable sector would have to offer higher wages in larger cities to remain competitive on the labour market with the tradable sector which is more productive in larger cities and could provide higher wages than in rural areas. Therefore the posts' argument is in principle correct, in spite of the post is not more productive in larger cities.

One of the reasons why the Supreme court accepted the request for appeal was novelty of the case being developed around the materiality of the wage differentiation across the country. The Supreme court admitted there is no any case law yet that would deal with such an issue.

However, all there courts - the District, the Municipal and the Supreme court ruled the wage difference between Prague and Olomouc was unlawful. In its justification the Supreme court admitted the character of local labour market affects wages, but this has not been reflected in the Labour Code. The court argued the Labour Code acknowledges possible differences in wages due to varying workplace conditions, but these varying conditions have to be internal to the workplace and they are explicitly listed in the Code. These conditions however do not contain wider social-economic characteristics of the local labour market like its size or local productivity. Practically, the Supreme court ruled the well known regularity of agglomeration economies which gets translated into higher wages in bigger cities is unlawful in the Czech Republic.

The aim of presenting anecdotal evidence from media, policy making and case laws was to show that even elementary understanding of the concept of agglomeration economies is largely missing in the Czech Republic. One reason why it might be so is complete lack of research there on this topic as geographically detailed data are not available. This thesis aims to fill this existing gap and provides evidence of agglomeration economies of similar magnitudes we observe in developed countries.

Construction constraints

Real estate development in the Czech Republic is notoriously known for complicated and lengthy permit processes and spatial planning system unable to reach its goals of promoting compact development over suburbanisation.

To provide an idea about the state of building permit system in the Czech Republic, 2020 Doing Business index (World bank, 2020) ranked the country in dealing with construction permits 157th out of 190 countries covered. The index has its shortcomings, but it still communicates well that there is something wrong about building permit process there.

However, beyond the crude Doing business index, there is almost no evidence of how lengthy and complicated building permit processes are. A rare exception is Deloitte (2021) analysis of 60 residential development projects in Prague with mean duration of permit processes of 5.1 years. These processes include 4 distinct steps: Environmental impact assessment (EIA) initiation and consent, Planning permit and Building permit. To compare, Gyourko and Molloy (2015) report lengths of application delays in the US to be between 3 and 10 months. Additionally, Deloitte (2021) have analysed larger data sample for 752 residential projects across the Czech Republic for which they observe length of the building permit process only. For instance the length in Prague reaches almost 900 days making it the major part of the overall 5.1 year long process. They also find associations that permitting processes are on average shorter in smaller municipalities and longer in metro areas with more expensive housing when controlling for the metropolitan population.

Regarding the building permit system, to my knowledge there is no other quantitative analysis of the process done so far. It seems one of the reasons is lack of data. Deloitte (2021) use their database based on monitoring of each initiated residential project and its progress over time. There are survey data from annual surveys conducted among all Building permit offices dating back to 2010's (Institute for Spatial Development, 2021) which are used in this thesis. These surveys nevertheless do not contain information that directly addresses issues of inefficient permit processes, such as mean application delay and control variables related to projects submitted for a permit. There are only few variables in the surveys that could be used for these purposes, for instance share of appeals against the office's decision. Although these data are publicly available, I'm not aware of any quantitative analysis exploiting this dataset.

Similar to building permit process, effects of the Czech spatial planning on local development are also understudied. The Czech spatial planning is hierarchical with plans on national, regional and municipal level. Although the upper documents are binding for the subordinated documents, national and regional plans are predominantly concerned with transport and technical infrastructure and therefore most of of the powers regarding regulation of local (residential) development is left to municipalities.

To start with international comparison, Czech cities are comparable in terms of their density (on average 1,240 inhabitants per square kilometre) with the average of OECD countries, although the number of residents living outside of metro core areas is about 10% higher than the OECD average. However, the trends since 1990, when the country started to transition from planned to market economy, show sizeable suburbanisation. Between 1990 and 2014, the average density dropped by 10% and the share of residents living outside core areas increased by 14% which is the largest increase among OECD countries (OECD, 2018).

These figures suggest the spatial planning hasn't been very successful. Back in 2006, the Czech Government in its Spatial Development Policy stated in the article 22 of the proposal the goal "To determine the conditions for economical use of the built up area, and to secure the protection of un-built one. To create prerequisites for new use of abandoned areas above all (the so-called brownfields of industrial, agricultural, military or other origin)" (Government of the Czech Republic, 2006, p. 12).

However, detailed quantitative assessment of effects of spatial planning on the national level to my knowledge hasn't been done. For instance a report on effects of the Spatial Development Policy (Ministry of Regional Development of the Czech Republic, 2018) is rather vague and comments on overall trends and it mostly is not able to distinguish to what extent these trends were or were not in any way affected by the Spatial Development Policy or by more detailed lower level planning documentation. The underlying problem is that there is even less data regarding spatial planning compared to building permit processes. Unlike building permit process which belong to the state administration, most of spatial planning agenda actually belongs to local government competences and is done on the municipal level and local plans are mostly not reported to upper-level governments for monitoring or evaluation purposes. To my knowledge, there is only one dataset of developable land defined by municipal zoning plans which I have exploited in this thesis. The dataset was collected by Maier et al. (2016) who merged data provided by 206 local state planning offices which collected data from municipalities within their jurisdictions. The dataset is however not publicly available and due to the methodology of the data collection it required further major processing and specific research design as it is described in the Chapter 3.

As described above, although spatial planning in the Czech Republic is a widespread practice, rigorous evaluation of its economic effects is missing. This is a serious problem as municipal spatial planning is quite restrictive. Its methods and planning tools are largely dictated by the Building Act[11] and these have been considered by some planners as overly reliant on functional zoning and on the legacy of socialist spatial planning (Jehlík, 2013; Koucký, 2017). It is then hardly surprising this style of planning does not contain market-based instruments[12].

The vast majority of instruments used in the Czech Republic operate on a binary basis. They either allow or do not allow different types of development within designed zones given by binding zoning plans. Conversely, more flexible land use management tools are almost completely missing. For instance, while average share of property tax on overall tax burden in OECD countries in 2020 was 5.7% and in the UK, the US and Canada around 11%, the Czech Republic was at the tail of all countries with 0.6% (OECD, 2023).

Economic tools within the planning process itself are limited to planning contracts linked to development plans in which municipalities might require participation on development costs of utilities' infrastructure. Another tool is the subdivision agreement that also defines how development costs would be shared. However, the subdivision agreement requires unanimous consent of affected landowners which is very hard to reach practically (Vejchodská, 2017).

At the same time, implementation of economic tools in spatial planning might not be easy. Although more than three fourths of stakeholders attending participatory meeting regarding economic instruments in spatial planning in 2019 co-organised by the Czech ministry or Regional Development supported implementation of Swiss-inspired land value capture, Münich-inspired development agreement and German-inspired land consolidation, they also identified current low institutional capacity of the Czech public administration as one of the main risks for adoption of these tools (Vejchodská et al., 2019).

Although both academia and international organisations call for policies which should jointly take into account housing, transportation and labour markets (Thisse, 2018; OECD, 2017), Czech planning is instead silo-styled with individual agencies dealing with their narrowly defined agendas and it suffers from conflicts between spatial planning and sectoral plans, such as

[11] As the Building Act is meant the 183/2006 Coll. Act on town and country planning and building code (Building Act). Recently has been prepared and approved the new Building Act No. 283/2021 Coll. which is expected to become effective during 2023

[12] However, this does not seem to be unique to the Czech Republic alone. Vejchodská (2021) mentions the adoption of economic instruments in spatial planning closely follows former 'Iron curtain' as economic instruments are not common in the former Eastern block countries with the only exception of Estonia.

transportation planning or environmental protection legislation (OECD, 2017; Deloitte, 2021).

Stark example is practical division of spatial planning and regional planning despite both branches of planning operate on all three levels of government: the national, the regional and the municipal. While strategic planning is more tightly linked to the EU and national funding and grants, spatial planning deals predominantly with land use and design of corridors for infrastructure. Surprisingly, these two systems, one providing incentives and the second one defining limits and regulation, are rarely coordinated.

To conclude, the thesis responds to this lack of evidence of effects of spatial planning regulation and building permit processes utilising existing data, which are far from being optimal. Despite these limitations the thesis at least provides some initial insights.

Amenity values

The previous section has pointed out how legacies of the past socialist planning in the Czech Republic still affect contemporary spatial planning and tools being used. The legacy of the past planning also applies at a more detailed scale on city and neighbourhood-level urban design, although modernists' doctrine adopted by socialist planners competes with more recent so called 'New urbanism' doctrine popular among younger generations of planners and urbanists who mostly started their professional practice after 1990.

The principles of the modernist city design were outlined in the Athens charter (Le Corbusier and Eardley, 1973[1933]). They heavily departed from the European city building tradition as they called for strict separation of urban functions - housing, production and recreation - into separate zones connected by transport infrastructure which contradicts traditional mixed-use city. Regarding more detailed design, they promoted high-rise developments freed from clearly defined streets and instead designed solitary structures in park-like open spaces.

The charter tried to address issues prevalent at the turn of the twentieth century, such as high residential densities and overcrowding, provision of public green spaces, congestion, urban pollution and lack or natural sunlight and ventilation. Modernists' design however brought new challenges of disintegrated urban structure, low walkability, high demand for mobility and low quality of public spaces. These challenges have been addressed by the New urbanism movement[13] which emphasized clearer urban structure based on historical tradition of city building, emphasised local centres, mixed land-use of

[13]The New urbanism movement comes from the US where spatial development in the second half of the 20th century differed substantially from the one in the Central (socialist) Europe. Despite that, urbanists on the both sides of Atlantic and both in traditional democracies and post-communist countries addressed new challenges of the second half of the 20th century in a similar way by searching for inspiration and design principles in the pre-modern times

sufficient density, continuous street network and good design of public spaces preferring pedestrians and public transit use (Ellis, 2002).

Criticism of the modernist planning in the Czech Republic increased in the 1990's with general democratisation process and upcoming new generation of planners inclining toward the New urbanism. Despite that, nationally binding requirements on planning given by the Building Act and lower-level ministerial decrees did not respond to this critique much[14] contributing to tensions between older and younger generation of planners.

In this thesis I focus on the perceived value of public green open spaces. Modernism and New urbanism movements approach this very differently. While modernists called especially for sufficient provision of green spaces in terms of their size, New urbanism instead rather insists on a holistic high quality design of public spaces with lesser emphasis on their size only.

Modernists' design indeed increased provision of public spaces in terms of their size, and in particular of green areas. For instance the share of open spaces in the historic Prague centre is 30%, in 19th century blocks is around 40%, while in modernists compounds it is on average 69% with more than half of it consisting of open green spaces (Hudeček et al., 2018). The emphasis on size of provided greenery or public space is still present in the nationally binding regulation. Spatial requirement on size of public spaces is essentially the only requirement, with at least 5% share of area devoted to public spaces when excluding the road space (Ministry of Regional Development of the Czech Republic, 2006).

The Eastern European Modernists' development was indeed land extensive, perhaps partly driven by missing opportunity cost of land due to missing land markets (Bertaud and Renaud, 1997), although the excessive land demand does not seem to be unique to planned economies only. Along with vast green spaces, Modernists' design frequently featured wide infrastructure lines with large intersections and sizeable buffers. Lot of these areas fall within the category of 'Lost space' coined by Trancik (1986). These places are commonly quite large, but do not create much of value. Their sole function is being a buffer.

Excessive provision of space and its insufficient design have been criticized in the Czech context for instance by Hnilička (2012). He claims if areas in a zoning plan cannot be easily named in terms of their typology, they likely have no use. This seems to hold especially well for left over space between buildings and transport infrastructure or some spaces around free-standing buildings. Not to inflate public spaces, Hnilička (2012) recommends to restrict their size so high-quality design could be achieved. He refers to Léon Krier

[14]With a notable exception of the new Prague building code, which underwent major reform based on New urbanism principles. The new document was adopted in 2014. However, Prague is the only city in the Czech Republic entitled to issue its own building code. All other municipalities have to comply with the national code.

who suggested 25% to 30% is about the right share of public spaces, figures quite close to ones found in the Prague historic urban fabric.

In general, it is an important question to what extent quality and size of open green spaces matter in terms of their perceived value. This is even more important in Prague with its large share of green spaces, however many of them likely providing low amenity value. Prague has indeed excessive amount of publicly accessible green spaces - more than 90 square meters per resident - by far leading the ranking of large Central European cities followed by Budapest with a number slightly exceeding 40 square metres per resident (Útvar rozvoje hl. m. Prahy, 2012). Despite that, discussions regarding development of some underutilized areas or allotment gardens are always heated[15]. Whereas public seems to be very sensitive to possible reduction of open green spaces, there does not seem to be any discussion regarding actual quality of green space being provided.

Evidence of amenity value of green spaces in the Czech cities is scarce (Melichar et al., 2009; Melichar and Kaprová, 2013) and it analyse only effects of proximity and size of selected rather large urban green spaces. Beyond proximity and size, there is one recent evidence of effects of public spaces' quality in Prague shown by Vorel et al. (2022) who estimated effect of a park refurbishment on local property prices.

Better understanding of how people value green amenities beyond their size and proximity could bring new insights for urban design. For instance how to make the trade-off between size and quality of green spaces in the face of increasing opportunity cost of land, growing demand for new construction and pressures to better utilise existing urban land over expansive growth on city fringes.

[15] for instance an article Pražský magazin (2022) claimed the "Metropolitan plan endangers green spaces, ignores worsening climate"

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2 Estimating Agglomeration Economies without Wages: a Quantitative Spatial Model Approach Exploiting Commuting Patterns

Abstract

In this chapter, I analyse agglomeration wage elasticities in the context of the Czech Republic, where neither individual-level nor locally aggregated wage data are available. Instead, I use a quantitative spatial model following Ahlfeldt et al. (2015) to infer wages from commuting patterns on a very fine geographical level for a representative worker and for three groups of workers by their education. On a labour market level, I do find agglomeration wage elasticities of 6.7%. On a very local level, they are higher at 9% and dissipate quickly with distance. Overall, agglomeration economies tend to grow with workers' education, but their rate of decay across space is about the same independent of education achieved (JEL R11, J31, J24, R41).

2.1 Introduction

It is a well-documented fact that both population and the resulting economic activity are highly concentrated in space. Rosenthal and Strange (2004) illustrate this with the following figures: 75% of the US population lives in cities which cover only 2% of the area of the contiguous United States. The extent of such population concentration could be expressed alternatively with the Gini coefficient applied to a grid of cells of 0.01 by 0.01 degrees that have an approximate area of one square kilometre. The resulting Gini coefficient is 0.91.

If we look at the European Union measuring similarly the extent of population spatial concentration, the Gini coefficient reaches 0.85, showing a comparable level of population concentration in a limited land area. The population concentration in the Czech Republic, which is studied in this chapter, is a bit smaller than the averages for the US and the EU, with a Gini of 0.78[16], but still sizeable and comparable, for instance, with the UK. While population by

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[16] EU-level concentration is based on 1km population grid GEOSTAT 2011 data; Czech concentration is calculated as density within cadastral areas to account for their differences in size. Gini based on levels within cadastral areas change results marginally. Gini for the Czech Republic using GEOSTAT 2011 data yields a slightly higher value of 0.82

place of residence is already quite concentrated, jobs are concentrated even more, with Gini reaching a value of 0.90 in the Czech Republic.

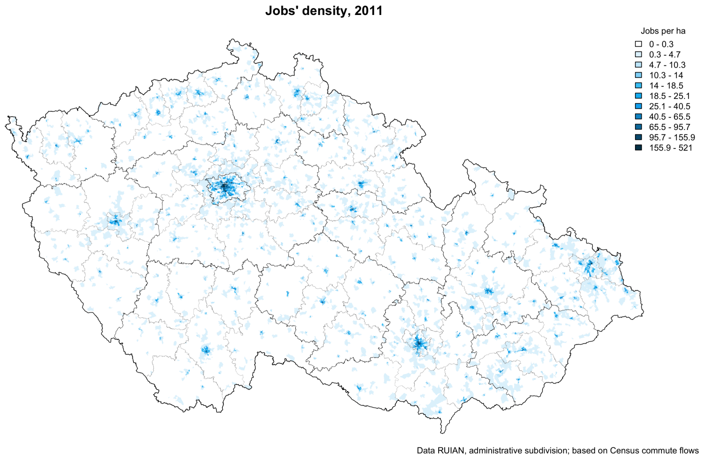

Figure 2.1.1: Jobs' density in the Czech Republic

This chapter shows an approach to estimate agglomeration economies without observing wages or other productivity related variables, and instead relies on workers' commuting behaviour only.

The motivation for this project is to analyse the magnitudes of agglomeration economies in the Czech Republic and the extent to which they are comparable with findings from other countries. The initial hypothesis is that the agglomeration wage elasticity in the Czech Republic is comparable to wage elasticities found in other European countries or in the US. To my knowledge there is no existing research addressing this issue, which is most likely caused by lack of data, as the most detailed wage data are currently provided on a regional (NUTS3) level, and personal income is not even surveyed in the Czech Census.

The lack of sufficiently detailed wage data is not limited to the Czech Republic. Whereas these data are commonly available in most developed countries, their availability in Eastern European countries, for instance, is limited and they are not available at all for many developing countries. The approach adopted in this paper, a quantitative spatial model following Ahlfeldt et al. (2015) exploiting commuting patterns, can circumvent such data limitations.

Additionally, being able to observe workplaces and places of residence on a detailed geographical level allows us to estimate agglomeration economies with respect to a very localised distribution of economic activity, something that cannot be achieved if wages are reported on a municipal or metropolitan level only. It has been already documented that agglomeration economies indeed dissipate rather quickly across space, especially in the case of knowledge spillovers or spillovers in services (Ahlfeldt et al., 2015; Rosenthal and Strange, 2001; Arzaghi and Henderson, 2008) so this justifies this geographically-detailed analysis.

Beyond the mean agglomeration wage elasticities, I also study how they differ across workers by their education. Distribution of human capital, measured by share of college educated workers, is also heavily skewed towards large cities, as documented in the figure 2.1.2.

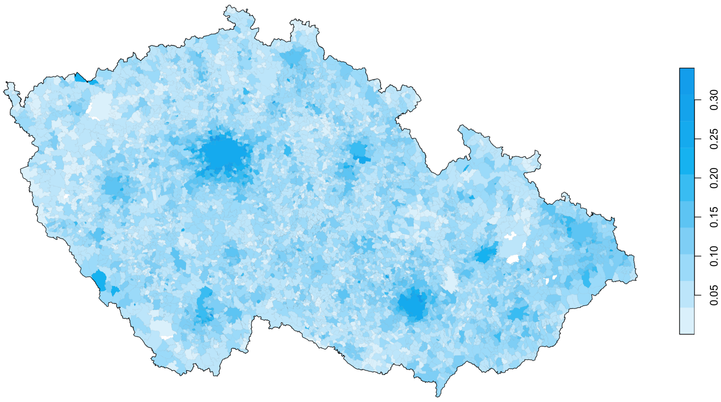

Figure 2.1.2: Share of college educated (high education)

Education does not only play a role in sorting into cities, but also in commuting behaviour and the resulting formation of local labour markets. While labour markets for low-educated people are rather small with relatively short commutes, labour markets for high-educated people are much larger, and there is a smaller number of them. The difference is captured in the two maps below in figure 2.1.3. In many places where low-educated people work locally, high-educated people instead commute to more or less distant larger towns and cities.

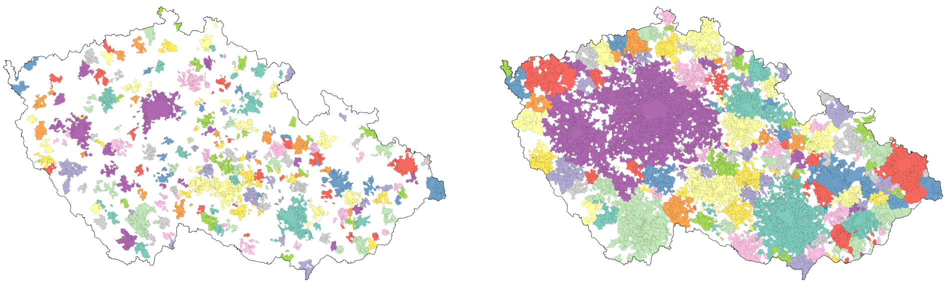

Figure 2.1.3: Commuting areas of low-educated and high-educated

The higher share of high-educated people in cities and the larger size of their labour markets is, as I show in this chapter, consistent with heterogeneous agglomeration wage elasticities rising with education. If workers with higher education benefit more from working in large cities, they outcompete less educated ones. Similarly, if the urban wage premium is higher for the better educated, it can support longer commutes than those of less educated people, for whom it does not pay off to undergo such costly trips.

While agglomeration economies are generally well understood and documented for developed countries and some developing countries (Duranton and Puga, 2004, Eberts and McMillen, 1999, Rosenthal and Strange, 2004 and Combes and Gobillon, 2015) and results to date were analysed in a meta-analysis by Melo et al. (2009), there is currently, to my knowledge, no research analysing agglomeration economies in the Czech Republic and post-socialist European countries, with the exception of very limited evidence of agglomeration economies studied at a regional level with a major focus on the whole of Europe (Brülhart and Mathys, 2008). This is likely due to the lack of wage data reported on a fine geographical level, such as municipalities or even finer geographies.

However, the range of countries where some research on agglomeration economies has been done is very limited when compared to the number of countries for which there is no evidence at all. Due to the lack of evidence of agglomeration economies in Central Europe and limited awareness of them, drafted regional development policies might not grasp the full development potential of local economies.

The same holds for rapidly urbanizing developing countries, where local evidence of agglomeration economies could be important input for spatial policies there. Beyond developing countries, existing research mostly focuses on one country at a time due to the availability of data in the same structure. This, however, limits possible cross-country comparison of agglomeration economies.

Both problems described above can be addressed when the analytical framework does not rely on directly observed wage data. In this chapter, I exploit Census-based data, but the study could be similarly reproduced with two alternative datasets that are gradually becoming available globally: cell phone location data and travel times from web map services. Sturm et al. (2023) show that these data, combined with satellite imagery, are sufficient to model a full equilibrium using their quantitative spatial model.

In this chapter, I use a commuting equilibrium condition from a quantitative spatial model developed in Ahlfeldt et al. (2015) that allows me to infer unobserved wages from observed commuting patterns reported at a fine geographical level for discrete groups of workers by their education. Then, in the second stage, I proceed with a conventional analysis of agglomeration economies, first aggregating wages to the local labour market level and regressing them on the size of the labour force, and then I exploit wages estimated for small local areas, regressing them on a measure of market access of all jobs, which successfully captures localised heterogeneity in density of economic activity.

Estimation of agglomeration economies on a labour market level allows me to compare my results from the Czech Republic with the wide existing body of literature focusing mostly on developed countries. In general, I do find slightly higher values than are common in the literature. My preferred specification yields agglomeration wage elasticity of 0.067, slightly larger than, for instance, the 0.06 reported by Ciccone and Hall (1996) for the US.

Then, exploiting granular spatial data, I estimate agglomeration wage elasticity at a very local level at around 0.09, with spatial decay time semi-elasticity of -0.27, meaning agglomeration economies attenuate by some 24% with each additional minute of increased distance. These results are comparable with Ahlfeldt et al. (2015) who estimated agglomeration wage elasticity at 0.071, with spatial decay of -0.36, for the city of Berlin, exploiting variation caused by its division (1961) and reunification (1989).

Results for the three education groups - workers with primary education or lower, high school and university degree - on a labour market level show monotonously increasing agglomeration wage elasticity of 0.038 (not significant), 0.068 and 0.075 for the three groups respectively. Estimated elasticities are almost identical to the ones found by Bacolod et al. (2009).

The last part considers agglomeration wage elasticities for the three education groups on a very local level and their spatial decay. Estimated magnitudes of agglomeration economies on the local level are very similar to the ones for labour market area in the case of the two less educated groups, whereas they reach 0.11 for university educated workers. Regarding the distance decay, all three groups of workers exhibit similar values between -0.28 and -0.32. This result is rather novel compared to the literature and cannot be directly compared with existing findings.

This chapter shows it is indeed feasible to supplement unobserved wage data with observed commuting flows and commuting times, and estimate agglomeration economies. This opens an opportunity to apply this approach to countries where wage data are not available, or to apply it to multiple countries to estimate their agglomeration economies consistently.

Second, the chapter presents evidence of agglomeration economies from previously unstudied formerly planned Eastern European socialist countries. The results show agglomeration economies there are comparable with those in developed countries in Europe or in the US.

Third, estimated agglomeration economies increase with workers' education. This last finding has multiple implications for urban development and subsequently for urban planning. Increasing mean achieved education over the twentieth century is likely to have strengthened the urbanisation process as a distinct channel. This process, however, might not have ended yet, and we might expect further urbanisation as mean human capital is expected to increase.

Additionally, heterogeneity in agglomeration economies has implications for urban structure and social composition of cities. A wider college wage gap is expected in central areas of large cities, but there are other implications for more remote locations and exurbs of large cities. Central Europe has developed a very dense settlement pattern, and each large city is surrounded by many smaller towns and villages. When agglomeration economies for the highly skilled are meaningfully larger than for the low skilled, and the labour markets of large cities span larger areas, the highly skilled could move their residence to previously more independent towns with their own labour markets and start converting them into bedroom communities for the highly skilled, who remain employed in the cores of the large cities. This process would likely cause tensions between incumbent residents and incomers over amenities, development policies and public goods provision.

The rest of the chapter is structured as follows: Section 2 provides more context regarding theory and evidence of agglomeration economies, Section 3 presents the theoretical model and empirical specifications, and Section 4 reviews the data used. Then, Section 5 provides estimates for a representative worker, Section 6 shows estimates for the three types of workers by their education, and Section 7 concludes.

2.2 Theory and evidence of agglomeration economies

Reasons for agglomeration

Urban economics research has always tried to explain what drives people to spatially concentrate to the extent we observe. Economic theory provides at least two distinct channels that could cause agglomeration: local productivity advantages (also called productivity amenities) and local residential amenities (also called consumption amenities). On top of that, both channels could be exogenous or endogenous, or, in the words of Cronon (1991), they might be of first nature (determined by physical geography), or second nature (artificial, but fixed for a long time in a place), or result from a current concentration of economic activity that could be partially caused by the two other channels. Another reason for spatial concentration which is distinct from the previous economic channels is location of political power and political institutions as shown by Ades and Glaeser (1995).

When tracing the earliest origins of cities, Mumford (1961) lists a few reasons for city formation that could be called residential amenities. These are places of religious gatherings, worship of ancestors or other cultural landmarks. Aside from these, another reason for city formation was concentration of political power. Although possibly not as important as in the past, residential amenities still seem to play a role as an agglomerating force. Glaeser et al. (2001) show evidence of more pronounced population growth in amenity-rich cities compared to amenity-poor places. To list a few examples of residential amenities within the taxonomy introduced above, instances of wholly exogenous first nature residential amenities include nice weather and access to beaches or natural parks. Second nature residential amenities include cultural institutions such as theatres, museums or green spaces, and finally, among contemporary (or not place-embedded) amenities, could be well-educated, rich neighbourhoods and retail services.

While the existence of cities in ancient times could be driven by political or cultural reasons, the rapid urbanisation starting in the 19th century during the industrial revolution is more likely to have been triggered by the productivity advantages of more concentrated economic activity. Examples of purely exogenous or first nature productivity advantages are natural resources, navigable rivers or sea harbours. Second nature productivity advantages include durable infrastructure investments, such as railways, highways or real estate. Third, there are productivity advantages independent of the first and second natures rooted in the contemporary economy. These have been described by Marshall (2006), who identified three potential channels of input sharing, labour pooling and knowledge spillovers, arguing that these agglomeration forces decrease the transportation costs of moving goods, people and ideas (Ellison et al., 2010). This last type of productive advantages based on Marshall are investigated in this chapter.

Localisation and urbanisation economies

Duranton and Puga (2004) define sharing, matching and learning as three microfoundations of agglomeration economies, adjusting Marshall's original taxonomy slightly to relate it better to the economic theory. Ellison et al. (2010) have shown that Marshallian agglomeration forces in the US manufacturing sectors are indeed quite sizeable. Although each channel is weaker than natural advantages, jointly they are stronger. Furthermore, learning (or knowledge spillover) has been shown to be weaker than the remaining two, but this result could be driven by their limited focus on manufacturing industries where knowledge spillovers might play a less important role. Marshallian forces are commonly assumed to play a role within industries and are called localisation economies.

Alternatively to Marshall, Jacobs (1969) proposes urban diversity as a key mechanism sparking innovation. As urban diversity typically increases with city size, city size is used as a proxy for this agglomeration force, which is called urbanisation economies. Empirically, urbanisation economies have been studied more thoroughly, and more evidence is available. However, it is empirically often hard to disentangle urbanisation and localisation economies from one another as there is frequently a high correlation between overall city size and size of related industries, especially if industries are aggregated into few categories or in the case of services (Graham, 2009).

Faggio et al. (2017) present a synthesis of the two approaches and show evidence of complementarity between Marshallian and Jacobs theories due to heterogeneities across industries and firm types. Whereas input sharing plays a more important role for industries frequently co-locating together, very much in the Marshallian spirit, labour pooling and knowledge spillovers are more important for industry pairs that co-locate rarely; this is consistent with Jacobs' theory, which claims innovation and new work often result from the random encounters and cooperation that are so frequent in larger cities.

Regarding magnitudes of localisation and urbanisation economies, Graham (2009) analyses separately 27 manufacturing and service sectors and finds magnitudes of localisation economies of 0.03 and 0.01 for manufacturing and services respectively. For urbanisation economies, he finds respective elasticities of 0.07 and 0.19. However, the author admits the results could be biased due to the endogenous city size that is not addressed in the identification strategy.

Urbanisation economies empirics

There is a wide range of literature estimating the effects of urbanisation economies with results of city size effect on productivity or wages spanning between 3% and 8% depending on the context (Rosenthal and Strange, 2004). However, more recent literature typically reports results toward the lower bound of the range. A seminal paper focused on the US by Ciccone and Hall (1996) measuring productivity with labour input and gross state output and instrumenting population size with lagged population, distance from the eastern shore and presence of the railway in the 19th century estimated productivity elasticity with respect to density to be 6%. In a later study on European countries, Ciccone (2002) found agglomeration elasticity of a slightly lower magnitude of 4.5%.

Instrumenting actual population could mitigate endogeneity of city size, but there remains the problem of potential sorting into cities and the so-called endogeneity of labour quality (Combes et al., 2010). Since Glaeser and Mare (2001), this problem has usually been addressed by using individual-level panel data that allow one to isolate individual fixed effect. With this approach, using both instrumental variables to address city size endogeneity and individual-level panel data, Combes et al. (2010) estimated agglomeration wage elasticity in French municipalities of 2% and 3.5% when measuring job density and job market potential respectively. The relatively lower magnitudes are consistent with findings from a meta-analysis by Melo et al. (2009), according to which, using individual fixed effects decreased the magnitude of estimates by 3 percentage points. The same meta-analysis also confirms that larger magnitudes by 1 to 3 percentage points are found when a market potential measure is used. However, this result was statistically not significant from zero.

Although the individual-fixed effect mitigates the problem of the sorting of more able workers into larger cities, there arose concerns regarding potential underestimation of the dynamic effect of learning in larger cities. Using conventional instruments for population size and individual-level data de la

Roca and Puga (2017) have shown the agglomeration wage elasticity is 2.4% in a static model similar to Combes et al. (2010), but it increases to 5% when the dynamic effect of learning in big cities is considered.

Duranton and Puga (2001) has shown using French data that both mechanisms of localisation and urbanisation play some role even within industries. The two mechanisms apply differently in different stages of product development and production. While innovation benefits from diversity and locates in large cities, further mass production benefits more from local specialized industrial clusters that are more prevalent in smaller towns. Faggio et al. (2017) support this theory with their analysis of UK data. They show in particular that knowledge spillovers are important for young firms and new industries.

Agglomeration economies distance decay

Most of the research to date relies on data spatially localised for rather large geographies, such as regions or states (Brülhart and Mathys, 2008; Ciccone and Hall, 1996; Ciccone, 2002) or metropolitan areas, labour markets or cities (Charlot and Duranton, 2004; Bacolod et al., 2009; de la Roca and Puga, 2017; Combes et al., 2010; Glaeser and Resseger, 2010), which does not inform us well about the very localised nature of productivity spillovers that decline steeply with distance, which has been pointed out in general by Rosenthal and Strange (2008), and Arzaghi and Henderson (2008), who have shown this in the case of the information-intensive advertising sector.

A few studies have addressed the problem of too large geographical areas in the past and more have been done recently. Rosenthal and Strange (2008) use Public Use Microdata Areas, geographies containing at least 100,000 persons, providing greater detail than previous studies, but these are still spatially crude as their smallest constructed local areas are rings of a 5-mile radius. They do, nevertheless, find agglomeration attenuation as adding workers within 5 miles compared to a ring from 5 to 25 miles increases productivity four to five times more.

A more geographically detailed analysis has been done by Graham (2009), who used more than 10,000 wards in the UK. Even more granular geographies of individual city blocks are used by Ahlfeldt et al. (2015), who employ a quantitative spatial model with which they can model otherwise unobserved wages on the level of city blocks. They find substantial spatial decay with distance-in-minutes exponential decay of -0.36, meaning the agglomeration economies drop to one half when one is two minutes away from its source and they fall below one percent of their original size when the distance is a quarter of an hour. However, they studied only one city.

Agglomeration economies and human capital

Agglomeration economies might not only differ within and between industries or by industrial sector, but also by workers and particularly by their human capital. Thisse (2018) concludes that agglomeration economies are stronger for advanced, knowledge-based industries in which information is the most valuable input. As a large portion of information cannot be codified, and its transmission relies on face-to-face contact, the value of interpersonal proximity rises as well as productivity resulting from this knowledge exchange. Because knowledge-intensive industries require more human capital, this implies that agglomeration economies should be more pronounced among more skilled workers.

In this chapter, I relate increasing urbanisation economies with education to differences in commuting patterns, in particular longer commutes of more educated workers and the resulting larger labour markets. This observation of heterogeneity in commuting by education is not new in the literature. There is some evidence regarding differences in commuting patterns between the low skilled and the high skilled in the US dating back at least to the 1950s. Using descriptive statistics for 1950s West Virginia, Thompson (1956) has shown a weak association between skills and length of commute, and the same was more convincingly confirmed by Wheeler (1967) using data from late 1950s Pittsburgh and by Gera and Kuhn (1981) using 1971 Toronto metropolitan area data. Guest (1976) also argue that there is evidence of more skilled workers commuting for longer distances, especially in older metropolitan areas, based on data for 62 SMSAs from the 1970 Census.

While average agglomeration economies are well documented for developed countries, there are far fewer studies looking at heterogeneity by education. Glaeser and Resseger (2010) have shown agglomeration economies for the third of least and most educated US metros measured by share of college degree holders are 0.028 (insignificant) and 0.128, estimated with OLS model without further controls. Bacolod et al. (2009) estimate urbanisation economies at the metropolitan level of 0.039, 0.070 and 0.073 for workers without a high school qualification, with a high school qualification, and with a college degree respectively. The authors further show that urbanisation economies are particularly strong for workers with high cognitive skills, while the effect is smaller for people skills[17] and negative for motor skills.

Charlot and Duranton (2004) investigate the extent to which communication has external effects. They distinguish between formal knowledge, which can be proxied by education or experience, and tacit knowledge, which is reflected in their communication index based on a survey of work-related communication. They find that bigger and more educated cities lead to more

[17] People skills are related to the communication index in Charlot and Duranton, 2004, who argue that the level of communication of an individual worker relies both on his or her formal skills and social skills.

communication, and more communication increases productivity. In terms of magnitude, they attribute 10% of agglomeration economies and 17% of social returns on education to the communication channel. These results seem to be consistent with Bacolod et al. (2009), who find that the effect of people skills on the size of urbanisation economies to be positive, but relatively small compared to the effect of cognitive skills. Faggio et al. (2017) analyse agglomeration economies through co-agglomeration of manufacturing sectors and find different channels of agglomeration economies play a role with respect to mean education within individual sectors. While the importance of labour pooling and input sharing decreases with the education level of an industry, knowledge spillovers are important for medium and high education industries.

Unlike previous studies showing evidence of stronger agglomeration economies for the more educated, Rosenthal and Strange (2008), who measure urbanisation economies at the local level within up to 5 miles for workers without and with college degrees, find both elasticities to be similar and around 0.05, less than ten percent larger for those with a college degree. Whereas the majority of the literature agrees on at least modest increasing returns from agglomeration for the educated and skilled, Adamson et al. (2004) find the opposite and attribute it to higher demand for urban amenities by the skilled.

The presence of amenities could indeed bias estimates of agglomeration economies for the low and high skilled, particularly if the quality of amenities increases with city size and the more skilled are more sensitive to amenities than the low skilled[18]. Moretti, 2004 has shown, using a modified version of the Rosen-Roback framework (Roback, 1982), that if highly skilled workers care about amenities and the low skilled do not, then the high skilled will sort into places with more amenities and will be willing to accept lower wages there as they are compensated by the amenity value. However, if productivity of a city is endogenous to the share of the high skilled, the higher concentration increases the productivity of the high amenity places and the effect on the wages of the high skilled is ambiguous.

Another finding regarding urbanisation economies by type of workers is decline of urban wage premium for the low skilled. According to Autor (2019), in the second half of the 20th century, there was an urban wage premium for both college and non-college workers. The wage premium for the less educated, however, declined between the 1970s and 2015, most notably after 2000. This was caused by automation and non-college workers switching from medium-skilled jobs to low-skilled jobs, so non-college workers are nowadays employed in less skilled occupations than they used to be in the past. This finding that most agglomeration economies for low skilled workers have vanished in the past 20 years nonetheless does not explain why commuting patterns between high skilled and low skilled workers differed before the wage premium gap widened.

[18] Diamond (2016) has found higher sensitivity to amenities for college educated US workers compared to ones without a college degree.

An explanation could be different (utility) costs of commuting between the high and low skilled in the middle of the twentieth century when fixed and variable costs of car commuting relative to costs of time were likely higher, therefore making commuting relatively costlier for low income, low skilled workers.

Alternatively, Eckert et al. (2022) focus rather on growth of urbanisation economies for selected knowledge intensive services. They show, using US data, that urbanisation economies grew significantly between 1980 and 2015, but most of this growth was driven by business services. The wage premium between the least and most dense cities for these industries has grown from 42% to 111%.

2.3 Theoretical framework and empirical specification

Wage model

As wages on a fine geographical level are not available in the Czech Republic, the first part of the task focuses on retrieving wages for sufficiently small geographical units - 18,902 elementary statistical units with positive number of jobs across the country.

To obtain wages, quantitative spatial model developed by Ahlfeldt et al. (2015) is used and its key features are described in this section. Their model assumes an economy consisting of discrete locations $\mathbb{N}$ which have both jobs and residences. In their framework, there are homogeneous workers o who inelastically supply one unit of labour, they reside in locations $i \in \mathbb{N}$ and commute to locations $j \in \mathbb{N}$ to their workplaces. Their indirect utility function v_{ijo} (2.3.1) increases with local amenities B_i in their place of residence and with wage $\overline{w(\varphi)_j}$ they earn at a workplace.

Workers and firms. Unlike in Ahlfeldt et al. (2015) where wages are in each location j same for all workers, I extend the model to account for heterogeneity in workers' education φ in the second part of the chapter, so there are multiple education groups labelled with a subscript f. It is assumed education does not affect underlying workers' preferences, does not affect what housing they consume and does not affect commuting technology, that would otherwise make the time distance matrix $\mathbb{N} \times \mathbb{N}$ different for groups of workers by their education. However, groups of workers by education might differ in their distribution of idiosyncratic preference shocks and in perceived (utility) costs of commuting.

Workers' indirect utility decreases with commuting costs d_{ijf} separating their workplace and residence, and also decreases with housing costs Q_i. Workers' constant share of income spent on housing is $1 - \beta$ with $0 < \beta < 1$. Each worker has an idiosyncratic taste shock z_{ijof} for workplace-residence pairs which are randomly drawn from a Fréchet distribution such that $F(z_{ijof}) =$

$e^{-T_i E_j z_{ijof}^{-\varepsilon_f}}$ where T_i is the mean utility of living in i and E_j is the mean utility of working in j.

$$v_{ijof} = \frac{z_{ijo} B_i \overline{w(\varphi)}_j Q_i^{\beta-1}}{d_{ijf}} \tag{2.3.1}$$

Solution to the model yields the gravity equation (4.2.4) of commuting probability $\pi_{ij|i;f}$ between i and j subject to living in i. The equation relates wages and utility of working in locations j with costs of commuting from residences i to workplaces j and observed commute flows expressed as a probability of commuting between i and j. The so called bi-lateral resistance in the numerator is a product of wages $\overline{w(\varphi)}_j$ earned in a location j and the mean utility E_j of working in j discounted by commuting costs d_{ijf} of reaching a workplace j from a residence i. The denominator, so called multi-lateral resistance, is a sum of all products of the mean utilities and wages discounted by commuting costs for all locations s that are accessible from a residence i. Parameter ε_f is a Fréchet distribution dispersion parameter controlling variance of the idiosyncratic taste shocks of workers. The higher is the ε_f, the smaller are idiosyncratic taste shocks and the more responsive are workers to adjust their commuting subject to price signals given by wage differences across space. In other words labour supply increases with ε_f.

$$\pi_{ij|i;f} = \frac{E_j(\overline{w(\varphi)}_j / d_{ijf})^{\varepsilon_f}}{\sum_{s=1}^{S} E_s(\overline{w(\varphi)}_s / d_{isf})^{\varepsilon_f}} \tag{2.3.2}$$

The commuting probability equation (4.2.4) is used to derive commuting labour market clearing conditions, as number of workers with education f working in location j, H_{Mjf}, has to be equal to the summed products of population with education f living in i, H_{Rif}, and probability of commuting of that education group from i to j subject to living in i: $H_{Mjf} = \sum_{i=1}^{I} \pi_{ij|i;f} H_{Rif}; i,j \in \mathbb{N}$. Substituting equation (4.2.4) into that relation yields the commuting labour market clearing condition for a location j:

$$H_{Mjf} = \sum_{i=1}^{I} \frac{E_j(\overline{w(\varphi)}_j / d_{ijf})^{\varepsilon_f}}{\sum_{s=1}^{S} E_s(\overline{w(\varphi)}_s / d_{isf})^{\varepsilon_f}} H_{Rif} \tag{2.3.3}$$

Commuting costs are modelled as $d_{ijf} = e^{\kappa_f \tau_{ij}}$ iceberg commuting cost between i and j with a semi-elasticity κ_f measuring a log change of commuting probability given one unit increase in commuting time τ_{ij}. It is shown in the equation (2.3.3) the commuting costs are raised to the dispersion of tastes parameter ε both in the numerator and in the denominator. The product of the commuting semi-elasticity and the dispersion of tastes is defined as $\nu_f = \kappa_f \varepsilon_f$ so the commuting costs to the power of epsilon (from equation 2.3.3) could be written as: $(e^{\kappa_f \tau_{ij}})^{\varepsilon}_f = e^{\nu_f \tau_{ij}}$.

Workplace utility shocks E_j cannot be separately identified from the true wages $\overline{w(\varphi)_j}$ from data, so the predicted wage $w(\varphi)_j$ later used in the analysis is the wage paid in a location j as if E_j was constant across space and normalized to 1, meaning as if all benefits of working in any workplace were fully capitalized into wages. Then lets define a vector $\omega(\varphi)$ as wages to the power of dispersion of tastes parameter ε_f: $E_j\overline{w(\varphi)_j}^{\varepsilon_f} = w(\varphi)_j^{\varepsilon_f} = \omega(\varphi)_j$.

Substituting explicitly modelled iceberg commuting costs and the transformation of true wages $\omega(\varphi)$ into equation (2.3.3) yields the equation (2.3.4). In this equation $\omega(\varphi)$ is the only unknown variable as the other variables are observable and the parameter ε_f could be inferred from data. Ahlfeldt et al. (2015) show that equation (2.3.4) forms a system of I equations with a vector of I unknown $\omega(\varphi)$ and there exists a unique vector $\omega(\varphi)$ solving this system.

$$H_{Mjf} = \sum_{i=1}^{I} \frac{\omega(\varphi)_j / e^{\nu_f \tau_{ij}}}{\sum_{s=1}^{S} \omega(\varphi)_s / e^{\nu_f \tau_{is}}} H_{Rif} \tag{2.3.4}$$

The parameter ε_f is calibrated using relation shown in the equation (2.3.5). According to this equation, variance of log of observed wages should be equal to the $(1/\varepsilon_f)^2$ multiplied by variance of log of estimated wage differentials $\omega(\varphi)$. As distribution of wages is observed on the regional level, these distributions are used for the calibration.

$$\sigma^2_{\ln \widehat{w}(\varphi)} = (1/\varepsilon_f)^2 \sigma^2_{\ln \omega(\varphi)} \tag{2.3.5}$$

The last parameter to be estimated to be able to solve the equation (2.3.3) is ν_f, semi-elasticity of probability of commuting from i to j for workers of education f with respect to the distance between both places. This is done by using gravity equation with the following empirical specification:

$$\ln(\pi_{ij;f}) = \nu_f \tau_{ij} + \upsilon_i + \varsigma_j + \epsilon_{ijf} \tag{2.3.6}$$

To model discrete groups f of workers defined by their level of education φ separately and mutually independent, it is assumed workers of different education are perfect substitutes. Additionally, to keep the framework as simple as possible, it is assumed there are types of firms f, each employing workers of f education type, and all producing a homogeneous good:

$$Y_f = A(M)_f H_{M_f} f(\varphi) \tag{2.3.7}$$

Where output Y_f of a firm type f is a function of local total factor productivity that is itself a function of local density measured by jobs' market potential M, size of labour force H_{M_f} of education type f and its education φ. Education enters the production function within the function $f()$ which is monotonous and increasing in years of education.

$$A(M)_{jf} = \bar{A}_{jf} \left(\sum_{\tau_{js}=1}^{S} H_{M_{\tau_{js}}} e^{\delta_f \tau_{js}} \right)^{\lambda_f} \tag{2.3.8}$$

Local total factor productivity $A(M)_{jf}$ for a location j and firms' group f consists of exogenous component $\bar{A}_{jf}$ and endogenous component relying on distribution of economic activity around j. Distribution of economic activity around j is measured within discrete rings defined by time distance τ_{sj} from j to surrounding locations $s \in S$. Jobs in each ring are discounted by exponential decay function $e^{\delta_f \tau_{sj}}$ where δ_f is a decay parameter for an education group f. δ_f measures to what extent agglomeration economies dissipate in space. The whole jobs' market potential term is raised to the power of λ_f which captures the overall size of agglomeration economies for education group f. This functional form largely follows Ahlfeldt et al. (2015).

Commuting and heterogeneity in λ. The implications of heterogeneity of urbanisation wage elasticities λ_f for labour market formation for education groups f could be shown with comparative statics taking derivative of the probability of commuting from a residence i to a workplace j (equation 4.2.4, or its logged form in equation 2.3.9 for simplicity) with respect to the urbanisation wage elasticity λ. The equation 2.3.9 substitutes wages w_{jf} with the local productivity shifter and jobs' market potential $\bar{A}_{jf}\bar{H}_{M_j}$.

$$\ln(\pi_{ij;f}) = \lambda_f \varepsilon_f ln(\bar{H}_{M_j}) + \varepsilon_f ln(\bar{A}_{jf}) - \nu_f \tau_{ij} - ln \left(\sum_{s=1}^{S} (\bar{H}_{M_j}^{\lambda_f \varepsilon_f} \bar{A}_{jf}^{\varepsilon_f} / e^{\nu_f \tau_{is}}) \right) \tag{2.3.9}$$

The derivative of the equation (2.3.9) with respect to λ_f is shown in the equation (2.3.10) where $\varSigma'$ is the derivative of the last term of the equation (2.3.9).

If an economy consists of locations $\mathbb{N}$, then a change in commuting from a given residence i to any workplace j depends on the size of j's employment $\bar{H}_{M_j}$, dispersion of individual tastes ε_f and the term $\varSigma'$ which is however the same for all commuting pairs between i and $j \in \mathbb{N}$.

However, in general the result could be both positive or negative depending on the size of j's employment relative to the employment in all other locations in $\mathbb{N}$. This is intuitive as if a share of commuters to some locations increases, it has to decrease for others. Therefore a relative change in commuting for two possible workplaces is more straightforward to interpret.

$$\frac{\partial \ln(\pi_{ij;f})}{\partial \lambda_f} = \varepsilon_f ln(\bar{H}_{M_j}) - \varSigma' \tag{2.3.10}$$

The equation (2.3.11) shows an implication of the equation (2.3.10) how commuting from a residence i to two alternative locations j labelled 1 and

2, $(1,2) \in \mathbb{N}$, relatively changes when λ_f changes. All terms but $ln(\bar{H}_{M_1})$ and $ln(\bar{H}_{M_2})$ are the same, so all else equal the change in relative commuting probability from residence i depends solely on relative job's market potential of the two alternative workplaces.

The dispersion parameter ε_f controls relative change in commuting. With low ε_f, meaning high importance of individual idiosyncratic preferences, relative change in commuting will be minor. On the contrary, if ε_f is high, meaning preferences are more homogeneous across individuals, relative changes in commuting will be more pronounced.

$$\frac{\frac{\partial \ln(\pi_{i1;f})}{\partial \lambda_f}}{\frac{\partial \ln(\pi_{i2;f})}{\partial \lambda_f}} = \frac{\varepsilon_f ln(\bar{H}_{M_1}) - \Sigma'}{\varepsilon_f ln(\bar{H}_{M_2}) - \Sigma'} \tag{2.3.11}$$

All else being equal, if workers with higher education experience higher urbanisation economies λ_f, they will have spatially larger labour markets as it has been documented in the data. The definition of labour markets follows OECD (2012) where a spatial unit belongs to a labour market if the share of workers commuting to the agglomeration core (or one of agglomeration cores) exceeds given threshold.

It follows from equation (2.3.11) that if there is a marginal residential location i not integrated in any particular labour market with its high-density core j because the size of the commute flow ij is just below the threshold, increasing λ_f would lead to an increase in the size of commute flow ij which would exceed given threshold leading to integration of i into the labour market with its core in j.

Agglomeration wage elasticity models

The second part of the analysis is addressing the effect of labour market size on productivity. Contemporary literature has shown there are major limitations to inferring causal links between city size and productivity. Combes et al. (2010) mention two endogeneity problems: the endogenous quantity and quality of labour. The endogenous quantity of labour is a reverse causality problem: More productive areas might attract more workers who make these places larger and not vice versa. The endogenous quality of labour is caused by potential sorting of more able workers into more productive cities. The first endogenous problem could be tackled with instrumental variables while the second one is commonly overcome by using panel data with observations on an individual level including individual-level fixed effects. Unfortunately, individual-level data are not available in the Czech Republic so the labour quality endogeneity cannot be addressed in this analysis.

However, it worth mentioning de la Roca and Puga (2017) have brought new evidence into the discussion about the endogenous quality of labour. Based on their individual-level panel data from Spain they have found the return of acquired working experience with respect to a city size is persistent for an individual. In other words a worker moving from a larger city to a smaller one would have on average higher wage in the new location compared to her local peers all else being equal. They conclude models with individual fixed-effects omit this dynamic channel of a city size effect on productivity and also claim there is not sufficient evidence of sorting based on unobservable worker characteristics. Based on this argumentation I will assume in my analysis these findings hold also in the case of the Czech Republic and therefore I will not assume presence of sorting based on unobservables.

Urbanisation economies on a labour market level. The first empirical specification in the equation (2.3.12) is designed to be comparable with existing body of literature analysing agglomeration economies on the labour-market level. In the first section the model is estimated for a representative worker, and in the second section three separate models are estimated for the three groups of workers f defined by their education. The empirical specification for all the models is the same. Wages w_{brf} are aggregated from elementary statistical units to labour market areas b that are assigned to one of region r based on location of their core. Log of wage is regressed on log of labour market size H_{M_b} measured as a number of jobs, on a share of workers in 11 discrete categories of education within a labour market b, on a share of workers in 12 broad NACE industry categories within a labour market b and on a region fixed-effect R_f.

$$\ln(w_{brf}) = \lambda_f \ln(H_{M_b}) + \boldsymbol{EDU\beta_{1f}} + \boldsymbol{NACE\beta_{2f}} + \boldsymbol{R_f} + \epsilon_{brf} \qquad (2.3.12)$$

Due to the labour quantity endogeneity problem two stage least squares model with an instrumental variable is used. The instrumental variable is similar to the frequently used lagged population (Combes et al., 2010; de la Roca and Puga, 2017), but instead of population itself, size of housing stock measured by gross floor areas of buildings built before 1920 $H^{1920}_{M_{br}}$ is used. Although lagged population is available back to 1869 on the municipal level, the municipal level is too coarse for further models using finer geography. For that reason past housing stock is used in both models for consistency. The first stage of an econometric specification is as follows:

$$\ln(H_{M_{br}}) = \ln(H^{1920}_{M_{br}}) + \boldsymbol{EDU\beta_1} + \boldsymbol{NACE\beta_2} + \boldsymbol{R} + \epsilon_{br} \qquad (2.3.13)$$

Urbanisation economies on the local level. In the second part, importance of agglomeration economies on a very local geographical level is analysed. As in models on the labour-market level, first the model is estimated for a representative worker and later for the three sub-groups of workers defined by their education f.

Wages w_{jrf} measured at the level of elementary statistical units j located in a region r for an education group f are regressed on a job market potential measured as a sum of discounted jobs $H_{M_{\widehat{\tau_{js}}}}$ located in discrete distance bins s and separated from j by estimated commuting time $\widehat{\tau_{js}}$. Each discrete distance bin is discounted by exponential decay function $e^{\delta_f \widehat{\tau_{js}}}$ where δ_f is a distance decay parameter.

There are in total 29 distance bins. Minimal travel time even within an elementary statistical unit is defined to be 10 minutes, then there are one-minute steps until 30 minutes followed by two-minute steps until 50 minutes. Jobs further than 50 minutes are not considered. Additionally, shares of workers in NACE industries and share of workers by their education are included as controls.

$$\ln(w_{jrf}) = \lambda_f \ln\left(\sum_{\widehat{\tau_{js}}=12}^{50} H_{M_{\widehat{\tau_{js}}}} e^{\delta_f \widehat{\tau_{js}}}\right) + \boldsymbol{EDU\beta_{1f}} + \boldsymbol{NACE\beta_{2f}} + \boldsymbol{R_f} + \epsilon_{irf} \tag{2.3.14}$$

Equation (2.3.14) is first estimated with the GMM using R library momentfit (Chausse, 2022) to be able to jointly estimate both coefficients λ_f and δ_f. The model is estimated both under an assumption of exogeneity of surrounding economic activity, and assuming it is endogenous and instrumented by building stock built prior 1920. In this specification shares of workers by 11 categories of education and 21 NACE industries are included as controls, as well as region fixed-effects R_f.

After obtaining estimates of δ_f, $\sum_{\widehat{\tau_{js}}=12}^{50} H_{M_{\widehat{\tau_{js}}}} e^{\delta_f \widehat{\tau_{js}}}$ is evaluated for each j and the equation (2.3.14) is re-estimated with the conventional OLS and two stage least squares where evaluated job market potential is instrumented with respectively calculated market potential of building stock built prior 1920. In this specification county-level fixed effects are included, along with controlling shares of 11 education groups and shares of employment in 88 second-level NACE industries.

2.4 Data and wages calibration

Data used

The analysis is conducted at the level of Elementary statistical units (ESU) that are defined by the Statistical office as the smallest units for which data is reported. Jobs per ESU are very skewed to the right with median value of 21 and mean of 190. Size of ESU is less skewed with median 240 hectares and mean 354 hectares[19]. In total, there are 22,654 elementary statistical units,

[19] Map of geographical subdivision and distribution of population and ESU sizes are in the Appendix

but not all of them contain either jobs or residents. For that reason only 18,902 units with positive employment are used in the analysis. All key data are either originally reported on this geographical level, or are aggregated from exactly geocoded data to this geographical unit.

The key data source recording workers' commuting behaviour is 2011 individual-level Census. The subsample of working individuals was used, with almost 1.4 million observations for which commuting pattern and both places of work and residences are known. These observations count for almost half of all workers in the data[20].

In detail, 16% of all workers work in their home elementary statistical unit, 29% commute regularly elsewhere and 2% commute irregularly. For remaining workers commuting is unobserved an imputed based on observed commuters. Remaining workers consist of 12% whose place of work is unknown and 36% of workers for whom no commuting behaviour is recorded[21]. Lastly, there is 5% of workers without stable workplace. These workers are not included in the analysis.

Additional information from the Census used in the analysis are commuting times reported in discrete categories that were transformed into continuous variable. Using time distance reported in the Census provides more accuracy compared to a simple euclidean or network distance, and to some extent could be preferred to travel time models as one does not have to explicitly define starts and stops of trips as averaged reported durations already take into account spatial distribution of residences and jobs within individual geometries.

Information about workers' education was used to create continuous variable of years of schooling and also to define three sub-groups of workers. Low education group contains categories of no education, uncompleted primary education, completed primary education and secondary vocational education without state exam. Medium education contains vocational education with state exam, general secondary education and upper-secondary education. High education contains post-secondary vocational education, undergraduate (Bc.) education, graduate education (Master level) and postgraduate education (Dr.). Lastly, age of workers was included to be used as a control variable in the estimation of commuting time for unobserved workplace-residence pairs.

To construct an instrumental variable instrumenting population by elementary statistical units, dataset of statistical buildings provided by the Czech

[20] 37,248 observations of workers commuting abroad were all dropped as the analysis focuses on the area of the Czech Republic only. These workers also account only for 0.83% of workforce, excluding unemployed and women on maternity leave.

[21] In the third chapter of the thesis I do compare number of commuters in years 1991, 2001 and 2011. Unreported commuting behaviour is rather rare in both 1991 and 2001 Censuses and number of commuters is quite stable in these two periods, so the two could be used as a baseline. Then there is a substantial drop in commuting in 2011 if unreported commuting behaviour is not taken into account. However, if commuting is imputed for individuals with unknown commuting pattern, overall commuting in 2011 resembles volumes from 1991 and 2001.

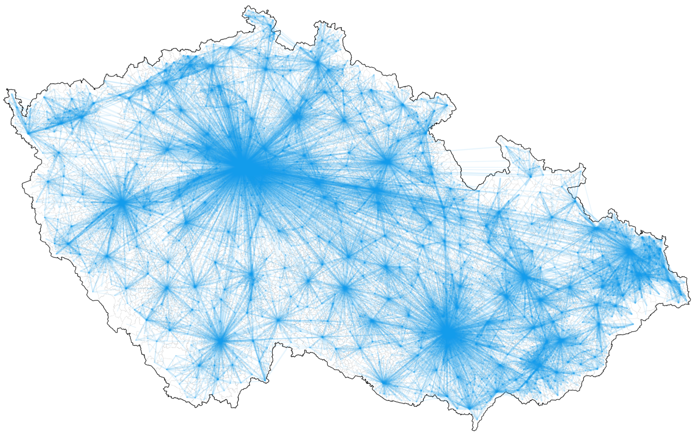

Figure 2.4.1: Commuting flows at a municipal level, at least 5 commuters

statistical office is used. The data has a form of a point geometry representing entrances into individual buildings with almost 2.8 million of observations.

Among others, the data contains information about period of construction or latest major refurbishment with earliest category of buildings built or renovated before 1920[22]. Then the data contains information about number of floors of a building. Both of these entries are primarily based on the 2011 Census which on top of information about individuals collected additional information about inhabited buildings. For that reason information about non-residential buildings could be missing. In particular, 30% of observations miss information about period of construction or refurbishment. This does not seem to be a major problem as the resulting variable is used to instrument population. Subset of buildings built or refurbished prior 1920 has approximately 227 thousand of observations (8% of current buildings), out of which only 3 were dropped because they were missing information about number of floors.

The point layer of building entrances was then merged with an area of buildings' footprints from the cadastral maps to construct resulting variable gross floor area which is a product of building footprint and a building floor count.

Wages resulting from the calibration of the quantitative spatial model could be only indirectly validated as wages, even for a sub-sample of population, are not available at a fine geographical level. To validate them, latest available wages reported by the Czech statistical office at the county level from 2004 were used. Additionally, distribution of calibrated wages was compared with nationally-binding minimum wage effective in 2011.

[22]Potential problem could arise from the fact that buildings demolished before 2011 are not included in the dataset. This however does not seem as a major threat in the Czech context as replacement of older buildings with newer ones is rather rare and even the Czech statistical office does not record any information about housing depreciation.

Wages estimation

Distance matrix. While observed commuting flows of workplace-residence pairs with number of commuters and their mean commuting time have in total 591 thousand observations, they cannot fill-in the full workplace-residence commuting matrix as some trips are in reality not taken.

However, the full commuting time matrix is necessary input into the quantitative spatial model to solve for unobserved wages. Additionally, by assumption, individual education groups use the same commuting technology and experience the same commuting times, so their commuting times obtained from the Census (that might differ for the same workplace-residence pair between education group) need to be replaced by values common for all the three groups.

To populate the whole commuting time matrix, observed commuting times τ_{ij} from residence i to workplace j are used to predict commuting times $\widehat{\tau_{ij}}$ for all combinations of $i \times j$ for which euclidean distance between i and j is less or equal than 60 kilometres. Maximum distance threshold is imposed due to the computational tractability. Including further locations would significantly slow down the algorithm estimating commuting times. Despite the 60 kilometre restriction, there are still 65.5 million linkages between workplaces and residences. Also as it is shown on the figure 2.4.2, there is only a small number of commutes longer than 60 kilometres.

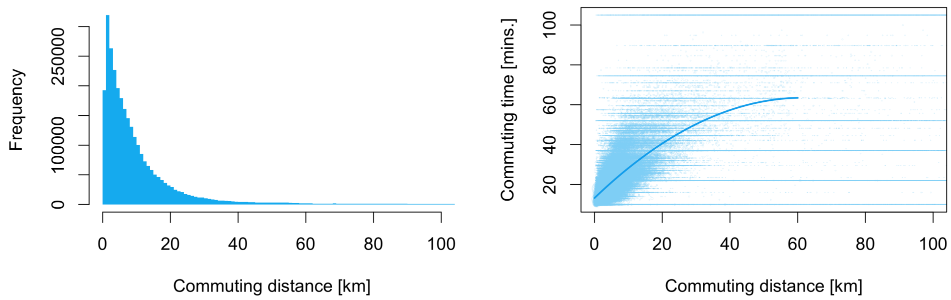

Figure 2.4.2: Commuting distance and commuting time

Commuting time model is shown in the equation (2.4.1). This model is individually estimated for each elementary statistical unit of workplace j. As individual observations are used commute flows ij with workplace in the given elementary statistical unit j. If there is less than 400 such observations, iterative algorithm adds surrounding destination workplaces s until minimum amount of 400 observations is reached. Data also contain some errors such as very short commuting times despite long commuting distances. For that reason outliers with residuals over 2 standard deviations are detected and dropped out of the dataset in the first stage and the model is re-estimated without them.

Observed commuting time τ_{ij} is regressed on a set of terms interacting distance and distance squared between i and j with an angle between i and j to its sixth power. The approach is inspired by Cheshire and Sheppard (1995) who in their hedonic model wanted to control for varying commuting speeds to the central business district from multiple directions, although they used a different functional form. Additionally, mean age of commuters and age squared are added as controls. Model is estimated as weighted least squares with number of commuters of each commute flow used as a weight.

The functional form of the equation (2.4.1) is sufficiently flexible to capture heterogeneous commuting speeds from different directions. As an example could serve the city of Liberec at the North of the Czech Republic which is locked between two mountain ranges and served by a highway from the South. As it is seen on the figure 2.A.4 in the Appendix, areas especially to the South of the city have much better connectivity than others. The drawback of the functional form is its discontinuity at the beginning and the end of the circle which measures angular deviation. With a limited number of data points at both ends, results for some elementary statistical units exhibited for instance non-monotonous changes in commuting times that is highly unlikely. To solve for this issue, model for each unit j was estimated twice, once with an angular deviation measured from the North, and secondly measured from the South, and higher of the two predictions of commute times was used.

$$\tau_{ij} = \beta_0 + \sum_{m=1}^{2} \sum_{n=0}^{6} \beta_{1mn} dist_{ij}^{m} angle_{ij}^{n} + \sum_{a=1}^{2} \beta_{2a} age_{ij}^{a} + \epsilon_{ij} \tag{2.4.1}$$

Resulting estimates of commuting times are aligned with expectations. Figure 2.A.5 shows mean commuting speed from distances between 8 to 12 kilometres. On average, larger cities are more congested and resulting speeds are lower. Slower commutes are also in places with more rugged terrain, such as in the North and the North-East.

Bi-lateral commuting resistance. The gravity equation (2.3.6) for the whole workforce is estimated with the Poisson Pseudo Maximum Likelihood estimator to take into account count data of number of commuters and then with the OLS estimator as a check. For all specifications only a subset of commutes shorter than 60 kilometres is used as these account for most of the observed trips while longer commutes are more frequently errors. Independent variable τ_{ij} is the mean commuting time aggregated from the data. Residence and workplace fixed effects are included in all specifications.

As it could be seen from the specifications (1) to (3), restricting sample to larger flows slightly increases magnitude of the estimate. Estimates using OLS are of half the magnitude when including all commute flows with more than 3 commuters, but the gap seems to narrow when restricting the sample to larger flows with at least 11 commuters. It seems commute flows with few commuters only are less regular with longer commutes and therefore drive estimated coefficient downward.

The estimated coefficients are smaller than ones reported by Ahlfeldt and Wendland (2016) who found -0.074 to -0.12 for area around Frankfurt am Main for commute flows of at least 10 commuters. Ahlfeldt et al. (2015) report -0.07 within Berlin[23]. For the rest of the analysis I choose $\nu = -0.36$ following the result from the preferred specification (2).

	Poisson likelihood			OLS	
	(1) all	(2) 3+ commuters	(3) 10+ commuters	(4) 3+ commuters	(5) 10+ commuters
ν	-0.031^{***}	-0.036^{***}	-0.042^{***}	-0.018^{***}	-0.029^{***}
	(0.000)	(0.001)	(0.001)	(0.000)	(0.001)
$\tau_{ij} \leq 60km$	✓	✓	✓	✓	✓
Res., work. FE	✓	✓	✓	✓	✓
pseudo.r.squared	0.023	0.021	0.016		
within.r.squared				0.121	0.177
nobs	537118	226933	54450	226933	54450

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are commuting flows between individual elementary statistical units (ESU).
Standard errors clustered at the level of ESU workplace.
All specifications are using only commutes shorter than 60 kilometers.

Table 2.4.1: Estimation of commuting probability time semi-elasticity

Estimates in the table 2.4.2 are also estimated according to the equation (2.3.6) with the Poisson Pseudo Maximum Likelihood on a subset of commute flows with more than 3 commuters, as in the specification (2) in the table 2.4.1. However, the three columns are estimates for distinct worker subgroups with low, medium and high education.

Unlike in the table 2.4.1, predicted commute time $\widehat{\tau_{ij}}$ is used instead of observed commute time. Smoothing the data with prediction instead of using observed data seems to affect estimates upwards in magnitude as all the three coefficients are strictly larger than the estimate for overall population reported in the specification (2) of the table 2.4.1. Estimates in the columns (1) to (3) are then used in the later stages of the analysis. Commuting costs are rather similar for Low and Medium educated workers and both are larger when compared to costs perceived by High educated workers. This pattern is consistent with Tsivanidis (2018), who found commuting costs in Bogotá to be -0.033 and -0.024 for low skilled and high skilled respectively.

As it has been already shown for a representative worker, the estimated parameter ν_f is a product of κ_f and dispersion of tastes parameter ε_f. Evaluating with the calibrated ε_f, resulting parameters κ_f are -0.0154 for low

[23] Although my estimates are lower, it should be added the coefficient ν is a product of κ and ε, heterogeneity in tastes parameter. As I show later, I calibrate ε at 3.13, unlike Ahlfeldt et al. (2015) with their value of 6.83. Calculating κ, I obtain -0.0115 that is quite close to -0.0148 by Ahlfeldt et al. (2015)

	Poisson likelihood / education groups		
	(1) Low	(2) Medium	(3) High
ν_f	-0.054^{***}	-0.060^{***}	-0.040^{***}
	(0.001)	(0.001)	(0.001)
$\tau_{ij} \leq 60km$	✓	✓	✓
Res., work. FE	✓	✓	✓
pseudo.r.squared	0.017	0.016	0.011
nobs	84147	82645	37119

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are commuting flows between individual elementary statistical units (ESU). Standard errors clustered at the level of ESU workplace.
Low education group contains no education, uncompleted primary education, completed primary education and secondary vocational education without state exam. Medium education contains vocational education with state exam, general secondary education and upper-secondary education. High education contains post-secondary vocational education, undergraduate (Bc.) education, graduate education (Master level) and postgraduate education (Dr.).
All specifications are using only commutes shorter than 60 kilometers and more than 2 commuters. Travel times are predicted according to the model (2.4.1).

Table 2.4.2: Estimation of commuting probability time semi-elasticity by education

educated, -0.0175 for medium educated and -0.0143 for high educated. Utility costs of commuting are therefore about similar for low and high educated, while they are slightly higher for medium educated.

This non-monotonicity could be caused by actual modal choices made with respect to education. Whereas low educated with low opportunity cost of time might use for their short commutes public transit whereas high educated with high opportunity cost of time might commute by car as such commuting is cheap relative to their wages so both groups end up with lower costs of commuting. For medium educated workers with longer commutes car commuting could be less affordable relative to their earnings.

Wages calibration. The labour market clearing condition expressed by the equation (2.3.4) is solved numerically with an iterative algorithm.

The procedure is done for each region separately while Prague and Central Bohemian region are treated as a one region because these two regions are functionally integrated, unlike remaining regions where inter-regional commutes are scarce[24] and are dropped to make the procedure computationally more feasible.

When calibrating the wage differentials within a region, Number of workers of education f in each elementary statistical unit $H_{M_{jf}}$ are represented by one equation (2.3.4). The only unknown is the unique vector of $\omega(\varphi)_j$. At the beginning of the algorithm, all wage proxies $\omega(\varphi)_j$ are set uniformly to equal 1 and with this vector $\omega(\varphi)_j$ predicted number of workers $\widehat{H_{M_{jf}}}$ for each location j is calculated. Based on the ratio between observed and predicted

[24] Inter-regional commutes account only for 6.7% of all trips when excluding commuting from Central Bohemia to Prague and vice versa.

number of workers $H_{Mjf}/\widehat{H_{Mjf}}$ wages are adjusted such that wages are adjusted proportionally to $H_{M_{jf}}/\widehat{H_{M_{jf}}}$. Algorithm is re-iterated until changes of vector $\omega(\varphi)_j$ between iterations are marginally small or until 100 iterations are reached. In case of wage models by education, convergence is reached mostly within ten to eleven iterations. The result is a vector of a function of wages $\omega(\varphi)_j$, which are being paid in each workplace j.

To calculate wages $w(\varphi)_j$, parameter ε is calibrated using the equation (2.3.5). As individual wages or sample of wages on the regional level are not observed, variance of actual wages was estimated fitting log-normal distribution through the reported 1st and 9th deciles, the 1st and 3rd quartile and median of regional wages. The fitted distributions are plotted in the appendix. Mean wage $\widehat{w}$ resulting from the fitted distribution, observed mean wage $\widetilde{w}$, the ratio of both estimated and observed wages, and two alternatively calibrated ε for each region are reported in the table 2.4.3.

To be consistent with the equation (2.3.5), both variances $\sigma^2_{\ln \widehat{w}(\varphi)}$ and $\sigma^2_{\ln \omega(\varphi)}$ should be either variances of individual-level wages or variances of wages for the respective geographical units. However, with the current model only mean wages for a workers' group and for each geographical unit could be calibrated, while observed information about distribution of wages is based on individual wages for each region. For that reason two alternative approaches are taken to calibrate ε.

ε_1 is calculated with variance of mean wages $\sigma^2_{\ln \omega(\varphi)}$ among elementary statistical units, instead of among individuals. As productivity and wages are highly heterogeneous, it is assumed variance of wages among elementary statistical units is larger than variance among individuals and therefore resulting ϵ will be overestimated.

ε_2 is calculated with variance $\sigma^2_{\ln \omega(\varphi)}$ of wages among modelled workers where each worker is assigned a wage by his or her workplace. This approach however smooths out variation in wages among workers in each workplace and thus leads to lower variance in wages than true variance is and as a result ϵ calculated with this method would be underestimated.

While it cannot be determined what the true bias of the two approaches to calculate ε is, the true value is believed to lay somewhere in between of the two values. Therefore average of the two population-weighted averages 3.13 is resulting preferred value.

To compare this result with other papers focusing on whole countries, Monte et al. (2018) estimate the parameter at 3.3 for the US at a county level and Bryan and Morten (2019) estimate 2.7 for the US and 3.2 for Indonesia. Calibrated ε at 3.13 therefore seems to be within reasonable range of existing estimates.

The same procedure used to calculate ε for a representative worker reported in the table 2.4.3 was used to calculate ε_f for the three education groups of

region	H_{M_r}	$\widetilde{w}$	$\widehat{w}$	$\widetilde{w}/\widehat{w}$	ε_1	ε_2
jic	163.44	23922.74	22872.81	1.05	4.04	3.30
jim	317.58	25952.85	24428.85	1.06	3.10	2.38
kar	75.03	21954.99	21055.12	1.04	4.63	2.62
kra	143.22	23255.33	22251.57	1.05	4.38	3.07
lib	108.10	24464.77	23169.77	1.06	4.28	2.76
mos	316.95	25922.33	23746.19	1.09	3.20	2.35
olo	156.04	23513.63	22191.93	1.06	3.86	2.77
par	133.56	23703.60	22757.71	1.04	4.24	3.28
plz	157.89	25190.67	23690.51	1.06	4.39	3.06
str	816.44	35083.90	32127.46	1.09	3.23	2.27
ust	190.57	24854.56	23002.79	1.08	3.68	2.40
vys	130.79	22992.90	22368.90	1.03	4.11	3.38
zli	160.00	23442.67	22366.97	1.05	3.76	2.80
w. mean					3.64	2.62
mean					3.13	

H_{M_r} is a size of regional labour market in thousands. $\widehat{w}$ is a mean wage calculated from the log-normal distribution fitted to the distribution of actual wages observed on the regional level with their mean $\widetilde{w}$.
ε_1 is based on wage distribution by elementary statistical units, ε_2 weights individual elementary statistical units by number of jobs.

Table 2.4.3: Calibrated ε for individual regions

workers. In the table 2.4.4 are reported workforce weighted mean ε_1 and ε_2, their standard deviations and resulting mean values of ε for each education group.

The results show ε is reasonable similar for workers with primary education and secondary education (high school), while it is approximately one third smaller for workers with college education and higher. Lower ε means relatively higher weight of individual idiosyncratic shock. In other words, a worker group with lower ϵ is less responsive to wage differentials as their individual idiosyncratic preferences for working in j and living in i have higher weight.

As individual idiosyncratic preference shock affects preferences for a workplace-residence pair, its relatively lower value could be driven by either the residence or the workplace components, or by both of them. If residential amenities are somewhat differentiated, more educated workers might have idiosyncratic preferences over some amenities and not others.

Another plausible explanation is via the workplace and labour market. Highly educated workers are likely more specialized and therefore less mutually substitutable. As a result, they might choose otherwise less probable workplaces, because jobs there might provide them with the best possible firm-employee match.

Calibrated nominal wages are shown on the map 2.4.3 below. The map shows significant wage differentials across space with high wages in urban cores, lower wages on urban fringes and in smaller towns and the lowest wages in regional peripheries.

Wages validation. Due to the data limitations, wages calibrated using

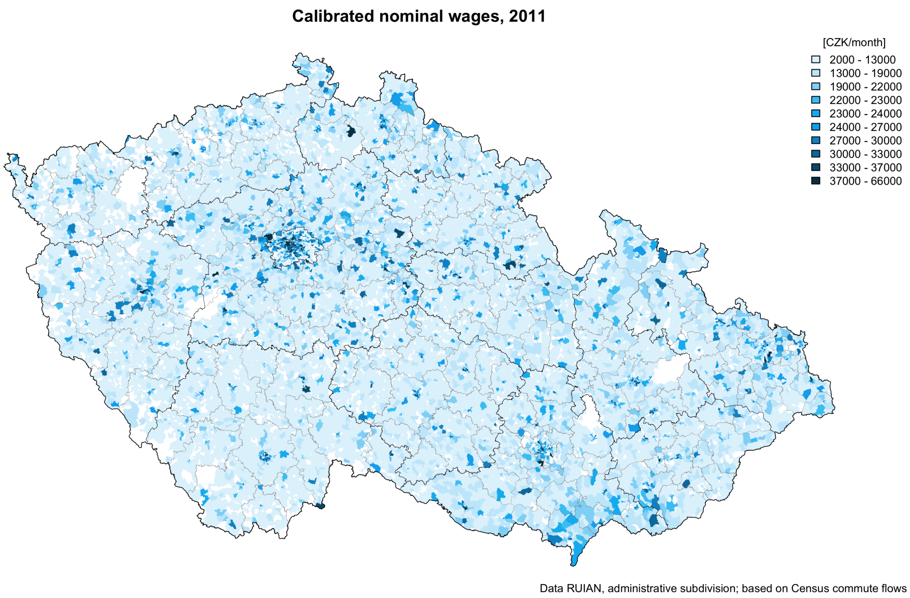

Figure 2.4.3: Wages by workplace

education	ε_1	σ_{ε_1}	ε_2	σ_{ε_2}	mean ε
low	4.13	0.40	2.92	0.53	3.52
medium	4.02	0.29	2.85	0.31	3.43
high	3.11	0.40	2.40	0.33	2.76

Table 2.4.4: Calibrated ε for education groups

the quantitative spatial model cannot be directly validated. However, two indirect validation exercises using older data reported on the county level, and comparison with a nationally-binding minimum wage level are performed.

First, calibrated wages by elementary statistical units are aggregated into counties, weighted by number of workers in each elementary statistical unit. These county-level calibrated wages based on 2011 data are compared with latest available administrative wage data by counties from 2004. These data are however not without issues: wages reported there are only for workers in firms above 20 employees and they are reported by county of firms' headquarters. This combined with a fact that observed wages pre-dates modelled wages by some seven years leads to likely lower match between observations and the model.

As it is seen on the figure 2.4.4, the fit between observed and modelled data looks reasonable. Modelled wages are calibrated to match mean wage on a regional level, so a proper way to test for predictive power of the quantitative spatial model is to include region fixed-effects. When including region fixed-effects and weighting counties by their size of workforce, correlation between the two is 0.5 and it decreases to 0.27 when counties are not weighted, showing more severe deviations for smaller counties.

Second, if the wage prediction by the quantitative spatial model is correct, minimal predicted wage should be reasonably close to the nationally binding minimal wage that was set at 8000 CZK per month (320 EUR) and effective

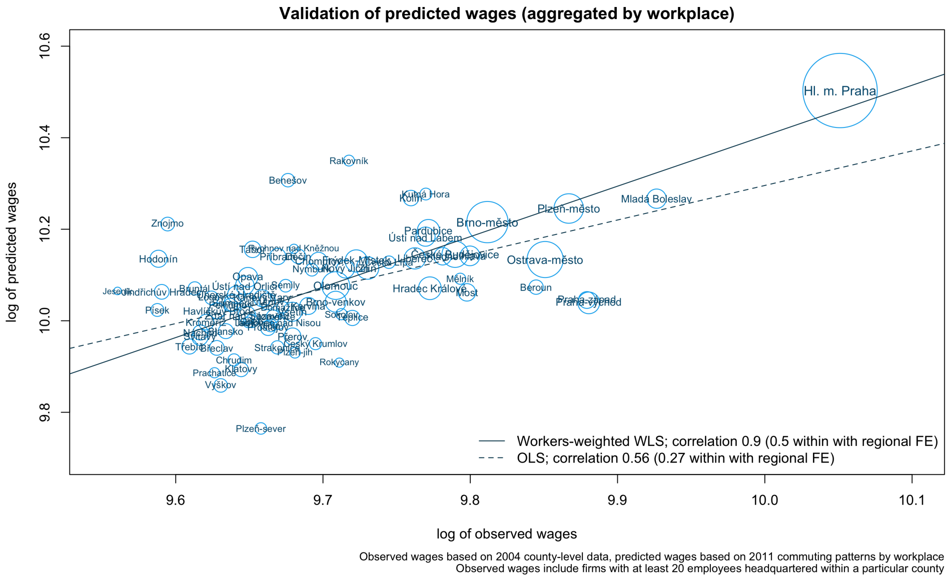

Figure 2.4.4: Predicted and observed wages, county level

between January 2007 and August 2013. The left histogram on the figure 2.4.5 with frequency of wages by elementary statistical units shows the modal wage to be slightly below the minimal wage. As the distribution is very skewed to the right, there is a limited number of observations with wages significantly lower than the mode. The reason why the mode is below the minimum wage could be partly driven by self-employed workers or workers in shadow economy who face lower or no taxation and social security contributions and therefore they are willing to accept lower wage before tax and social security payments which is inferred from the model.

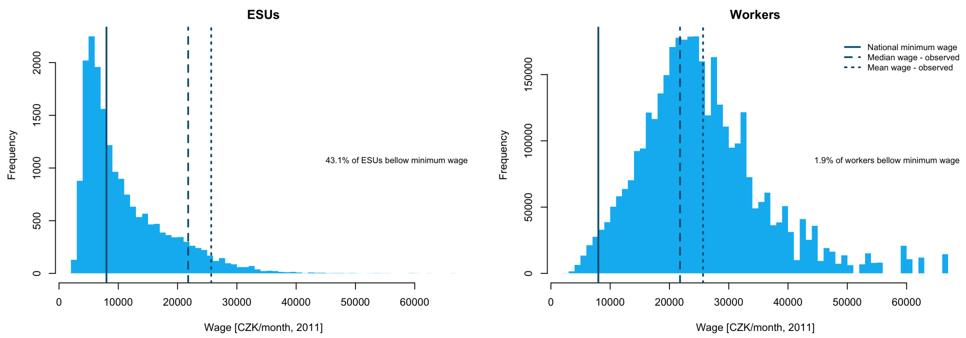

Figure 2.4.5: Wages distribution

It worth noting these low-wage elementary statistical units host actually small number of jobs as it is seen on the right histogram of the figure 2.4.5, where distribution of wages by individual workers is plotted. According to this plot, only 2% of workforce works for a wage below the minimum wage.

2.5 Estimation of urbanization economies

In this section mean wages resulting from the quantitative spatial model and for a representative worker are used in the second step to estimate magnitude of urbanisation economies. First, wages are aggregated to labour markets to easily compare results with existing literature, and second, magnitudes of urbanisation economies together with their spatial decay are estimated using detailed geographies of elementary statistical units.

Labour market level

The figure 2.5.1 shows mean wages for individual labour markets against number of workers in a given labour market. In this plot there are no controls and resulting wage elasticity with respect to city size is 0.11. That is very close to Glaeser and Resseger (2010) who report 0.13 for the US, measuring GDP per capita with respect to population. These results however cannot be interpreted causally, as the magnitude is likely biased upward due to workers' sorting both on observables and unobservables, and due to population size endogeneity.

Urbanisation economies on the labour market level are estimated according to the equation 2.3.12 and results are shown in the table 2.5.1. The column (1) is essentially the fitted line with a slope 0.11 from the figure 2.5.1 with region fixed effects included, but with no further controls. In the column (2) shares of workers by 11 education groups and shares of workers by 12 broad NACE categories are included. Including workers' education and industry decreases estimated coefficient only marginally.

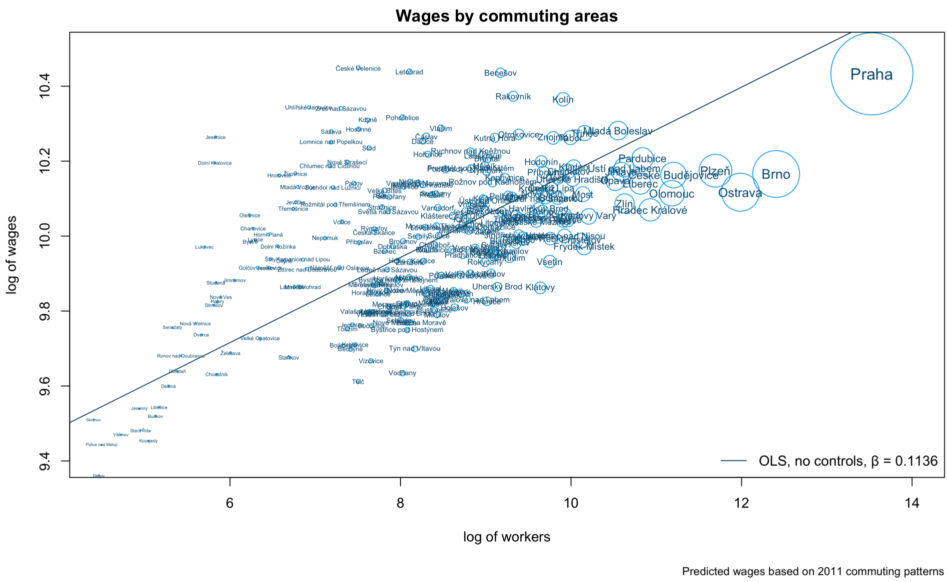

Figure 2.5.1: Wages by labour markets, no controls

To take into account possibility of endogenous population size caused by migration to more productive cities, model in the column (3) is re-estimated with the instrumental variable method. The labour market size is in the first stage regressed on gross floor areas of buildings built before 1920, an instrument conceptually similar to frequently used lagged population (Combes et al., 2010; de la Roca and Puga, 2017). The first stage is estimated according to the equation 2.3.13. The instrument has sufficient predictive power as Kleibergen-Paap statistics surpasses conventional threshold of 10.

The resulting urbanisation wage elasticity is estimated at 0.067. Combes et al. (2010) find decrease in urbanisation economies by approximately one fifth if they instrument labour market size. My results show decline roughly by one third on the labour market level suggesting stronger migration to productive cities.

Too compare findings with existing literature, my results are slightly higher but of the same orders. Ciccone and Hall (1996) report 0.06 for the US, Ciccone (2002) 0.045 for European countries and de la Roca and Puga (2017) 0.046 for Spain, in all cases referring to their results based on similar methodology. These results could be still biased upwards due to the sorting on unobservables that has been shown for instance by Combes et al. (2010). de la Roca and Puga (2017) come to the similar results when they use the same methods as Combes et al. (2010), but they argue inclusion of the worker fixed effect would underestimate the role of learning in big cities and cause urban wage premium to be in total biased downward. When they incorporate dynamic aspect of learning in cities, their medium-term wage elasticity rise to 0.05, so the dynamic effect of learning in big cities closes the gap in magnitudes of urbanisation economies when they are estimated with individual-level fixed effects and without them.

	(1) OLS	(2) OLS	(3) IV
λ	0.114***	0.108***	0.067**
	(0.019)	(0.014)	(0.020)
Kleibergen-Paap			201.2
Region FE	✓	✓	✓
Edu. share		✓	✓
NACE share		✓	✓
R^2	0.587	0.739	0.726
Adj. R^2	0.562	0.697	0.682
within.r.squared	0.491	0.679	0.663
nobs	251	251	251

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are labour market commuting areas. Standard errors clustered at the region level are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 12 broad NACE economic sectors.

Table 2.5.1: Agglomeration economies: OLS and IV by labour markets

Urbanisation economies on local area

In the second part, fine geographical detail of elementary statistical units is exploited to estimate not only magnitude of urbanisation economies, but also their decay across space. The underlying assumption is productivity increases with amount of economic activity in its proximity measured by number of jobs and the effect decreases with distance distance separating these jobs, as it is expressed in the equation 2.3.8.

To estimate urbanisation economies magnitude λ and spatial decay δ, the econometric specification 2.3.14 is used. As the specification is non-linear, conventional OLS or IV methods cannot be used and the equation is estimated with GMM using the R library momentfit (Chausse, 2022). The table 2.5.2 shows in the columns (1) to (3) results if surrounding economic activity is assumed to be exogenous and the columns (4) to (6) treat surrounding economic activity as endogenous and instrument it with gross floor areas of buildings built before 1920. The instrument is conceptually similar to the lagged population, but its advantage is that building data are available for the whole area of the country and are exactly geocoded, so they can be aggregated to small elementary statistical units for which historical population data are not available[25].

In all specifications employment within its own location j is excluded from the calculated jobs' market potential. The reason is inability to observe the size of employees' firm. There is a threat employment in a location j is correlated with firms' size in the location and as larger firms are expected to be more productive, not controlling for their size when regressing wages on local jobs' market potential would overestimate resulting urbanisation economies wage elasticity. Models where own employment in j was included indeed yielded substantially higher elasticities.

All specifications are estimated with region fixed effects as wages were calibrated on the regional level and there might be possibly some inconsistencies between regions, although wage levels in all regions were adjusted such that their weighted means match observed mean values on the regional level.

The columns (1) and (4) with no further controls show that the model does not yield any plausible. Adding shares of workers by 11 education groups in the columns (2) and (5) already helps to obtain reasonable results. Primary parameter of interest is δ which is be used in the following step in a conventional OLS and IV estimator. Estimated δ does not statistically differ between the two cases when surrounding economic is assumed to be exogenous, or to be endogenous and instrumented. In the last specification in the columns (3) and (6) additional controls of share of workers working in 21 NACE sectors are added. Although the specification assuming exogeneity in the column (3)

[25] On the labour market level, correlation between gross floor areas of buildings built before 1920 and 1869 population is 0.91, and correlation with 1921 population rises to 0.93.

yields some 30% larger estimate of δ, preferred instrumented specification in the column (6) with a value of -0.27 is not statistically significantly different from previous results in columns (2) and (5). Resulting decay is also reasonably close to the estimate of -0.36 by Ahlfeldt et al. (2015)[26].

	Without instrument			Instrumented		
	(1)	(2)	(3)	(4)	(5)	(6)
λ	-0.003	0.179^{***}	0.137^{***}	-0.002	0.086^{***}	0.065^{***}
	0.004	0.011	0.010	0.005	0.011	0.011
δ	-28.118	-0.331^{***}	-0.414^{***}	-28.118	-0.300^{***}	-0.274^{***}
	38.872	0.017	0.030	82.388	0.035	0.043
Region FE	✓	✓	✓	✓	✓	✓
Edu. share		✓	✓		✓	✓
NACE share			✓			✓
Num. obs.	18768	18768	18768	18768	18768	18768

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are elementary statistical units (ESU) with positive employment. Standard errors are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 21 1st level NACE economic sectors.

Table 2.5.2: Urbanisation economies decay estimation

The estimated coefficient δ of -0.27 confirms that urbanisation economies are very local in nature. To evaluate estimated coefficient, effective importance of economic activity in a given distance could be calculated. If an economic activity producing spillovers moves from an original distance of 5 minutes from j to a new distance 10 minutes away from j, its spillovers would decrease to one fourth ($e^{-0.27\times10}/e^{-0.27\times5}$).

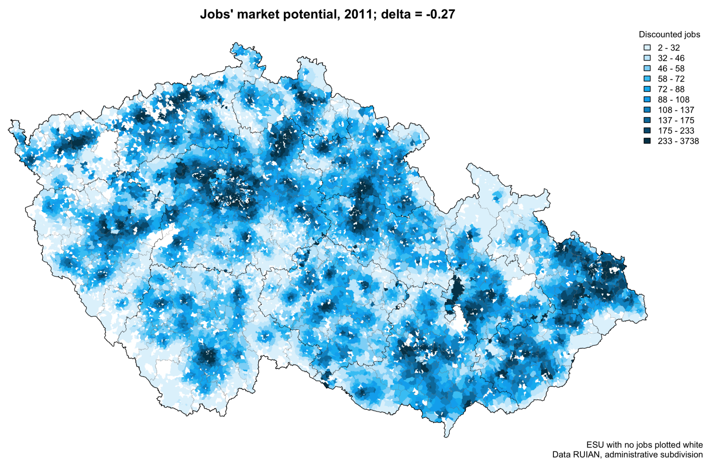

Figure 2.5.2: Jobs' market potential

[26]In an earlier version of the paper, value of the distance decay parameter was obtained algorithmically running equation 2.3.14 repeatedly with different values od δ and choosing preferred one which minimized sum of squared errors. Despite using data on municipal level and approximating time with a square root of distance, resulting δ was -0.38 which is within the range of estimates obtained with GMM.

Effective jobs' market potential for each elementary statistical unit j evaluated at the decay parameter $\delta = -0.27$ is visualized on the map in figure 2.5.2. The map shows in darker colour places with major jobs' concentration, such as Prague, regional capitals and county seats, and in light colours areas of regional peripheries. There is however a lot of variation even on a city level as it could be seen in the case of Prague - while the centre and the East have among highest market potentials, hilly, less connected and more residential North-west reaches quite lower values.

Calculated jobs' market potential using estimated parameter δ is used as a regressor in the equation 2.3.14 re-estimated with OLS and IV estimators. In these specifications more granular fixed effects and more NACE categories are included as the problem is less computationally demanding compared to the previous GMM estimation.

The column (1) of the table 2.5.3 reports urbanisation economies without any further controls. Resulting value of 0.26 is quite high, especially when compared with results in the columns (2) and (3) where shares of workers by education and NACE industries are added. In these subsequent models estimates decrease approximately to two thirds of the original value in the column (1). Compare this result with the table 2.5.1 where wage elasticity with respect to the overall labour market size was measured. Adding education and industries controls there changed results only marginally. It could be concluded more productive industries or more educated workers are on average not that much sorting into larger labour markets, but they do sort on a local scale with more productive industries and more educated jobs being located in more central and denser locations.

The columns (4) and (5) instrument jobs' market potential with gross floor areas of buildings built before 1920. The resulting coefficients drops to approximately one half of the estimates using OLS. This decrease is again more pronounced than for the models on the labour market level. The interpretation is that jobs sort to more productive places relatively more within a labour market than between labour markets.

When comparing results for the labour market areas and for local elementary statistical units, the overall pattern of higher magnitudes obtained at the local level is consistent with findings by Ahlfeldt and Pietrostefani (2019). They estimate the elasticity of density with respect to population for OECD countries at 0.43 and based on this result they conclude the wage elasticity should be roughly slightly more than twice larger with respect to density than with respect to population. In the appendix I show association between population and density for the Czech Republic with estimated elasticity of 0.3. This suggests estimated wage elasticities with respect to density should be approximately three times larger than with respect to population. This roughly holds for models without any controls: 0.26 in the column (1) of the table

	(1) OLS	(2) OLS	(3) OLS	(4) IV	(5) IV
λ	0.258***	0.163***	0.165***	0.080**	0.096***
	(0.029)	(0.020)	(0.013)	(0.026)	(0.023)
Kleibergen-Paap				107.0	431.4
Region FE	✓	✓		✓	
County FE			✓		✓
Edu. share		✓	✓	✓	✓
NACE share		✓	✓	✓	✓
R^2	0.212	0.415	0.447	0.406	0.441
Adj. R^2	0.212	0.412	0.442	0.403	0.436
within.r.squared	0.121	0.347	0.322	0.337	0.315
nobs	18768	18768	18902	18768	18768

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are elementary statistical units (ESU) with positive employment. Standard errors clustered at the level of fixed effects are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 88 2nd level NACE economic sectors.

Table 2.5.3: Urbanisation economies with distance decay

2.5.3 and 0.11 in the column (1) of the table 2.5.1. The difference in preferred IV specifications is however smaller, with 0.10 for density in the column (5) of the table 2.5.3 and 0.07 for population size in the column (3) of the table 2.5.1. Empirically, Melo et al. (2009) in their meta-analysis find estimates for densities to be larger by 0.01 to 0.03, but this finding is not statistically significant.

2.6 Heterogeneity in urbanization economies

In this section models of urbanisation wage elasticities are re-estimated for the three worker subgroups defined by their education: Low, Medium and High. The low education group consists of workers with no education, uncompleted primary education, completed primary education and secondary vocational education without state exam. The medium education group contains vocational education with state exam, general secondary education and upper-secondary education. The high education group contains post-secondary vocational education, undergraduate (Bc.) education, graduate education (Master level) and postgraduate education (Dr.).

Local high to low education wage premium for municipalities with extended powers[27] (abbreviated as 'ORP' in Czech) is shown on the figure 2.6.1. Although there is in general some noise, major cities such as Prague and Brno can be easily identified as large clusters with substantial wage premium for high-educated. On the other hand, hinterlands of these large cities have rather small high education wage premium. Additionally, post-industrial regions with low amenity values, such as the North-West and to a lesser extent

[27] Aggregated from elementary statistical units for which both types of jobs are present.

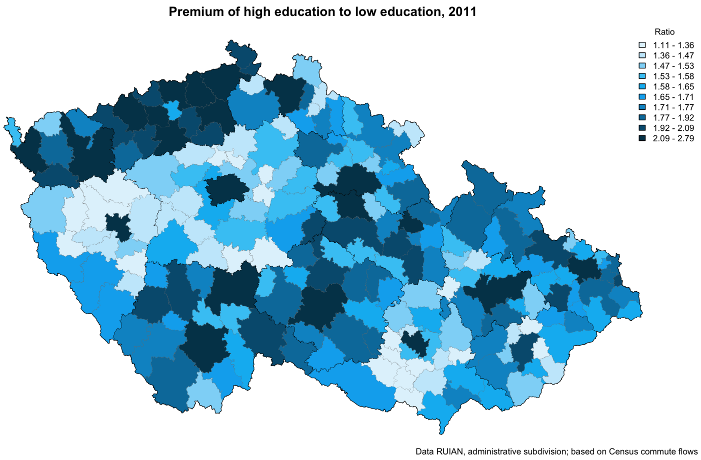

Figure 2.6.1: High to low education wage premium

the East, have substantial high-education premiums. This result is consistent with the Rosen-Roback framework if low educated are (much) less sensitive to amenities than high educated (Moretti, 2004; Diamond, 2016).

Labour market level

Models on the labour market level are estimated according to the equation 2.3.12. Results in the table 2.6.1 below mimic the columns (2) and (3) of the table 2.5.1 which shows estimates for a representative worker. All specifications include region fixed effects defined by location of the labour markets' core. Then all specifications contain a share of workers by education and a share of workers by NACE industry as controls. In the columns with even numbers labour force size is instrumented with gross floor areas of buildings built before 1920.

First, differences between OLS and IV are similar to the results for a representative worker, as the estimated urbanisation wage elasticity coefficients drop roughly to one half. Additionally, results for a representative worker are almost the same as results for medium-educated workers reported in the columns (3) and (4) of the table 2.6.1.

Regarding magnitudes of the estimated coefficients with respect to the education of workers, the results are consistent with existing literature with urbanisation wage elasticity growing with level of education.

Preferred IV specification yields the elasticity of 0.038 for low-educated (which is not statistically different from zero), 0.068 for medium educated and only slightly higher value of 0.075 for high-educated. This pattern of results is similar to Ahlfeldt et al. (2021) who also find lower estimated elasticity for workers with primary education than for workers with either secondary or tertiary education, for whom the estimates are similar[28].

[28] Additionally, their estimated difference is more pronounced for workers over 30 years of age and for women.

	Low edu.		Medium edu.		High edu.	
	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
λ_f	0.083***	0.038	0.103***	0.068***	0.136***	0.075*
	(0.014)	(0.024)	(0.013)	(0.015)	(0.016)	(0.027)
Kleibergen-Paap		116.8		144.5		88.1
Region FE	✓	✓	✓	✓	✓	✓
Edu. share	✓	✓	✓	✓	✓	✓
NACE share	✓	✓	✓	✓	✓	✓
R^2	0.595	0.570	0.741	0.729	0.734	0.715
Adj. R^2	0.515	0.485	0.686	0.673	0.649	0.623
within.r.squared	0.541	0.513	0.696	0.683	0.681	0.658
nobs	207	207	197	197	141	141

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are labour market commuting areas. Standard errors clustered at the region level are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 12 broad NACE economic sectors.

Table 2.6.1: Agglomeration economies: OLS and IV by labour markets and education

Urbanisation economies on local area

To analyse localised nature of urbanisation economies, the procedure for the three education groups is the same as for a representative worker which was described in the previous section. First, distance decay parameter δ_f is estimated for each education group, and second, jobs' market potential is evaluated with the parameter δ_f and used as a regressor in standard OLS and IV models.

Results in the table 2.6.2 are estimated according to the equation (2.3.14). The odd-numbered columns correspond to the column (3) and the even-numbered columns correspond to the column (6) of the table 2.5.2 with estimates for a representative worker.

When looking at the estimates of δ_f, the magnitudes are broadly similar in five out of six specifications. In case of non-instrumented result for high-educated workers, the model did not yield plausible results. Estimates of preferred IV specifications are very similar across all three education groups and in fact cannot be distinguished one from the other on conventional confidence levels.

It is a priori unclear whether δ_f controlling the spatial decay of productivity spillovers should differ by education or not as there are the three Marshallian channels operating at the different spacial scales: input-sharing on a large scale, knowledge spillovers very locally, and labour pooling on all scales (Rosenthal and Strange, 2001) and these channels might differ in terms of their importance by workers' education group. It is anyway a curious result the spatial decay of urbanisation economies is about the same for all three education groups.

	Low edu.		Medium edu.		High edu.	
	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
λ_f	0.081***	0.021*	0.122***	0.041***	−0.001	0.060***
	0.007	0.009	0.009	0.010	0.011	0.017
δ_f	−0.378***	−0.297***	−0.437***	−0.324***	−28.118	−0.277***
	0.025	0.090	0.030	0.064	21.727	0.056
Region FE	✓	✓	✓	✓	✓	✓
Edu. share	✓	✓	✓	✓	✓	✓
NACE share	✓	✓	✓	✓	✓	✓
Num. obs.	17467	17467	16307	16307	12622	12622

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are elementary statistical units (ESU) with positive employment in given educational level. Standard errors are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 21 1st level NACE economic sectors.

Table 2.6.2: Urbanisation economies decay estimation, education groups

To compare, for within-industries localisation economies, distance decay has been found to vary substantially, with higher decay for services or IT and lower decays for manufacturing (Rosenthal and Strange, 2004; Arzaghi and Henderson, 2008).

Estimated δ_f are used to calculate jobs' market potential for each education group. The table 2.6.3 shows results estimated according to the equation (2.3.14) with odd-numbered columns corresponding to the column (3) and even-numbered columns corresponding to the column (5) of the table 2.5.3 with a representative worker results. As in the previous specifications, gross floor area of buildings built before 1920 is used as an instrument.

The preferred IV specifications again show drop in the magnitude of estimated coefficients when compared to the OLS estimates. Estimate for a representative worker using IV estimator was 0.096 (table 2.5.3, column (5)) that is rather close to the estimate for high-educated in the column (6) of the table 2.6.3. This suggests the overall magnitudes estimated for educational groups are slightly lower than for a representative worker. However, standard error for medium-educated workers in the column (4) does not rule out possibility the number is the same as 0.096 on conventional confidence levels.

The pattern of estimated urbanisation wage elasticities at the local level is the same as for labour market level. The magnitude of elasticity is growing with education and the elasticity for high-educated is more than three times as large as for low-educated workers. Additionally, the estimated magnitudes for low and medium educated workers are about the same for both labour market level and detailed local level using jobs' market potential. However, for the high-educated the wage elasticity on local level is almost 50% larger than on the labour market level. It is fair to add the estimate is less precise

	Low edu.		Medium edu.		High edu.	
	(1) OLS	(2) IV	(3) OLS	(4) IV	(5) OLS	(6) IV
λ_f	0.092***	0.033*	0.127***	0.067***	0.170***	0.110***
	(0.010)	(0.015)	(0.011)	(0.016)	(0.015)	(0.030)
Kleibergen-Paap		415.5		424.3		296.4
County FE	✓	✓	✓	✓	✓	✓
Edu. share	✓	✓	✓	✓	✓	✓
NACE share	✓	✓	✓	✓	✓	✓
R^2	0.384	0.378	0.426	0.420	0.442	0.439
Adj. R^2	0.377	0.372	0.419	0.413	0.434	0.431
within.r.squared	0.302	0.295	0.335	0.328	0.347	0.343
nobs	17467	17467	16307	16307	12622	12622

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are elementary statistical units (ESU) with positive employment. Standard errors clustered at the county level are shown in parentheses.
Gross floor areas of buildings built before 1920 are used as an instrument.
Edu. share controls for share of workers by their education (11 groups). NACE share controls for share of workers working in 88 2nd level NACE economic sectors.

Table 2.6.3: Urbanisation economies with distance decay, education groups

than the estimates of the two groups with lower education, but the result is supportive of the claim that high education occupations are the ones most benefiting from urban density, possibly due to the knowledge spillovers and ease of communication.

2.7 Conclusions

This chapter investigated urbanisation wage elasticities, which are positive effects of the size of local labour markets on workers' wages, in the Czech Republic where detailed wage data are not available. Urbanisation wage elasticities were estimated for a representative worker and for three groups by workers' education: low-educated with mostly primary education, medium-educated with mostly secondary education and high-educated with mostly tertiary education.

To overcome the problem of unobserved wages, a quantitative spatial model following Ahlfeldt et al. (2015) was used. In particular, a commuting market clearing equilibrium condition linking wages, commuting costs and number of workers by their place of residence and number of workers by workplace was used to infer wages when all the other variables are observed. Given detailed spatial data aggregated from the individual-level 2011 Census, wages across the country are calculated for almost 19 thousand small geographical units.

Calibrated wages from the quantitative model are then regressed in the second step on a measure of labour market size. First, local labour market size is measured as the number of jobs in the whole labour market defined by commuting patterns following OECD functional urban area delineation methodology (OECD, 2012). Second, to be able to capture the localised nature of urbanisation economies, geographical detail of the data is exploited to construct local job market potential summing all jobs around each location up to 60 kilometres and discounting them by time distance.

To account for endogenous city size or local job concentration, all preferred specifications were estimated with the instrumental variable estimator using gross floor areas of buildings built prior to 1920 as an instrument. Conceptually, the instrument is similar to lagged population, but due to the exact geocoding of each building it can be aggregated to smaller geographical units used in the analysis.

For a representative worker, urbanisation economies at the labour market level were estimated at 0.067, at the upper bound reported in the literature. The elasticity at the local level using job market potential was estimated at 0.096 with distance decay of -0.27. When compared to Ahlfeldt et al. (2015), elasticity is slightly higher and distance decay slightly less steep.

For the three workers' education groups, urbanisation wage elasticities were found to rise with education achieved. On a labour market level, estimated elasticities are 0.038 (insignificant), 0.068 and 0.075 for the low, medium and highly educated respectively. Localised urbanisation wage elasticities measured with job market potential are 0.033, 0.067 and 0.110 for the low, medium and highly educated respectively, with the distance decay parameter close to -0.3 for all three groups.

The chapter brings several new insights. First, observed commuting patterns coupled with commuting times could be used to study agglomeration wage elasticities without observing wages directly. With the increasing availability of localised cell phone data and travel time data from web services, this approach could be used to estimate agglomeration economies across countries within a single methodology and with the same data.

Second, the chapter adds another piece of evidence to still scarce literature on heterogeneity in agglomeration economies by education or skills. The results confirm increasing urbanisation economies with education achieved, and the effect is more pronounced at a local level, although spatial decay of urbanisation economies for all groups is about the same.

Third, the chapter contributes to the literature on Czech economic geography and labour markets as it is, to my knowledge, the first paper to analyse agglomeration wage economies in the country on a detailed geographical level due to the notorious lack of wage data reported for sufficiently small geographical units.

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2.A Appendix

Administrative subdivision

The figure 2.A.1 shows administrative subdivision of the Czech Republic, particularly spatial units used in the analysis. The Czech Republic consists of 13 self-governing regions (thicker grey colour on the map) as an intermediate governing level between the state and municipalities. Additionally to the regions there is the capital city of Prague that has self-governing powers both of a region and a municipality.

Then there are 76 counties (thinner grey on the map) that used to define jurisdictions of local state administration offices before the public administration reform in 2000's which replaced counties with self-governing regions. The capital city of Prague was an exception and was subdivided into 10 districts being equivalents to counties. However, in this analysis Prague is treated as a one distinct county. Although counties are nowadays rarely used for public administration purposes, they are still convenient as a subdivision of the country into smaller units.

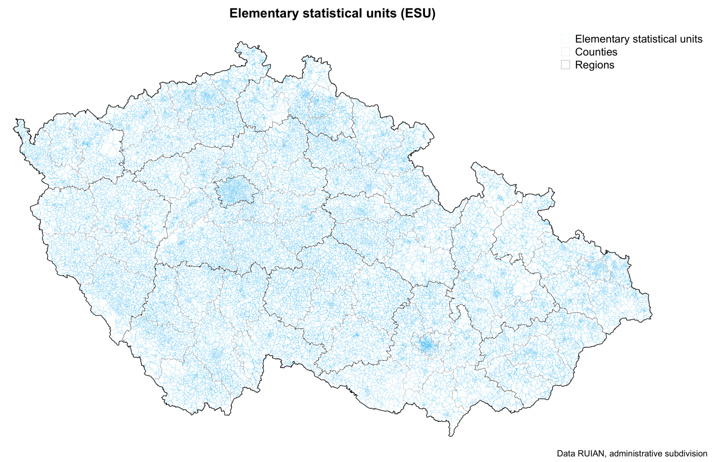

Figure 2.A.1: Administrative subdivision

The smallest unit in the Czech Republic for which statistical data are available are elementary statistical units (ESU, light blue on the map). They usually have hundreds to thousands of inhabitants and smaller municipalities frequently have only one ESU. Distribution of jobs by ESU and their sizes is shown on the figure 2.A.2.

Distribution of jobs is skewed to the right with few ESUs having thousands of jobs. Otherwise the mode is around 8 jobs per ESU. Modal area of an ESU is around 400 hectares that would correspond to a square with an edge 2 kilometres long. Larger ESUs are rather exceptional.

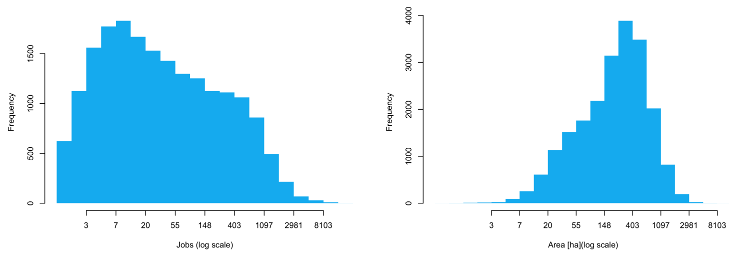

Figure 2.A.2: Elementary statistical units population and size distribution

Data sources and processing

The primary data source, individual-level 2011 Census data, were obtained directly from the Czech statistical office. The source individual data were aggregated to the ESU units for further analysis.

In an earlier version of the chapter and for the purpose of defining individual labour markets, commuting flows on municipal level from 2011 Census were used[29]. All commute flows on municipal level are provided with source and destination municipal codes to allow matching to spatial data. The data are split into two databases. In the main database all commute flows are reported and for the purpose of the analysis only regular daily commutes are used. The second part of the data reports only commute flows with more than 10 commuters. For these flows, among others, number of commuters by education is reported. However, these commutes contain both regular and irregular commuters.

Administrative subdivision of the Czech Republic is provided on the geoportal of the Cadastral Office[30]. Dataset with information about individual buildings was acquired from the Czech statistical office[31]. County-level 2004 wage data were partly downloaded from the regional offices of the Czech statistical office and for regions not reporting these archived data they were requested directly from the Czech statistical office. Regional wage statistics for 2011 were obtained from the Ministry of Labour and Social Affairs[32].

The whole analysis was done in R (R Core Team, 2019). Data in Excel were uploaded using 'readxl' package (Wickham and Bryan, 2019). Data manipulations were done using 'dplyr' package (Wickham et al., 2019) and 'stringr' package (Wickham, 2019). Spatial data manipulations and visualizations were done with 'sp', 'sf' and 'rgdal' packages (Pebesma and Bivand, 2005, Pebesma, 2018, Bivand et al., 2019). To fit log-normal distribution through observed quantiles package 'rriskDistributions' was used (Belgorodski et al., 2017). Econometric models were estimated with core function lm and package 'fixest' (Bergé, 2018). Poisson likelihood models were estimated with a library

[29] Data provided on DVD, item 170215-14, ISBN:978-80-250-2539-0
[30] https://www.cuzk.cz
[31] https://www.czso.cz/csu/rso/budovy-s-cislem-domovnim-vchody-bod
[32] https://www.mpsv.cz/web/cz/aktualni-publikace-jednotlivych-kraju

'gravity' (Woelwer et al., 2020). Model results and tables were exported to Latex with 'texreg' and 'xtable' packages (Leifeld, 2013; Dahl et al., 2019).

Labour markets

Definition of labour markets in general follows methodology of functional urban areas (FUA) by OECD (2012) which is based on observed commute flows. Using 2011 municipal-level Census data, each municipality is assigned into a labour market if at least 15% of its workforce commutes to the labour market core, or any other municipality within the labour market. For commuting areas defined for education groups, 15% of workers within respective education group is used as the threshold. Unlike in OECD (2012), there is no minimal size of of a labour market core. Overall labour markets are shown on the figure 2.A.3.

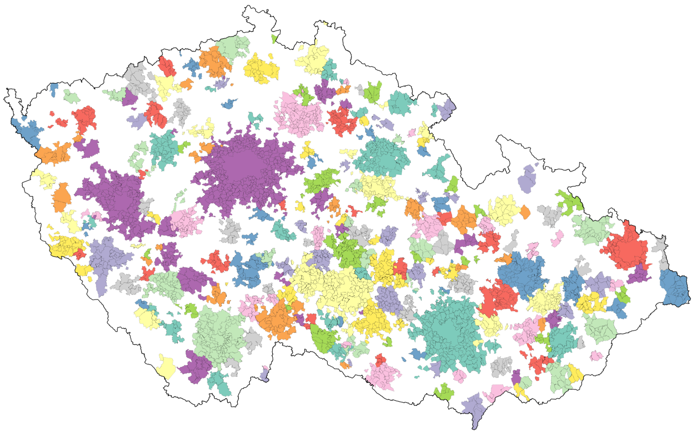

Figure 2.A.3: Defined labour markets

Commuting times

to estimate commuting times between all pairs of residences and workplaces up to 60 kilometres apart, relatively flexible model inspired by Cheshire and Sheppard (1995) is used. The model includes polynomial up to the sixth degree of angular deviation between workplace and residence from a given direction and these terms are interacted with linear and quadratic distance. As a result, commuting travel speed and its concavity differs by commuting direction providing sufficiently good prediction of travel times between workplace-residence pairs that are not observed in the data.

Each model for each ESU is estimated with at least 400 observations. In most cases there are not that many commute flows terminating in an ESU, so required minimum of 400 commute flows are selected also from neighbouring ESUs algorithmically increasing distance by 1 kilometre steps until target 400 commute flows are reached. Mean distance of included commute flows is 6.4

kilometre, 3rd quartile 9 kilometres and maximum 30 kilometres. Additionally, the model is in the first stage estimated according to the equation (2.4.1) and extreme observations with residuals above or below 2 standard deviations are dropped. On average, 5.7% of observations are not therefore included in final estimation. Mean R squared for all 22,654 models is 0.70 with standard deviation of 0.079 so the models have relatively good fit.

Example of modelled commute time for the central area of the regional capital Liberec is shown on the figure 2.A.4. Heterogeneity in commuting speed with respect to direction could be easily seen. Access from the South via highway to Prague is particularly fast compared to all other directions. While Liberec is rather extreme in its differences in commuting speed due to its location in mountains, the map shows how flexibly the method used accommodates such heterogeneity with respect to direction.

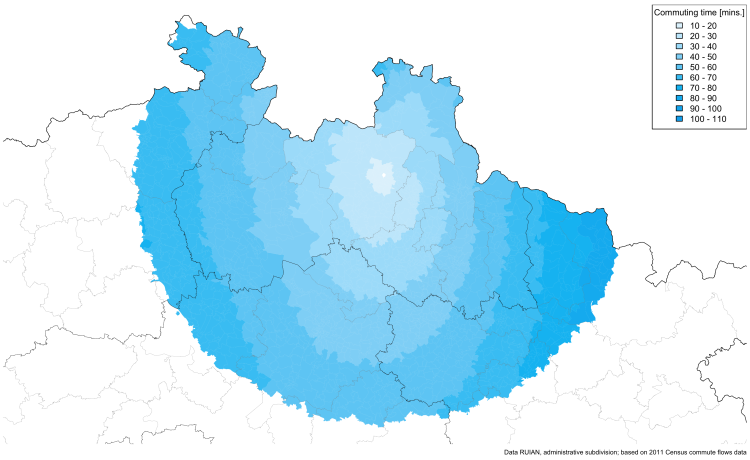

Figure 2.A.4: Predicted commuting times to Liberec

Figure 2.A.5 shows evaluated mean commuting speed to each elementary statistical unit from other elementary statistical units eight to twelve kilometres away. The map reveals some expected patterns: commuting to larger cities is slower likely due to congestion while commuting speed is relatively high in remote areas with exception of hilly and mountainous regions, for instance along the Northern national border.

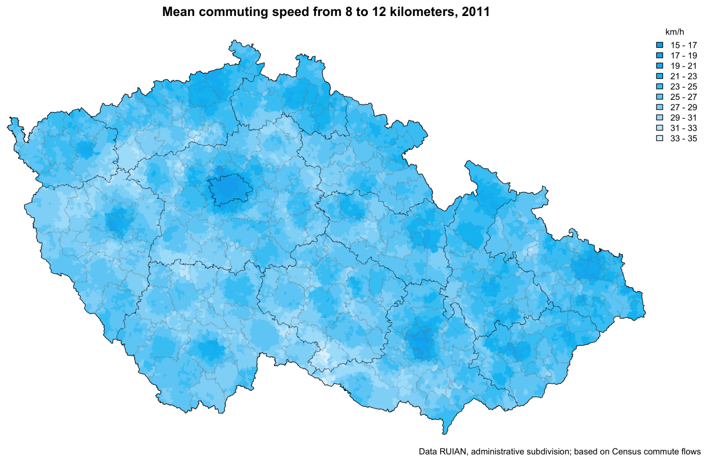

Figure 2.A.5: Predicted commuting speed

Jobs' market potential

Mean local employment density for a labour market measured as jobs' market potential in each elementary statistical unit weighted by its overall employment is positively correlated with overall labour market employment as it is shown on figure 2.A.6.

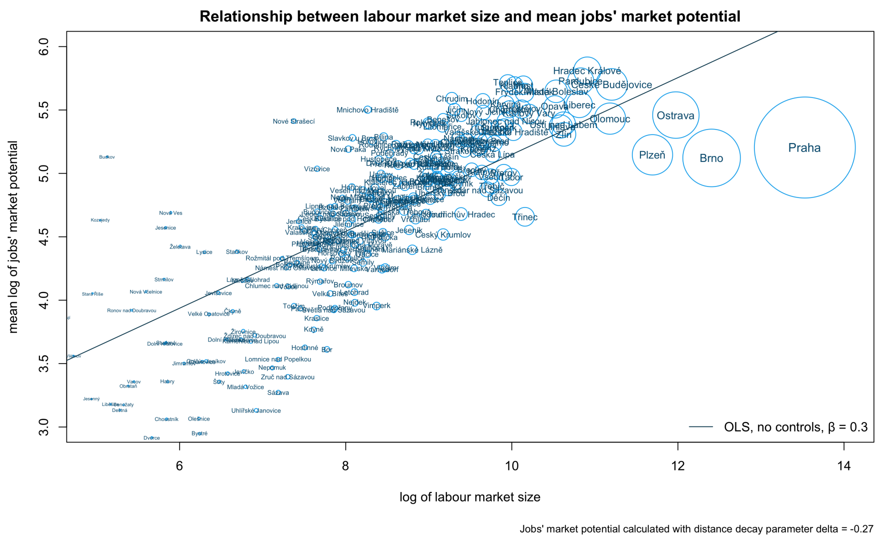

Figure 2.A.6: Urban size and urban density

Without any controls the density elasticity with respect to labour market size is 0.3 and decreases to 0.25 when shares of workers by education and region fixed effects are added. The trend holds well for most of the city sizes, but the four largest cities are quite below the trend. This could be caused by more polycentric urban structure resulting from more severe congestion that larger cities are facing. Alternatively, another reason could be integration of smaller regional towns into the functional urban area which defines labour markets.

The results are not dissimilar from ones found in literature.Ahlfeldt and

Pietrostefani (2019) found the density elasticity with respect to the city size of 0.43 for the OECD functional urban areas and Combes et al. (2019) 0.3 for French cities.

Wages

To calibrate dispersion of tastes parameter *epsilon* according to the equation (2.3.5), variance of wages $\sigma^2_{\ln \widehat{w}(\varphi)}$ is needed. However, for the regional level which is used in this analysis only particular quantiles of wages distribution are reported, in particular the first decile, the first quartile, median, the third quartile and the ninth decile. Using these information about wages distribution, assumed log-normal function is fitted though the points to obtain standard deviation. Fit of the log-normal cumulative density functions through the observed quantiles is shown in the figure 2.A.7. Results are shown for all individual regions and jointly for Prague and Central Bohemian region, which are treated as a single region in the analysis as they exhibit exceptional integration via daily commuting unlike other regions.

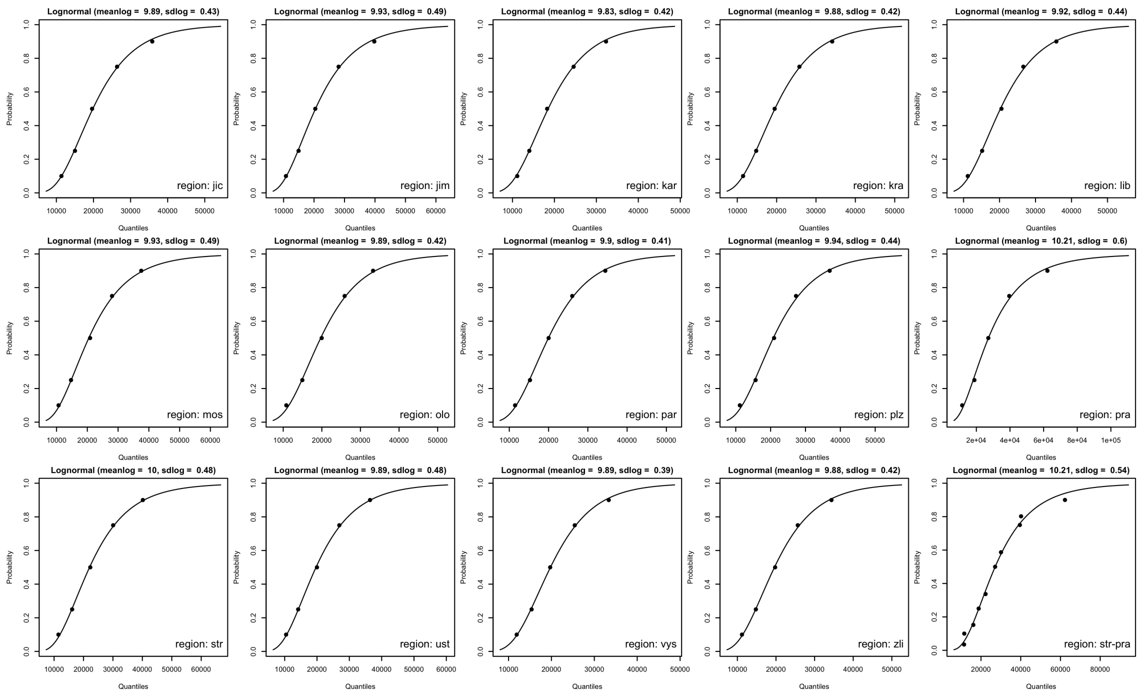

Figure 2.A.7: Log-normal fit through points of wages distribution

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3 Planning Constraints and Spatial Misallocation: Evidence from Lifting the Iron Curtain

Abstract

I show that, without persistent spatial planning and building permitting process that do not reflect the pent-up demand for housing, large cities in the Czech Republic would be even larger and overall economic output would be higher.

I propose a novel housing supply function explicitly depending on the maximum allowed density of development, amount of zoned developable land, and stringency of the local permit process. Additionally, the function incorporates the concept of "kinked supply function" resulting from the durability of housing capital. I then embed this function within a quantitative spatial model framework based on Ahlfeldt et al. (2015).

Analysing data from the Czech Republic during its transition to a market economy between 1991 and 2011, I find substantial variation in long-term housing supply price elasticities with an inter-quartile range spanning 0.39 to 0.77. However, low supply price elasticities in many places are not caused by constrained planning, but rather low price levels of real estate.

Counterfactual analyses show that a combination of relaxing stringent policies by upzoning by 50%, or increasing developable densities by 50% and keeping permit stringency at the first pentile of the national level, would increase indirect utility by up to 4% along with the re-allocation of up to 2.6% of the workforce, generally from rural areas to cities. (JEL J22, P25, R13, R23, R31, R52)

3.1 Introduction

Developed economies have seen a massive shift in economic sectoral composition over the past 50 years, attributable to deindustrialisation and computerisation. There are no reasons not to believe that forthcoming years will see

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I'm also grateful to Deloitte Real Estate Advisory, Czech Republic and Dataligence for providing me with real estate asking price data.

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Earlier versions of the chapter were titled "The Impact of Construction Constraints on Spatial Allocation during Economic Transition".

another major shift caused by the arrival of the Fourth industrial revolution marked by automation and utilisation of artificial intelligence. One important dimension of the past structural shift which will likely hold for the forthcoming one as well is an unequal impact across space. To illustrate this, in the period from 1980 to 2010, marked by computerisation and mass use of the Internet, share of the US urban population grew from some 75% to 81% and at the same time urban wage and rent premiums grew from 22 to 34 and from 48 to 66 percent respectively (Boustan et al., 2013). High value-added jobs in services and in innovation, both of which have grown and are expected to grow, are more often located in large and diverse cities, while declining jobs that could be automated are more often located in smaller towns[33].

As shown by Hsieh and Moretti (2019), aggregate growth is reduced when productive places impose more stringent construction regulations, so effectively real estate prices rise there and disincentivise in-migration. The labour force then remains in less productive places. According to their estimates, stringent policies limiting housing construction decreased aggregate US output growth by 36% in the period from 1964 to 2009. This is a major threat to future development as high-productivity places seem to increasingly cluster in space in large and more developed urban areas, which at the same time are more likely to impose more stringent construction regulations (Hilber and Robert-Nicoud, 2013)[34].

The aim of this chapter is to investigate the extent to which real estate supply constraints, specifically spatial planning and building permits, affect spatial distribution of economic activity. The hypothesis is that persistent spatial planning and a stringent building permission process limiting new construction did not allow for sufficient response to changes in demand across space, impeded construction in productive, competitive regions and, as a consequence, caused spatial misallocation of economic activity as households remained "locked-in" to places where they were initially located. Two separate constraints to new construction are analysed in detail: amount of developable land zoned for construction and stringency of building permit regulations when approving new construction.

The chapter examines an exogenous shock to the economic structure caused by the transition from a planned to a market economy in the Czech Republic. During the study period, between 1989 and 2011, the formerly planned economy transitioned to a market economy leading to a massive sectoral shift

[33] Duranton and Puga (2001) present theory and evidence that innovative industries concentrate their development activities in diverse cities and are likely to relocate production to specialised factory towns. Carlino and Kerr (2015) provide evidence of innovation clustering, particularly in large metropolitan areas.

[34] While labour misallocation with respect to places of high productivity is of primary interest here, an alternative perspective looking at the consumption side instead of the production side of cities might consider the growing importance of amenities in big cities. Hilber and Robert-Nicoud (2013) have shown that high-amenity places also tend to be more regulated

of employment. This, however, was not spatially neutral as jobs were more likely to decline in small labour markets and grow in large ones. At the same time, spatial planning in large cities did not adjust to meet the new spatial pattern of demand for real estate. This provides a particularly convenient research context as the economic structure changed significantly, unexpectedly and quickly, while planning remained rather rigid.

In the early 1990s, the Czech Republic started a transition from a socialist planned to a market economy in the aftermath of the 1989 'Velvet Revolution'. The shock of the structural economic transformation was quite large in magnitude and very fast. To illustrate the shift, employment in agriculture decreased from 11.5% in 1991 to 2.6% in 2011. During a period of two decades, almost 0.5% of the whole workforce left the agricultural sector annually. An equivalent drop in agricultural employment took 47 years to happen in the US: from 11.2% in 1950 to 2.6% in 1997[35].

Construction constraints

While the effects of housing supply constraints have been studied over the past few decades, the vast majority of research has focused solely on the housing market within a partial equilibrium framework using cross-sectional data[36]. Therefore, general equilibrium effects reaching beyond the housing markets are not yet well documented, with the exception of a few papers.

Real estate supply constraints could arise for two reasons. They are either caused by the first-nature (physical) geography, commonly by water bodies or slopes too steep to develop, as shown in the US by Saiz (2010). The second group of supply constraints falls within the category of artificial constraints determined by human activity. Supply is constrained either by a lack of developable land in places that were already developed (Hilber and Vermeulen, 2016) âĂŞ it is constrained endogenously through the political process with resulting public policies such as zoning (Hilber and Robert-Nicoud, 2013) âĂŞ or it could be affected by other policies that are not rational choices, or residents or governments at any level. Persistent spatial planning, which is explored in this chapter, is an example falling within the latter category.

Effects of construction constraints can be analysed within two theoretical frameworks: either a closed-city model assuming the population of a city is fixed, or an open-city framework, where the city is embedded within the larger economy, with a mobile population so households can freely migrate into and out of the city. Choosing one of these two frameworks determines the nature of the results. In the closed-city model, the population is fixed, and therefore

[35]In the same period 1991 to 2011, agricultural employment in Austria - a neighbouring country with a common pre-1918 history - saw a decline of only 37%, from 7.8% to 4.9%, compared to 77% in the Czech Republic; US figures based on US. Bureau of the Census (1975) and Federal Reserve Bank of St. Louis (2022); Czech figures based on 1991 and 2011 population censuses; Austrian figures based on The World Bank (2022)

[36]For a review see Gyourko and Molloy (2015).

a change of housing supply function affects the amount of real estate floor area delivered to the market, which affects rents (Brueckner, 2009). The closed-city framework is, however, not very realistic as population across cities is, at least to some extent, mobile. If regulations are imposed in a city in an open-city framework, then the initial increase in rents would decrease utility, leading to a wedge in utilities in the city and the rest of the economy, triggering out-migration from the city, leading to a decrease in demand for housing and ultimately re-establishing a new equilibrium with a smaller city population. [37]. The implications of these two theoretical frameworks therefore differ. Increasing planning or construction constraints increases rents and decreases utility in the closed-city model, whereas in the open-city model, it decreases population size and overall city land value.

Within the closed-city framework Cheshire and Sheppard (2002) estimate the net effect of planning regulation to be equivalent to an income tax of 3.9% distributed proportionally among households by their income. Using a theoretical monocentric model evaluated for a medium-sized US city, Bertaud and Brueckner (2005) estimate the effect of a maximum height restriction to have a welfare cost equivalent to 2% of income. Hilber and Vermeulen (2016) estimate the effect of supply restrictiveness in the UK and find prices in the South-East would be roughly 25% lower if supply restrictiveness there were the same as in the North-East of England.

Using the open-city framework, Hsieh and Moretti (2019) calculate the effect of supply constraints on economic growth in 220 US metropolitan areas. They find economic growth between 1964 to 2009 lowered by approximately one third due to the housing supply constraints, which caused spatial misallocation of labour. Ahlfeldt and Barr (2020) model a city in an open-city framework with fully mobile households, and they estimate the welfare difference resulting from density constraints based on the change in land values. Taking the city of Houston as an example, had the 10-floor height ceiling been imposed there, the land value would have decreased by the equivalent of 5.8% of the city's GDP.

I study three specific policies and regulations that are expected to be the most important constraints for new construction in the Czech Republic and are likely to play an important role elsewhere. Using both reduced form and full equilibrium models, I analyse the effects of the amount of zoned developable land and the stringency of building permission processes. Then, using the full equilibrium model, I also consider the effect of maximum developable density regulation.

[37] Helsley and Strange (1995) show that there could be a positive relation between rents and the extent of regulation in the open-city framework if residential amenities are subject to congestion.

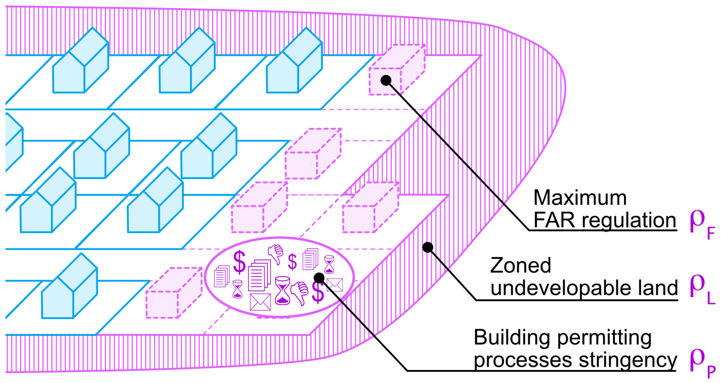

Figure 3.1.1: Channels of policy-caused construction constraints

Impacts of Reduced Construction

Spatial planning on a local level is a very common practice across developed countries. In the 32 OECD countries, 89 types of local plans were identified, more than 80% of which were zoning or boundary plans. Furthermore, 87% of these plans are legally binding, with 52% not allowing exemptions at all or only on rare occasions (OECD, 2017). Given such a prevalence of legally-binding local planning practice, understanding its effects is essential for informed policy making. Despite the still sparse quantitative evidence of the benefits of planning, we can estimate the costs of planning and alternative planning regimes could compete in political processes on the grounds of their expected costs and individual perceived benefits.

An important feature of planning in many countries is its local character, as planning is more or less within the competencies of local governments. However, local political processes might lead to inefficient outcomes as locals are not compensated for positive and negative externalities[38].

In the majority of countries, local planning is out of the reach of higher-level governments, so they cannot intervene in plans that might be beneficial for a local community but entail negative externalities for a larger region or a whole economy. While two thirds of national plans in OECD countries are binding for lower-level public authorities, the practical ability to influence local planning is limited as compliance with higher-level plans is not always enforced, for instance due to flexibility or ambiguity of national plans, missing enforcement mechanisms or missing resources for actual enforcement, or there is a lack of political will (OECD, 2017).

Construction constraints result in shortages in the housing market, which then affect other markets through general equilibrium adjustment. Whereas the output gap caused by spatial misallocation resulting from stringent planning, documented for instance by Hsieh and Moretti (2019), is not directly experienced as we do not have a proper counterfactual, increasing housing prices

[38]Drivers of stringent planning are discussed in more detail in the Appendix

in productive and constrained cities are much more visible and attract attention. According to the OECD (2021), in the decade between 2005 and 2015, middle income household spending on housing grew by 5 percentage points. However, as residence-job location is a joint decision, real costs of housing should also take into account the costs of commuting, which increased by an additional 0.2 percentage points over the period.

Another response to planning constraints, in particular when constrained productive cities are surrounded by more easily developable land, is though suburbanisation. The role of spatial linkages between places of employment and places of residence connected by commuting in the presence of construction constraints is discussed in Monte et al. (2018). If a construction constrained place receives a positive productivity shock, this increases local employment, and housing for newcomers is built in neighbouring locations where building new housing faces fewer constraints. The authors further argue that improvements in transport infrastructure to ease commuting could be an alternative policy option to reducing construction constraints. Using a quantitative spatial model on the US data, they show there is a substantially larger employment elasticity with respect to productivity shock (with mean value around 1.5) than residence elasticity with respect to productivity shock (of mean value around 0.5). They conclude that productive places do not necessarily have to be elastic in the provision of housing if there are other supply-elastic places from which commuting is possible.

The alternative of improving transport infrastructure to overcome housing supply constraints is, however, highly controversial at best from the perspective of current planning practice, which promotes transport oriented design and the reduction of automobile dependence. As housing supply is typically more elastic in undeveloped areas (Hilber and Robert-Nicoud (2013)), this approach would result in development sprawling excessively outward into the open landscape. In contrast, current goals in urban planning contain emphasis on compact and denser[39] development that is less dependent on automobiles, reducing land expansion by redeveloping already developed land and promoting walking and public transport within functionally mixed-use districts with accessible amenities (United Nations, 2017; United Nations Human Settlements Programme (UN-Habitat), 2022; OECD, 2022). While these planning objectives could, in some cases, decrease welfare, instead of increasing it, as Bertaud (2018) argues, the reasoning behind them is to mitigate market failures caused by the inability to internalise externalities.

Implications of construction constraints for wider economies should therefore be of interest to regional and national governments. Whereas they usually

[39]Increasing built-up densities is recommended by OECD (2022) and applies specifically to developed countries. Developing countries face other challenges and for that reason United Nations Human Settlements Programme (UN-Habitat) (2022) instead emphasizes the reduction of urban crowding.

cannot directly affect spatial planning policies as they are typically within the jurisdiction of local governments, they can still design incentives through legislation and broader policies to tackle overly restrictive planning.

There are several alternative approaches to measuring the extent of spatial planning or construction permit stringency. First, in some cases, planning or permit stringency could be measured directly, either as a result of actual permission processes âĂŞ by surveying planning and permit authorities âĂŞ or by observing constraints in planning documentation or from actual development. An example of the first approach is Hilber and Vermeulen (2016), who use the refusal rate of major residential projects in the UK. An example of the second one is the Wharton Residential Land Use Regulation Index (WRLURI, Gyourko et al., 2008, 2021) surveying authorities in the US. These observable proxies of local stringency could then be used to analyse their effects. The third category is represented, for instance, by Anagol et al. (2021), who used zoning data from Sao Paulo. Another example is Song (2021), who developed an algorithm to detect minimum lot sizes for all neighbourhoods in the US.

The second type of methods combine observed regulation data with other datasets, or do not need regulation data at all. These methods infer planning and permission constraints indirectly relying on imposing some theoretical structure to the problem. Glaeser et al. (2005) compare the market prices of condominium apartments with their marginal construction costs. Prices and marginal costs should be equal if the market is competitive and not regulated. Brueckner and Singh (2020) instead measure price elasticity of land with respect to permitted developable density, which, however, requires observed permitted densities. Using their model, they show that in more regulated places, the value of land increases the more density constraints are relaxed. This can be clearly seen in an extreme case: when density regulation is not binding at all, an increase in such regulation has no effect on land prices as land price is determined by optimal construction density chosen by the developer without being affected by non-binding density regulation.

Unlike the above described approaches, which rely on local plot-level data, the stringency of planning and permission could also be measured with long-run housing supply price elasticity. More constrained places are less supply-elastic, so they respond less with new construction to an increase in prices. For instance, Saiz (2010) estimates the long-run housing supply price elasticities for US metro areas. An alternative approach has been adopted by Hsieh and Moretti (2019), who model the problem in general equilibrium and relate changes in local productivity to changes in house prices and population on the metropolitan level in the US. They argue that the growth in local productivity results in population growth in unconstrained places, whereas it leads to an increase in property prices in constrained places.

To date, most articles on the effects of real estate supply constraints have focused either on effects on prices, on quantity of new housing or on both outcomes in the partial equilibrium framework.

To study the problem in the general equilibrium framework entails several challenges. The theoretical model has to feature all key markets in the economy and has to be able to include many individual geographies on a sufficiently detailed level. Then, there is a necessity to observe all data required by the model on a given geographical level. These data have to be provided with nation-wide coverage to study interactions within the whole economy. This could be especially challenging in the case of local policies constraining real estate supply. Direct evidence of the extent of regulation is hard to obtain due to its local and diverse nature[40] and when data are available, they are commonly cross-sectional without an opportunity to exploit variation over time (Gyourko and Molloy, 2015).

An additional difficulty with planning constraints is their endogeneity. In the US and elsewhere, spatial planning (or zoning) is largely local policy and therefore it is endogenous to a variety of local characteristics, such as residents' income, preferences for amenities, neighbourhood characteristics or public amenity provision, which make estimating the effect of planning alone difficult, especially when panel data are not available (Gyourko and Molloy, 2015).

The main question I am asking is: to what extent do real estate supply constraints affect spatial patterns of economic activity? In particular, I am focusing on the artificial constraints that could be modified by alternative policies. Although knowing the extent to which "first-nature" constraints such as the presence of oceans, wetlands or steep mountains limit development is also informative, they cannot be easily relaxed and therefore are of lower importance from a policy-making point of view. Instead, although politically challenging, it would be possible to incentivise highly productive and supply-constrained cities to zone more land for development and zone it at higher developable densities, and at the same time decrease the stringency of new construction permits.

I utilise several directly observable variables, which are proxies for separate components affecting housing construction constraints, both natural and artificial. To measure natural construction constraints, I use current satellite-based land use data to measure the area of developable land and terrain morphology to exclude too steep slopes, as in Saiz (2010). Then, I use three separate datasets to proxy for artificial construction constraints: a nation-wide survey of building permission authorities with information about the number of appeals against their decisions, spatial data of zoned developable green-field land, and a building-level dataset with floor counts of buildings as existing

[40] For instance, for the US, the most comprehensive dataset is the survey-based Wharton Residential Land Use Regulation Index (WRLURI) collected first in the late 2000s and then for the second time one decade later (Gyourko et al., 2008, 2021).

building heights are commonly binding for new construction.

Using these data, I first present reduced-form evidence that broadly aligns with findings from western countries. As far as I know, no analysis like this has yet been done for the Czech Republic. Regarding methods, I use a spatial boundary discontinuity design combined with an instrumental variable approach to analyse the effects of building permission offices' stringency on size and quantity of new housing construction. Then, I use a regression discontinuity design based on municipal population thresholds motivated by the past system of intergovernmental financial transfers to estimate the effects of the amount of zoned developable land on local housing construction. Reduced-form approaches to analysing construction constraints are more prevalent in the current literature, so I can take my findings from this part as a benchmark and compare them with existing literature that employs comparable methodology.

Second, I use a quantitative spatial model based on Heblich et al. (2020); Ahlfeldt et al. (2015) and Monte et al. (2018), within which I embed a realistic housing supply function featuring both natural and artificial construction constraints and the kinked housing supply curve concept. I estimate key model parameters and calibrate the model on data from 1991 and 2011. Finally, I run several counterfactual scenarios with alternative relaxed planning policies showing the responses of property prices, local population and overall household welfare.

The research design I propose has several appealing features. First of all, the problem of construction constraint endogeneity is of lesser importance in the Czech Republic. I analyse a time period of economic transformation when spatial demand for new construction changed as demand had become driven by market forces and productivity, not planners' discretion. However, constraints in the form of planning policies remained in place due to the planning persistence and expert-bureaucratic nature of the Czech spatial planning system. It is, however, true that some municipalities in the post-2000 period did adjust their plans to attract more development, as will be described later[41].

Both reduced-form and general equilibrium analyses are based on a wide range of data collected on a fine geographical scale for the whole country. Measuring local construction constraints does not rely on the surveyed sample, but is based instead on administrative data - official surveys of building authorities conducted by the Ministry of Regional Development. Zoned developable land data also come from an administrative dataset, the regularly updated Land analytical documents[42]. Although these two data sources are not without shortcomings, they provide almost universal coverage of the whole country

[41] Further details regarding Czech planning are provided in the Appendix.

[42] Land analytical documents (Uzemne analyticke podklady or UAP in Czech) are data about current land use and spatial planning regularly updated every four years (every two years until 2016). Each municipality with extended powers is obliged by law to regularly commission the data update.

and can serve as two separate proxies for artificial construction constraints, each capturing slightly different types of constraint. Detailed individual geo-located building-level data then allow me to estimate the effects of these two construction constraints on new construction.

In the partial-equilibrium framework, I find negative effect of both a more stringent building permission process and a lower amount of zoned developable areas on housing supply, which is consistent with the theory and empirical evidence in the literature.

The effect of building permission stringency is not homogeneous with respect to housing typology. There is an extensive-margin effect for single family dwellings: increasing stringency by 10% decreases growth of new units by 0.6%. Then, there is an intensive-margin effect for apartment buildings: increasing stringency by 10% has no effect on the growth rate of new buildings, but apartment buildings are, on average, 3.3% smaller in terms of their gross floor area.

The amount of zoned developable land is measured as developable gross floor areas relative to current gross floor areas of housing stock. It has a negative effect on new construction only in areas where property prices are above construction costs, meaning there is no excessive oversupply of housing remaining from previous periods when demand for housing was higher. For both types of residential real estate - detached houses and apartments - increasing gross developable floor areas relative to existing stock by 10% increases the growth rate of new construction by approximately 1%.

In the second part, which uses a quantitative spatial model, long-term housing supply price elasticities are calculated. Their mean value for individual municipalities is 0.64 and the interquartile range spans 0.39 to 0.77. They are roughly 50% larger than the estimates by Caldera and Johansson (2013) for Central Europe, but they are still quite low when compared, for instance, with the US. The supply price elasticities would be substantially larger, with a mean of 3.25, if all municipalities had the same property prices set at the level of construction costs. This indicates that regulation is not the cause of low supply price elasticities in many remote places. Instead, low supply price elasticities in remote places are driven by low property prices there as the market is in the region below "the kink" in the kinked housing supply framework.

Counterfactual scenarios where alternative policies of relaxing building permission processes, upzoning developable land, and increasing allowed densities of development were considered show non-negligible increases in households' indirect utility ranging from 0.5% to 4% depending on the particular combination of policy changes. The policy changes would also lead to a decline in average property values and to migration of up to 2.6% of workers, generally from remote areas to large cities. Durability of housing stock turns out to reduce these migratory flows.

The results show that households' indirect utility and wages would be higher and rents lower if artificial housing supply constraints were relaxed as, on average, new construction would be cheaper and high-productivity places could grow larger.

Additionally, the chapter shows further evidence about issues related to the transition from a communist planned to a market economy. While the role of durable physical capital in fixing people to places that have lost competitiveness has been already described in the case of Russia, the channel of persistent spatial planning is, to my knowledge, an original contribution. On top of existing real estate in places that have lost competitiveness, persistent planning makes investment in these declining places relatively easier compared to places which have become productive and will grow.

Lastly, the chapter brings estimates of housing supply price elasticities and provides evidence of the negative effects of constraining policies on new housing development in the Czech Republic on a fine geographical level that has not been done so far.

The rest of the chapter is structured as follows: Section 2 provides the historical context of the Czech transition from a planned to a market economy and introduces building permission and planning processes as well as other country-specific features of the real estate market. Section 3 reviews the data used, then Section 4 presents empirical reduced-form evidence of the negative effects of supply constraints. Section 5 introduces the quantitative spatial model and presents counterfactual analysis, and section 6 concludes.

3.2 Context

In late 1989, the 'Velvet Revolution' started the democratisation process in Czechoslovakia and transition of the country from a planned to a market economy. Before that, the communist party had ruled the country since the 1948 coup, after which they swiftly started transforming the post-war economy into a command economy. The period immediately after the World War II could also be marked as a time when the modernist movement became the dominant ideology in city and spatial planning, both in the Eastern bloc and globally. The key theoretical text of the modernist movement in Europe at least was the Athens Charter (Le Corbusier and Eardley, 1973[1933]) which promoted functional zoning to segregate residential, production and recreation areas. Separated zones then should be connected with transportation infrastructure. These modernist principles were the core of the Czechoslovak spatial planning theory (Durdík, 2019).

Spatial planning in Czechoslovakia prior to 1989 was tightly linked to the national central planning system, kept a strong position and had the ability to determine spatial development over the whole period until the collapse of the communist regime, as ultimately the state was responsible for economic and spatial planning, functioned as a developer, and controlled the land[43]. Despite the 1989 revolution, some decisions made in the past have affected, still affect and are likely to affect current and future spatial development as the planning system has not undergone reform to the same extent that other areas of public policy have.

According to some Czech planners, spatial planning in the Czech Republic did not undergo major reform after the 1989 revolution and remained rooted in modernist principles. (Koucký, 2017, p. 75) claims that "still today, notions of city development linger deep in the 1970s and 80s and in the directively managed society" (translated by the author) or "The directive and restrictive form of urban planning used in the Czech Republic up until today has become obsolete. It is linked to the socialists' five-year planning and predictable typology. It assumes a public clerk has a higher level of knowledge about future investments than a potential developer, and treats the city as a closed system with a single ideal solution" (Jehlík, 2013, p. 13, translated by the author).

While planners typically comment on within-city planning issues, it is reasonable to assume that the approach to planning has not changed much, even on a larger, regional, level. Past assumptions about the spatial development needs of individual urban areas might persist even though the new economic reality could exhibit completely different spatial patterns of demand for built-up space and new construction.

Gaddy (2014) claims that the distribution of physical capital and economic activity is a key obstacle during the transition from a planned to a market economy. Although he has focused on Russia and shown how the population there is overrepresented in low amenity areas, his conclusion seems to hold for much smaller countries with similar natural conditions. What seems to be the case in the Czech Republic is that the past centrally planned regime not only affects current economic development through the durable physical capital, but also through the legacy of the spatial planning as well.

Economic transformation

The economic structure has changed significantly following the reforms in the 1990s, but spatial planning regulation does not seem to have adjusted to the new economic reality. The likely result in such a case is spatial misallocation of economic activity, with workers stuck in less productive places leading to lower overall economic performance.

Figure 3.2.1 shows rural-urban division and the size of the economic transition following the 1989 revolution. The figure shows the change in employment in individual economic sectors between 1991 and 2011. On the vertical axis

[43] Tight linkages between national economic planning and spatial planning became weaker over time with legislative amendments (especially in 1958) attempting to give spatial planning more autonomy (Haganbart and Ebel, 2015).

is plotted the log difference between the number of jobs in 2011 and 1991 - sectors above 0 have grown while those below 0 have lost jobs[44]. On the horizontal axis is plotted the mean size of functional urban areas[45] where these jobs are located. The size of each circle marks overall employment in a given industry in 1991.

The pattern of industrial transition reveals one key observation: the transition did not affect all labour markets uniformly. Instead, smaller labour markets were the ones that lost more of their jobs because they were more specialised in agriculture and low value added manufacturing, whereas larger labour markets gained new employment in the growing service sectors.[46]. The transition had spatially unequal impact due to the different preconditions for competitive economic sectors: the shock was, on average, negative for small labour markets and positive for large ones.

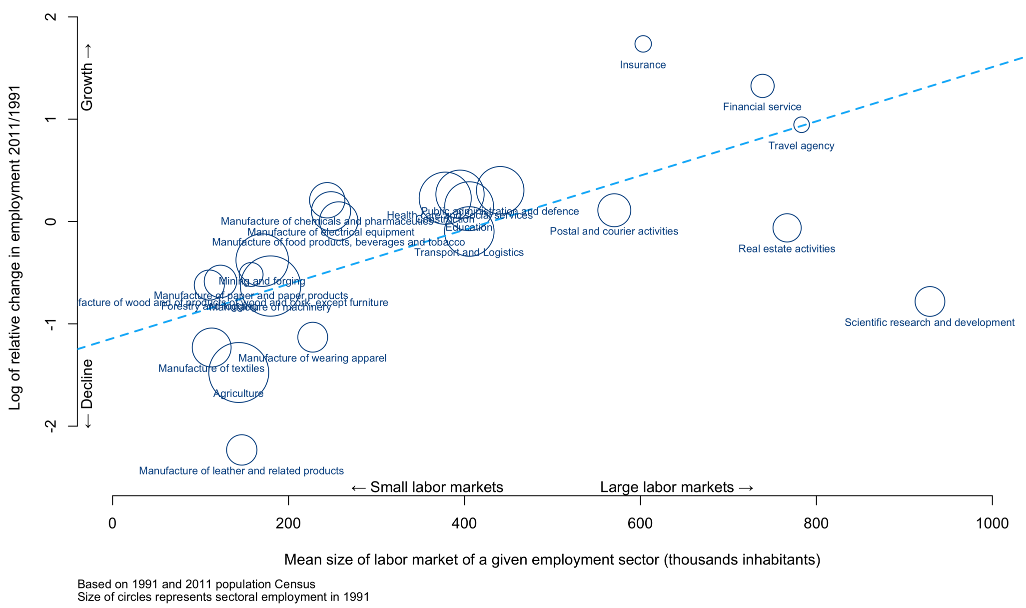

Figure 3.2.1: Relative change in industry employment by mean functional urban area size

To illustrate the sheer size of the employment shock, from 1991 to 2011, employment in agriculture dropped from 11.5% to 2.6%, and in machinery

[44]Due to the changes in economic sector classification, some sectors are not reported in the table. A clear case is 'Information technologies', which were not defined in the 1991 Census. Another case is all kinds of commercial services that were aggregated into a single category in 1991.

[45]Functional urban areas (FUAs) are not formally defined in the Czech Republic. The delineation used here is based on the 2011 Census and broadly follows the methodology of OECD (2012), but no minimum size of a FUA is required.

[46]A rather curious result is the absolute decline in jobs in 'Scientific research and development'. This could be driven by the past organisation of research activities, which were concentrated in special research institutes, and these could be either over-employed, or they reported all personnel including supporting staff. However, this requires further investigation.

manufacture it declined from 11.7% to 6.2%[47].

The industrial composition change is further illustrated with maps shown in Appendix 3.A where growth and decline of jobs by economic sector on the municipal level is shown for the four most declining and the four most growing economic sectors. Whereas regions around the largest cities tended to grow, smaller and more remote areas lost employment.

To conclude, the economic transition following 1989 was a major shock to the economy with highly unequal spatial impacts, and all of this has happened in an institutional setting with rather restrictive and persistent spatial planning, as will be shown in more detail in the following sections.

Durable immobile capital and planning persistence

Post-communist transition economies inherited many features that impeded their transformation to market economies. Gaddy (2014) builds on the claims of Thane Gustafson and argues that the most important heritage from a past political system is the spatial distribution of durable immobile capital. In the dynamic framework, the existing spatial distribution of immobile durable capital will affect the decision-making of agents in a given time and in the future. This, in turn, becomes an issue if durable immobile capital happens to be located in places that have lost their competitive advantage after the transition to a market economy. If there were no durable immobile capital, households and firms would just relocate to more productive places, but with durable immobile capital, they can enjoy lower real estate prices as its quantity remains while demand for it decreases. Low prices of real estate, therefore, lock populations into these low productive places.

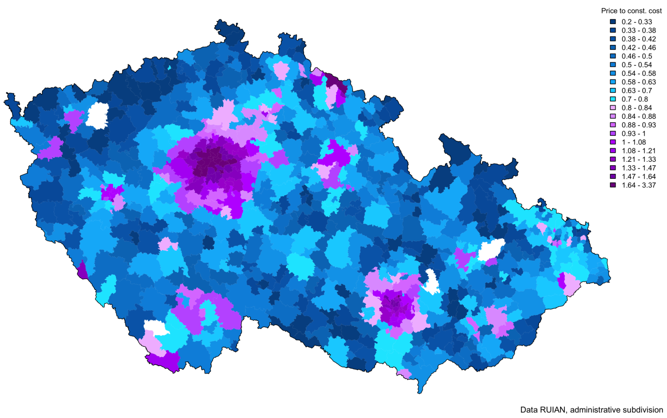

Figure 3.2.2: Prices of residential real estate relative to construction costs

[47] The employment shock does not seem to be part of a long-term industrial change as observed in the West. A comparison of 1991 data with the 1980 census shows there was a relatively stable pre-1989 industrial composition - correlation of sectoral employment shares between 1980-1991 (pre-revolution period) is 0.987. Then correlations of sectoral employment shares between 1991-2001 and 2001-2011 dropped to 0.892 and 0.826 respectively.

This effect of existing fixed capital seems to play a role in resources' allocation under the new economic conditions. During the economic transition, some regions gained jobs while others lost them. Employment decline is a negative demand shock that has specific implications for housing markets. As Glaeser and Gyourko (2005) argue, housing is a durable good that does not adjust quantity downward when demand decreases. Instead, when demand for housing declines, the amount of housing remains, and a new equilibrium can only be achieved through lowered prices. As a result, the housing supply curve is kinked. From an equilibrium point of maximum historical demand, it steeply declines, being almost perfectly inelastic. In the other direction, its slope might vary, and this depends on local geography, construction constraints and other factors affecting supply price elasticity. This framework is useful because it predicts that the housing supply curve will be very inelastic if current demand for housing is below maximum historical demand (assuming construction costs are fixed). There is a simple way to test whether a local housing market is in the region of an almost inelastic housing supply curve: real estate prices have to be below respective construction costs.

Figure 3.2.2 shows such a ratio of real estate prices to construction costs and reveals that there are major differences across the country. There are two larger regions - Prague and Brno, the two largest cities - and a few smaller ones where residential real estate prices exceed construction costs. This could be a sign of a restrictive building permission process. Glaeser et al. (2005) argue that the real estate price in a free market should be equal to marginal construction cost if there are no construction constraints. However, in the presence of construction constraints, real estate prices will exceed marginal construction costs, and the authors call it the 'regulatory tax'. At the same time, the vast majority of the country is in the region of demand not reaching its historical maximums.

With the exception of natural amenity rich areas at the national boundaries, construction-constrained places are mostly large regional capitals and their hinterlands, which experienced positive demand shock during the economic transition. Low responsiveness to this positive demand shock leading to insufficient new construction and rising property prices could be caused by persistent spatial planning and overly restrictive building permission processes. When Czech planners criticise current spatial planning, its lack of self-reflection and its reliance on obsolete modernist principles, they focus on functional zoning or expansive suburbanisation at the city fringe or within functional urban areas (Koucký, 2006, 2017; Jehlík, 2013), but they do not consider the negative legacy of planning on the national level. The continuity of the spatial planning system is viewed by some authors as its advantage (Maier, 2019), but the costs of its persistence are largely unknown.

If spatial planning is persistent in terms of the amount of space that could be developed in an individual municipality, and if there is a shock to the overall economy making some places more productive and some places less so, then the country under transition cannot reach its full potential because there will remain a spatial misallocation of labour. Whereas in areas hit by decreased demand the spatial planning is likely to become lax as zoned developable land significantly exceeds demand, places which experience a positive demand shock instead face relatively more constraints as too little land is zoned for development leading to fiercer competition for scarce developable plots.

While a direct test of the persistence of spatial planning is not possible due to the lack of data about spatial plans in the past, the persistence can be tested indirectly using data about the number of housing units actually built. For the period before 1991, this seems to be a sufficient proxy as, at that time, the state was the single entity responsible for both spatial planning and construction, and these two were linked to the national economic plan[48]. Therefore, the actually built units should serve as a good proxy for the planned capacity of future real estate.

The persistence of spatial planning is therefore tested indirectly with a simple model specified in the equation 3.2.1. The left-hand side variable is a log ratio of developable gross floor areas zoned in the spatial plans as of 2014 relative to the current existing gross floor areas in a municipality i as of 2011. This variable is regressed on a log ratio of the number of housing units built between 1961 and 1991 relative to housing stock in 1961 (which is log of relative growth in the *old* period 1961-1991) and a log ratio of the number of housing units built between 1991 and 2011 relative to the housing stock in 1991 (which is a log of relative growth in the *recent* period 1991-2011)[49].

The coefficient α_1 captures the elasticity between current developable capacities and lagged development in the period between 1961 and 1991, which took place in different economic contexts and could be interpreted as an extension of planning persistence. The second regressor of relative growth in the period 1991-2011 captures the demand-induced capacity of developable floor areas already taking place during the economic transition, which should reflect the adjustment of spatial planning to a new pattern of demand for real

[48]Further details about the spatial planning system are provided later in this section and in the Appendix

[49]Data used and construction of individual variables is described in the section Data and further in the Appendix

estate[50].

$$\ln\left(developable_i/developed_i\right) = \alpha_0 + \alpha_1 \ln\left(g_{old,i}\right) + \alpha_2 \ln\left(g_{recent,i}\right) + \varepsilon_i \quad (3.2.1)$$

The results of the estimated equation 3.2.1 are reported in the table 3.2.1. The model has been estimated separately for multiple size categories or types of municipalities, each one reported in a single column. The first six models are estimated for sub-groups of municipalities by their number of inhabitants in 1991, and in the last column, the model is estimated for municipalities that were county seats in 1974.

The overall pattern of the results shows planning is more persistent in larger municipalities, and it gets weaker as the population declines until it vanishes altogether for municipalities with a population below 10,000. Conversely, the demand-induced zoned developable areas from the period 1991 to 2011 play a role only in the case of municipalities with fewer than 1,000 inhabitants, and the size of the effect is smaller than the effect of planning persistence in the case of the larger municipalities.

In total, 71 former county seats[51] are by far the largest municipalities in the country, so this group of municipalities to some extent mimics the categories of the largest municipalities. The largest municipality which was not a county seat was the 13th largest in 1991, and the smallest county seat, with its 9,400 inhabitants, was the 140th most populous in 1991. The median population of a county seat was 29,550 and first quartile, 20,748.

It worth comparing the model of municipalities with over 20,000 inhabitants in column 2 and the model with county seats in the last column. The models have a similar number of observations, but the effect in the case of county seats is approximately one fifth larger, more precisely estimated, and the explanatory power of the model is significantly higher. On top of that, approximately one quarter of observations for this model are below a population of 20,000, where the effect would be assumed to be smaller. This suggests that there is a specific characteristic of county seats causing their stronger planning persistence[52]. One possible explanation is that county seats hosted

[50] Although in the case of the second regressor, the period of development from 1991 to 2011 pre-dates the left-hand side variable with zoning plan capacities as of 2014; in fact, these plans could have been effective for long after the period from 1991 to 2011. As a result, the causality could go either way: more rapid growth demanded more zoned developable land, or more zoned developable land attracted more growth. Nevertheless, the attention here is paid to the estimate of the first regressor looking at the period from 1961 to 1991, and the second one serves only as a control. Causal estimates of the effects of zoned developable land on actual construction follow in a later section.

[51] Administrative subdivision into counties with local offices of the state administration was largely abolished in the 2000s following administrative reforms after the accession to the EU.

[52] An explicit formal test of different persistence in planning and demand-induced capacity of plans by introducing interaction between a county-seat dummy variable and both regressors did not yield results statistically different from zero on conventional levels, but this

	ln(developable/developed) [as of 2011 (2014)] municipalities by size categories [thousand of inhabitants, 1991]						
	> 60	> 20	10-20	5-10	1-5	< 1	county seats
$\ln(g_{old})$	$0.824^{\cdot}$	0.464^{*}	$0.318^{\cdot}$	0.249	0.058	$-0.047^{\cdot}$	0.576^{**}
	(0.452)	(0.209)	(0.186)	(0.186)	(0.058)	(0.026)	(0.200)
$\ln(g_{recent})$	−0.187	0.015	0.232	0.101	−0.041	0.147^{***}	−0.209
	(0.503)	(0.221)	(0.288)	(0.211)	(0.066)	(0.026)	(0.241)
R^2	0.344	0.098	0.062	0.026	0.002	0.010	0.148
Adj. R^2	0.235	0.059	0.025	0.004	−0.001	0.010	0.116
Num. obs.	15	50	54	92	744	3410	56

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

g_{old} is housing growth between 1961 and 1991 relative to the housing stock in 1961 [(1991-1961)/1961].
g_{recent} is housing growth between 1991 and 2011 relative to the housing stock in 1991 [(2011-1991)/1991].
Observations are individual municipalities. Dependent variable is log difference between developable gross floor areas based on spatial planning documentation and gross floor areas already developed. Robust standard errors are reported in parentheses.
Population size categories are based on 1991 Census. County seats are as of 1974 according to Federální statistický úřad (1976). Developed gross floor areas are as of 2011. Developable gross floor areas according to planning documentation are derived from 2014 data.

Table 3.2.1: Persistence of spatial planning

offices responsible for procuring spatial plans for municipalities and their parts within the county[53]. These professional planning bodies could have survived the transition period within the municipal administration or as privatised companies providing services for municipal public administration, and when new spatial plans were commissioned, they drafted them in a similar manner as in the past.

The relationship between relative growth in the 1961-1991 period and the current amount of gross developable space in the zoning plans is shown on scatter plots for the same size categories for which the models are estimated in the Appendix section 3.A in the figure 3.A.12. The relationship for county seat towns is shown in figure 3.2.3.

To conclude, spatial planning seems to be persistent in municipalities with populations over 10,000, possibly even in those with populations over 5,000, but results for this group are imprecisely estimated. Planning persistence is even stronger for county seat towns. In their case, increased housing growth by 10% in the period from 1961 to 1991 is associated with 5.8% more zoned gross floor areas in their spatial plans in 2014. At the same time, there is no effect of recent growth in the period from 1991 to 2011 on the amount of zoned developable areas, which signals there is no adjustment to recent trends. These municipalities are typically employment cores of their functional urban areas, and the largest of them experienced the highest employment growth during the economic transition. Planning persistence and inability to adapt to demand for new construction induced by economic transition is likely to have resulted in spatial misallocation as these places were not able to meet demand for housing supply.

could be caused by noise in the data increasing estimated standard errors.

[53]As defined in the Building Act no. 50/1976 Col., article 18.

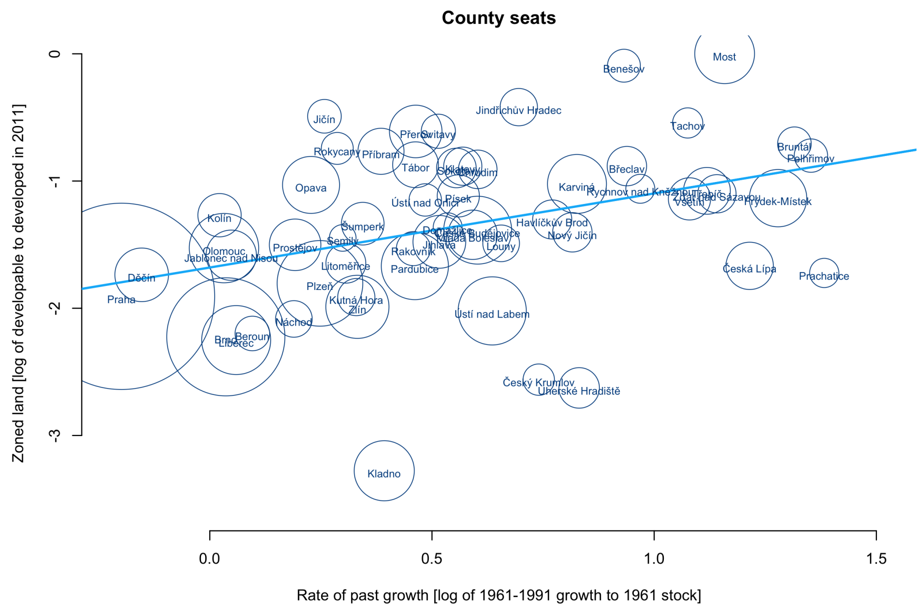

Figure 3.2.3: Relationship between past growth and developable areas in former county seat towns

Spatial planning and building permissions in the Czech Republic

Spatial planning and building permissions in the Czech Republic are two distinct systems in terms of processes and stakeholders involved. First, the spatial planning system regulates, through spatial plans[54], what land is developable, what is permitted functional use, and at what densities land can be developed. This policy is predominantly within the competencies of municipalities. The second system is the building permission process, which assesses the compliance of a particular project with environmental regulations, spatial plans, the building code and other mostly national regulations. The building permission process has, in general, two steps: a zoning permit, which assesses compliance with spatial plans and national regulations regarding land use, and a building permit, which assesses the compliance of the proposed building with the building code and similar regulations. Both of these processes are within state competencies, with little involvement from local governments. Below are described the key specifics of the spatial planning policy and building permission process, and further details and recent legislation development are provided in Appendix section 3.A.

Spatial planning is within the competencies of self-governing municipalities, but there are several steps where state administration is involved, and it steers the whole process. The process of municipal zoning plan procurement and approval includes three key agents: the municipal assembly, the spatial planning authority and the expert drafting the plan.

The spatial planning authority (state administration) is a plan procurer

[54]Spatial plans and zoning plans can be used interchangeably. The main parts of these plans are typically functional zoning and maximum permitted densities.

that formally manages the process[55]. The municipal assembly votes on the task of drafting the spatial plan at the beginning of the whole process, and then, at the end, votes to approve the proposed plan. The plan itself is drafted by experts, either employees of a municipality or external contractors, who prepare it according to the task approved by the municipal assembly.

The overall process of zoning plan procurement and approval is shown in figure 3.A.10 in Appendix A based on Plos (2013). While spatial planning is within municipal competencies, transitions between individual steps during the process specified by the Building Act have to be done by the procurer, the representative of state powers which should oversee compliance with the Building Act. The whole process can be divided into three main parts: the zoning plan task, in which the task of elaborating the plan is defined, the zoning plan draft, in which state authorities' statements on the design are collected, and the zoning plan proceedings, during which objections of landowners and the public are dealt with.

Initially, the municipal assembly decides whether to commission a zoning plan and start the procuring process. Then the procurer and a selected member of the municipal assembly prepare the task for drafting the zoning plan. The task is commented on by neighbouring municipalities, and it is subject to statements by state authorities. When the task is completed, the municipal assembly approves it, and drafting of the zoning plan starts.

After the zoning plan is drafted, the procurer calls a joint meeting, at which statements by state authorities and comments by neighbouring municipalities are collected. The procurer then delivers the zoning plan proposal in the form of a public decree, and the zoning plan proceedings phase begins.

When the decree is issued, anybody can make comments. Then, the procurer and a selected municipal assembly member try to accommodate all the statements and comments. Then, they call a public hearing, after which all affected landowners, authorised investors and public representatives can raise objections, and anybody else can comment. In the subsequent step, the procurer and the selected municipal assembly member attempt again to accommodate comments and objections. In general, if they are not successful, the zoning plan has to be re-designed, and the process is repeated if the updated version significantly differs from the previous one. When the proceedings are successful, the procurer prepares a zoning plan proposal that is ready to be approved by the municipal assembly. This description captures the key steps of the process without a focus on some provisions that might apply in specific circumstances.

Although building permission processes are within state competencies, due to the mixed-system of local-state public administration, they are administered by the building permission authorities, which exert state power, but they are

[55] Alternatively, the procurer could be an expert with state certification (Jirásek, 2014).

within the structure of municipal public administration of larger municipalities which serve wider areas of surrounding smaller villages[56].

The building permission process is notoriously complicated and lengthy - in 2020 the Czech Republic ranked 157th out of 190 countries in the Construction Permits section of the Doing Business index by the World bank (World bank, 2020).

The permission process consists of "two and half" steps illustrated in figure 3.A.11 in Appendix section A based on Plos (2013). First, the general design proposal is assessed by the Environmental Protection state office as to whether it is subject to Environmental Impact Assessment (EIA). For instance, large residential projects could be subject to the assessment depending on the office's decision. If a project is subject to the assessment, the developer has to provide the required documents, and the office will conduct the assessment. However, this step has been introduced rather recently and, because it is processed by a different office of public administration to the building permission offices, it is not captured in the data used.

In the case that a project is not subject to EIA, or it has obtained EIA approval, the developer submits project documentation for the zoning permit proceedings to the building permissions office. During this process, the office assesses whether the proposed building is in accordance with the local zoning plan[57] and issues an approval or rejection of the project.

When a project has a valid zoning permit, the developer applies for a building permit, and during this process the building permission office assesses whether the designed project meets the building code[58]. When the building permit is issued and comes into legal force[59], the developer can start project construction.

Selected stakeholders involved either in the zoning or building permit process can appeal against the decision of the building permission authority. Analysis of 60 residential projects in the capital of Prague conducted in 2019 has revealed the average duration of the EIA, zoning permit and building permit processes combined takes, on average, 5.1 years (Deloitte, 2021). This is excessively long when compared, for instance, to the US where the standard wait between application and approval takes 3.2 months for the least and 10.2 months for the most regulated communities (Gyourko and Molloy, 2015).

There is essentially no possibility of development "by right". All proposals

[56]The mixed system of public administration transfers execution of some state powers (in this case, building permissions) to the lower-level governments (Provazníková, 2015). The public administration system and subdivision of the Czech Republic is described in more detail in Appendix section 3.A.

[57]Spatial plan and zoning plan as well as spatial permit and zoning permit are used interchangeably when translated to English.

[58]The building code is provided by ministerial decree for the whole of the Czech Republic with the exception of Prague, which can issue its own regulation as a municipal decree

[59]There is a time window when some involved stakeholders can appeal to a higher-level authority or court.

for new development must be assessed in terms of their compliance with the zoning plan and building code[60].

Unlike in other countries, such as in the US, the building code defining the obligatory requirements for the quality and design of new constructions is a national regulation with limited variation in some parameters[61]. The only exception is the city of Prague, which has the right to issue its own building code. However, the Prague building code was in many ways quite similar to the national regulation until it was reformed in 2014, so it did not significantly affect the study period.

3.3 Data

Majority of the analysis is done at the level of municipalities as defined in later 2010's. Municipalities are convenient geography because many variables are collected and reported on the municipal level as municipalities are the lowest level of local government, each having a municipal assembly and its mayor. Additional convenient feature when it comes to analysis is size. Municipalities are quite small, both in terms of population and area. Median and mean size of a Czech municipality are 8.0 km^2 and 12.6 km^2 with median and mean working population (as of 2011) of 172 and 697 respectively. Fragmented municipal subdivision therefore allows to analyse easily outskirts of functional urban areas beyond city limits of larger towns and cities with sufficient spatial detail.

Workers and jobs

To measure population size, working population only is included: either employed or self-employed adults, or working pensioners. Data about working population are taken from the 1991 and 2011 individual-level anonymised Census records provided by the Czech statistical office. Data include, among other variables, municipality of residence, municipality of job location, commuting frequency and commuting duration. From these variables, commute flow sizes and durations were aggregated using all individuals reporting regular daily commuting pattern. All the other not commuting regularly are assumed to work in the municipality of their residence. From the commuting matrices number of residing workers and number of jobs is obtained for each municipality by summing up commuters either by place of residence or by workplace.

Response rate to the question regarding commuting is however not consistent across census years. The census year 2011 contains much higher share of unreported commuting behaviour when compared to the three previous

[60] There is an exception when an area is regulated by a binding regulatory plan that replaces zoning approval. In such a case, the zoning approval process is omitted. However, these regulation plans are rare.

[61] For instance requirements for parking space provision depend on municipal size category and several other local specifics

Censuses going back to 1980. In fact, number of inter-municipal commuters reported in the data would drop approximately by one third between 2001 and 2011, but this decrease is predominantly driven by unreported commuting. For this reason commute flows in 2011 including the flow of 'stayers' (workers who work and live in the same municipality) were proportionally adjusted to take into account unreported commuters. It is assumed workers who did not report their commuting behaviour altogether exhibit on average the same commuting patterns as workers who filled-in the census question. This adjustment procedure increased sum of expected intercity commuters in 2011 to approximately the same level as in 2001 when the share of unreported commuting was minimal.

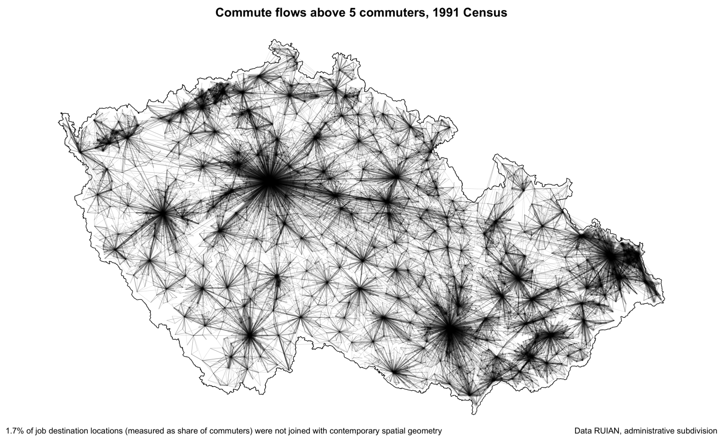

Figure 3.3.1: Commuting matrix plotted in space

Land use

To analyse land use, CORINE land cover vector data for years 1990 and 2012 are used. Data from 1990 were used to calculate share of developable land as a fraction of municipal area. Among developable land types are included urban green areas, agricultural and natural land, but woods were excluded as they are in general protected and cannot be easily developed.

From the 2012 data all already built-up areas including all artificial surfaces were obtained and were later used to measure developable, but yet undeveloped land.

Real estate stock and construction

The size and period of construction of individual buildings is obtained by merging buildings' footprints from the cadastral maps provided by the State Administration of Land Surveying and Cadastre with the database of buildings by their entrances provided by the Czech Statistical Office. Individual buildings in both datasets contain shared unique identifier so both datasets could be easily joined.

Cadastral map footprints are provided in the form of polygon geometry so area of each building could be measured. Buildings by entrances is a point layer with each point representing one entrance into a building. This dataset combines data from multiple administrative data sources including information about buildings collected in the 2011 Census. Among these data is a floor count, number of apartments within a building, period of construction and functional use. Using the building footprint area and the floor count, gross floor area (GFA) was calculated and buildings were divided into three functional categories: residential apartment, residential single-family and others, which represent commercial real estate. Period of construction was aggregated into decades from 1960s' onwards and into three longer periods periods before: until 1919 (the end of the WWI), interwar period, and from the end of the WWII until 1960.

Variables described above are available for buildings completed up to 2011 when data were collected during the Census. However, some information could be obtained even for buildings completed after 2011, in particular after 2014 when the time stamp of each data entry into database suggests completion of a building. For these buildings only the functional use is known. Size or a number of units within a building are unobserved and for that reason entries from this time period are worthwhile only for an analysis of single-family buildings with vast majority of them having only one apartment and for which gross floor area is not a crucial information.

Each building represented by a point geometry was also coded by municipality of its location so aggregates by municipality, period of construction and functional use could be done.

Real estate prices

Residential real estate offerings of apartments and single family houses for sale from major Czech real estate web listing services for year 2014 were provided by Deloitte Real Estate Advisory Czech Republic. These data include almost 240,000 listings with exact geographical location and common information about properties such as price, size, condition and unit equipment.

From these listing prices mean price per square meter was calculated for each municipality as a mean price for municipalities with more than 100 offers in the given year, or as a mean price of 100 offers most proximate to the geometric centroid of a municipality for municipalities with less than 100 offers. Although only 221 municipalities exceeded 100 offers in the given year, the index captures well local differences in price levels as the measure of maximum distance from which the furthest listing is drawn in case of municipalities with less than 100 offers has a median of 5.8 km, third quartile of 7.6 km and maximum of 24.1 km.

As the baseline time period of other data used is the year 2011 and earlier real estate price data prior 2014 were not available, real estate prices were adjusted with the Czech Statistical Office's general real estate price index change between 2011 and 2014 which is 2%. The relatively low price change is caused by stagnation of real estate prices after the global financial crisis which had prolonged effect in the Czech Republic.

Real estate construction prices are based on the 2011 price indices published at the Czech construction standards (Ceske stavebni standardy) web pages (RTS, 2021). The baseline hard costs of apartment and single family residential structures were 5,020 and 5,006 CZK respectively per cubic meter net of taxes (Approximately 200 EUR). To convert these values into final prices per square meter of leasable space, additional 15% of soft costs, 15% of developer profit and 15% value added tax are included. For the apartment buildings 85% utilization of gross floor area is assumed and 3.1 meter construction height of each floor. In the case of single family houses 95% of space utilization is assumed and construction height of 2.9 meters per floor. With this parametrization the development costs net of land acquisition are 27,900 and 23,200 CZK per square meter of leasable space in 2011 price levels (1,120 and 930 EUR respectively).

To estimate construction costs back in 1991, Czech Statistical Office's Price index of construction works starting in 1994 was used. Price changes before 1994 are assumed to be 10% annually, comparable with a change over the period from 1994 to 1998. Following this approach, nominal construction costs in 1991 were 33.9% of nominal costs in 2011. However this is almost identical to the overall price inflation (34.2%) so the real construction costs remained practically the same over the period.

Because construction costs differ for apartments and single family units, construction costs for individual municipalities were calculate as a weighted mean of the two, weighted by the number of units in apartment and single family houses completed over the study period from 1991 to 2011.

Development constraints proxies

Measuring stringency of spatial planning and building permit process in the Czech Republic is not straight-forward as there are no intentionally collected data to measure construction constraints. For that reason proxies using existing data had to be constructed to measure development constraints.

The first proxy is the appeal rate against decisions of Building permit authorities (later abbreviated as AR). As building permit agenda is within the state powers, the process of assessing zoning and building permit applications should be in theory free of local political inference. Instead, local governments should formulate their requirements on local development in the spatial planning regulation[62]. It is expected the appeal rate is close to zero if permit

[62] In case of Prague there is also its own Building code.

process is not overly restrictive and constraining. On the other hand, if permitting process is restrictive or local stakeholders actively intervene, the appeal rate is likely to be higher[63]. Appeals against decisions, in any case, prolong the approval phase of real estate projects and increase uncertainty involved in development and through these channels likely reduce housing supply price elasticity.

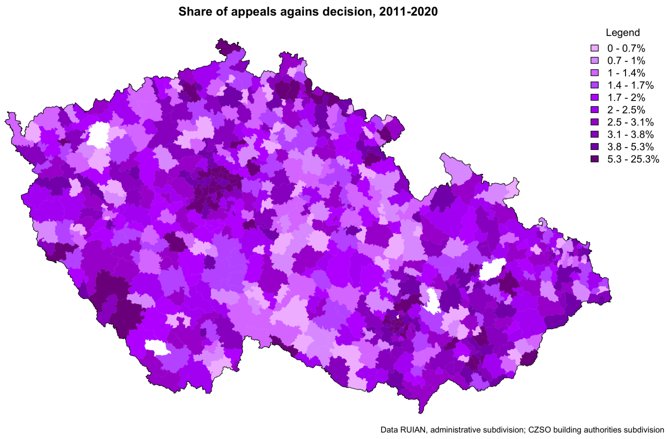

Figure 3.3.2: Appeal rate against decision of Building permitting authority

The appeal rate is constructed from annual surveys of 697 Building permit authorities available from 2011 to 2020 obtained from the Institute for Spatial Development (Institute for Spatial Development, 2021). These surveys contain some 100 questions and one set of questions include number of issued decisions based on individual sections of the Building Act. However, not all decisions are related to approval of new construction. Within the building permitting process, which consists of one or two stages depending on nature of considered building and developer's choice, there is up to ten distinct decisions that are all related either to zoning permit approval or building permit approval. The types of decisions also changed slightly over the study period as the Building Act was amended and some types of decisions have changed. Unlike decisions, appeals against decisions are not categorised and it cannot be inferred from the data against what type of decision the appeal was raised. However, it is assumed the most controversial decisions are indeed the ones considering new development or redevelopment. The appeal rate is therefore constructed as a number of all appeals divided by the sum of decisions regarding zoning permits and building permits.

The second construction constraint proxy focuses on the key type of regulation spatial planning documents can impose which is definition of developable land. Agenda of spatial planning is within municipal competencies so each municipality can set desirable amount of developable land as well as maximum density at which the land could be developed as long as the plan meets

[63]There is a formal model provided in the Appendix proving the appeal rate is a monotonic function of local permit stringency

requirements set by the national government, such as protection of woodlands, valuable agricultural land and many others.

Because spatial planning is within municipal competencies and possible forms of regulation are not standardised, there are no consistent data of spatial planning regulation with universal coverage of the whole country. However, state administration's local offices should collect information about developable land defined in spatial plans of municipalities within their administrative areas every 4 years[64]. These data are then processed by offices at the regional level. As the process of data collection suggests, the data are not completely consistent across space. Some administrative areas are not covered at all, in some areas data do include designed belts reserved for transport infrastructure while in others these are not included, or somewhere already developed land is included as developable while elsewhere it is not. Dataset available after the 2014 update from all regions was compiled by Maier et al. (2016) who kindly provided me with the data. The raw data contain approximately 145,000 spatial features.

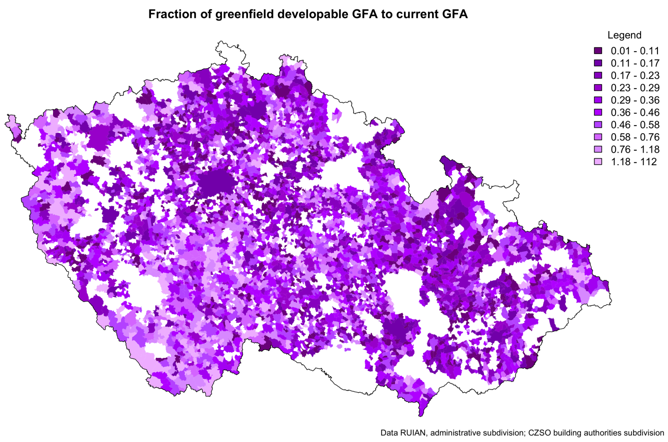

Figure 3.3.3: Developable gross floor areas

To make data consistent across space several adjustments were done. First, transport and technical infrastructure features were parametrically removed from the data using ratio of features' circumference to features' square root of area. After several tests ratio of 20 was used which removed obviously infrastructural features and did not remove areas of normal developable land. In some cases, however, infrastructural belts in the data are split into shorter sections which are therefore undetectable with the above described cleaning method. As a result, the whole dataset was manually cleaned and major linear features were removed.

The raw data are also not consistent in the definition of developable land. In some administrative areas the category of developable land includes also already developed land while in others does not. To overcome this issue, all

[64]Spatial analytical documents are procured by 206 local state administration offices at the Municipalities with extended powers level. Until 2016, the period of update was 2 years

areas classified as developed in the 2012 CORINE land cover dataset were removed from the developable land data.

To define actual gross floor area (GFA) capacity of the developable land requires to know maximum permitted floor area ratios (FAR)[65] which are unfortunately not available in the data. It is therefore assumed the maximum allowed land use density on developable land is the same as densities at which development in a municipality in the period from 1991 to 2011 was built. Designation of land as developable, rather than its particular functional use, seems to be the main regulation tool[66].

The approximated developable GFAs were summed for each municipality. For the reduced-form models developable GFAs were divided by the sum of the built-up gross floor area in each municipality in 2011 so the fraction of developable GFA to existing GFA was obtained.

3.4 Empirical reduced-form evidence

Effects of permitting process stringency

The aim of this section is to provide evidence that the appeal rate, proxy for local building permitting stringency, has negative effect on housing supply. However, regressing housing supply on appeal rate has limitations.

First of all, as equilibrium quantity supplied and quantity demanded are jointly determined, change in supply is affected by change of demand which cannot be directly observed and control for. If change of demand is not controlled, it is likely to cause omitted variable bias. This is a problem of cross-sectional designs with individual municipalities used as observations for which data regarding housing construction are usually available. To address this problem, I use the boundary discontinuity design (BDD) exploiting variation in building permit stringency and new construction along boundaries of Building permit authorities' administrative areas.

It is assumed demand is continuous across space and it is not affected by administrative area subdivision[67]. Conversely, stringency of assessing zoning and building permit applications exhibits a sharp change at borders of individual offices' jurisdictions. Based on these assumptions, differences in relative change of supply within the defined one kilometre buffer along the boundary

[65]Floor area ratio is a common regulation defined for developable land. It sets maximum gross floor area of built-up real estate relative to the size of a plot. For example FAR 2 allows to develop 2000 square meters of gross floor area on a 1000 square meter large plot.

[66]This is consistent with Pogodzinski and Sass (1994) who have found for Santa Clara County in California the zoned functional use follows the market (and therefore is likely not binding), while regulation of density decreases market value of land.

[67]Unlike in many other countries, taxes or endogenous amenities do not change significantly as one moves from one municipality to another. Property tax revenues in the Czech Republic are negligible compared to other tax revenues (0.6% compared to 5.7% average in OECD countries, OECD, 2023) and other tax rates are set uniformly on national level. Also local amenities consumption, such as schools, is not strictly dependent on place of residence.

should be caused by changes in the appeal rate which measures stringency of local construction permit process.

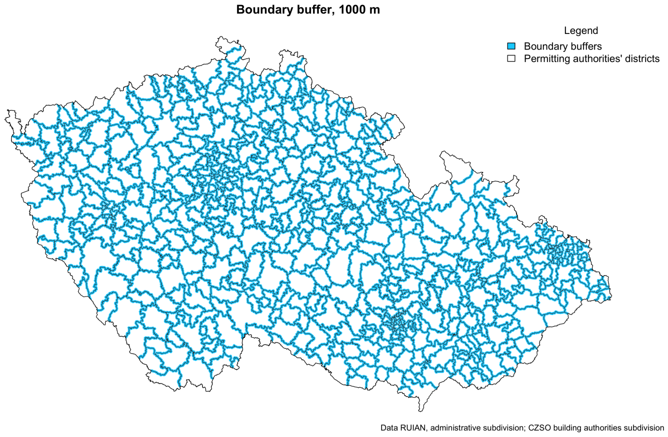

Figure 3.4.1: 1000 metres buffer of the Boundary discontinuity design

Second concern regarding the estimation strategy is whether the appeal rate is exogenous to local real estate market or whether it is conditionally independent when controlling for boundary fixed effects.

Strict exogeneity of the appeal rate is obviously not the case following simple visual inspection of the data shown on the figure 3.3. It shows substantially higher appeal rate in the two largest cities. The density of current land use, or something else correlated with density, likely affects mean expected appeal rate. It could be possibly driven by more stakeholders within proximity of a proposed project who might be negatively affected and have motivation to oppose it. Alternatively, in more densely developed areas land is scarcer and more expensive and developers might be willing to propose bulkier designs to fully exploit their land leading to stronger opposition from local stakeholders and ultimately to higher levels of appeal rate.

The above mentioned concerns should be however mitigated when boundary discontinuity design is used as it is assumed the endogenous component of the appeal rate is determined by variables continuous across space and the difference of appeal rates at the boundary should be attributed to differences in permitting processes' stringency of the two offices on both sides of the boundary uncorrelated with these local fundamentals. However, there remains a threat that developers' decisions regarding a project design are endogenously determined by local office's stringency. This possibility remains to be ruled out by using suitable instrumental variable to instrument actual appeal rate.

The model is estimated separately for single family houses and apartment houses according to the following equation where subscript t denotes the period of measured supply change relative to the housing stock size in previous period and individual observations i are aggregated on the level of elementary statistical units into which individual properties belong (the columns 1 to 3) and ϕ_f is a boundary fixed-effect capturing local changes in supply and demand.

$$\ln(H^R_{t,if}/H^R_{t-1,if}) = \beta \ln(AR)_i + \phi_{tf} + \varepsilon_{tif} \tag{3.4.1}$$

The left hand side variable, relative change of supply, is defined alternatively in a three different ways. First, it is measured as a change in number of completed buildings in the period 2001-2011 relative to the stock existing before. The second specification mimics the first one, but focuses on the period of completion between 2014 and 2020. These two specifications investigate the extensive margin effect focusing on number of houses. The third column estimates intensive margin effect analysing effect on mean size of houses built in the period from 2001 to 2011.

In the fourth specification, prices instead of supply changes are regressed on permitting stringency and in this specification observations i are individual properties:

$$\ln(Y^R_{if}) = \beta \ln(AR)_i + \phi_f + \varepsilon_{if} \tag{3.4.2}$$

The results of ordinary least squares models for both single family houses and apartments are reported below in the table 4.5.1.

	BDD # Bldg, 2001-2011	BDD # Bldg, 2014-2020	BDD Bldg size, 2001-2011	BDD Price
		Single family houses		
log(AR)	-0.012^{*} (0.005)	-0.006^{*} (0.003)	0.013 (0.011)	0.036^{*} (0.017)
boundary fixed effect	✓	✓	✓	✓
R^2	0.000	0.000	0.000	0.001
Adj. R^2	−0.148	−0.134	−0.219	−0.044
Num. obs.	14631	16140	9703	37397
		Apartment buildings		
log(AR)	0.002 (0.009)	−0.012 (0.007)	−0.041 (0.071)	0.001 (0.038)
boundary fixed effect	✓	✓	✓	✓
R^2	0.000	0.001	0.000	0.000
Adj. R^2	−0.346	−0.319	−0.504	−0.006
Num. obs.	5326	5881	1772	133952

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Individual observations for models (1) - (3) are aggregates of elementary statistical units. In model (4) individual observations are properties for sale.
Observations include administrative areas of Building permitting offices with non-zero appeal rate and boundaries with non-zero size of housing stock in the initial period.
Robust standard errors clustered at the boundary level are reported in parentheses.

Table 3.4.1: Effects of appeal rate, boundary discontinuity design

The results for single family houses are negative and statistically significant in case of extensive margin effect, with a point estimate twice larger for the earlier period. It seems there is no intensive margin effect. Curiously, positive and significant effect of permitting stringency on prices has been estimated for single family houses. This could be interpreted as either markets on both sides of the boundary are not perfect substitutes and reduced supply on one side increases local prices, or that more stringent permitting is itself an amenity for existing properties, or stringency is correlated with other policies with positive effects on property prices. No statistically significant results were obtained for apartment buildings[68]. However, there still remain doubts about endogeneity problems which are tackled in the subsequent part with instrumental variables approach.

The appeal rate is being instrumented with four instrumental variables, each of them trying to exploit different source of exogenous variation. In this part individual instruments are briefly described and more detailed discussion is provided in Appendix 3.A.

The first instrumental variable is defined as a relative change in building permit stringency before and after the 2012 Building Act amendment. The period 2012/2013 is specific for its notable discontinuity in trends - both in number of decisions issued by the Building permit offices and appeal rate. This break in trend could be most easily explained by amendment to the Building Act effective from the 1st January 2013[69]. Although the aim of the amendment was to ease the permitting process, additional state authorities issuing binding statements during the permitting process were included. As a consequence, already stringent locations could and likely have become even more stringent in their building permit processes.

The second instrument focuses on stringency of state authorities other than Building permitting offices. As it has been argued before, state authorities protecting public interests have quite strong position in the building permit process and they can grant exemption from regulation falling within their competency. These state authorities, such as public health, police or fire brigade, are assumed not to affect new construction through other channel than their involvement as a stakeholder in the building permitting process. It is assumed less stringent public authorities are more likely to provide such exemptions from existing regulation. The instrumental variable is constructed as a ratio of provided exemptions to number of processes that were interrupted due to the non-compliance with the regulation, the Building code in particular.

The third instrument is based on number of Building permit authority clerks per 100,000 square meters of gross floor area of new construction. The intuition is the larger staff at a building permit office given amount of new construction within its jurisdiction, the more thorough clerks could be when assessing individual applications. As a result, an assessment of a project would be likely more stringent. Because building permitting is within state compe-

[68]Somewhat surprisingly, in completely different context of California, Quigley and Raphael (2005) arrive to the same conclusion that increasing number of individual construction regulations in Californian cities negatively affects growth of single-family units, but have no effect on multi-family units. Adding one additional regulation on average decreases production of single family houses by 0.5%. However, they do not further discuss why results for the two types of housing are different.

[69]Details about the Building Act reforms are provided in Appendix 3.A

tencies, number of clerks seem to be primarily driven by nationally-given rules derived from number of residents within administrative areas of permitting offices, instead of by the development intensity that determines workload at a particular office. This conclusion is based on auxiliary models which are provided in Appendix 3.A.

The fourth instrumental variable is trying to exploit variation in stringency of state authorities protecting public interests in environmental protection. Share of land which is under national environmental protection is calculated for each Building permit office's administrative area. The assumption is the larger the share of land under this type of protection within an administrative area of a Building permit office is, the more are local clerks used to assess potential impacts on the environment and the more opposing against new development they might be. It worth noting the administrative areas of Building permitting offices rarely coincide with delineation of areas under environmental protection so it should not be the case the effect is driven by larger share of protected areas on one side of the boundary[70].

Equation 3.4.3 is the first stage of the two-stage estimation predicting the appeal rate with the four instruments introduced above.

$$\ln \widehat{(AR)}_i = \pi_a \Delta \ln (AR_i^{p/p}) + \pi_b \ln (ex_i/stop_i) + \pi_c volume_i + \pi_d protected_i + \phi_f + \varepsilon_{if} \tag{3.4.3}$$

The results of the first stage are shown in the table 3.A.2 in Appendix where the first column reports preferred full specification using jointly all four instrumental variables, and then in the columns (a) to (d) are reported auxiliary models where individual instruments are used one at a time.

All four instruments are statistically significant both when they are used jointly or separately. Their mutual independence is confirmed when instruments are used separately one by one and their estimated coefficients are largely unchanged with an exception of number of clerks per given agenda (the column c), where the estimated coefficient differ from the baseline specification by roughly 2 standard errors.

The second stage of the model using predicted values of appeal rate from the first stage is estimated according to the equation 3.4.4. To predict appeal rate, full specification with all four instrumental variables is used.

$$\ln (H_{t,if}^R / H_{t-1,if}^R) = \beta \ln \widehat{(AR)}_i + \phi_f + \varepsilon_{tif} \tag{3.4.4}$$

The results for both single family houses and apartment houses are re-

[70] The estimation strategy employs boundary discontinuity design, so results using this instrument are not mechanically driven by negative correlation between share of protected areas and new construction. Instead, as all estimation is based on a 1 kilometre wide belt along each boundary with boundary fixed effects included, fraction of actual protected areas entering estimation should be about the same on the both sides of a boundary.

ported in the table 3.4.2. In the case of effect on single family houses on extensive margin, increasing appeal rate by 10% lead approximately to 0.58% lower growth rate of new construction in the period 2001-2011[71]. The magnitude for the later period from 2014 to 2020 is one half of the estimate for the earlier period and is significant only at 10% level. Regarding the intensive margin, there is no evidence higher appeal rate affects mean size of newly constructed detached houses and there is also no evidence of price effect linked to the appeal rate. This implies communities across the boundary are substitutes and the appeal rate affects quantity of new construction but does not affect prices[72]. Also no effect on prices rules out an option the building permit stringency is itself an amenity with positive effect on price.

	BDD - IV # Bldg, 2001-2011	BDD - IV # Bldg, 2014-2020	BDD - IV Bldg size, 2001-2011	BDD - IV Price
		Single family houses		
log(AR)	-0.058^{**} (0.021)	$-0.024^{\cdot}$ (0.013)	-0.053 (0.041)	0.024 (0.047)
boundary FE	✓	✓	✓	✓
1.S. F-stat	346.213	346.213	346.213	346.213
R^2	0.000	0.000	0.001	0.001
Adj. R^2	-0.161	-0.145	-0.232	-0.039
Num. obs.	13101	14461	8731	39127
		Apartment buildings		
log(AR)	-0.014 (0.030)	-0.019 (0.021)	$-0.398^{\cdot}$ (0.211)	-0.044 (0.094)
boundary FE	✓	✓	✓	✓
1.S. F-stat	346.213	346.213	346.213	346.213
R^2	0.000	0.001	0.000	0.000
Adj. R^2	-0.354	-0.326	-0.484	-0.006
Num. obs.	4902	5421	1689	131824

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations for models (1) - (3) are aggregates of elementary statistical units. In model (4) individual observations are properties for sale.
Observations include administrative areas of Building permitting offices with non-zero appeal rate and boundaries with non-zero size of housing stock in the initial period.
Robust standard errors clustered at the boundary level reported in parentheses.

Table 3.4.2: Effect of appeal rate on new construction, BDD

For apartment buildings the extensive margin remains statistically insignificant as well as the effect of appeal rate on price. However, there seems to be an effect of appeal rate on intensive margin in the mean size of completed apartment buildings. When the appeal rate increases by 10%, apartment buildings have on average 3.3% smaller gross floor area. This intensive margin effect is statistically significant at the 10% level.

An argument why there is an extensive margin effect for single family houses and an intensive margin result for apartment buildings is not straight

[71] This baseline specification in re-estimated in Appendix using only one instrument a time. Three out of four point estimates with a single instrument are up to one standard deviation from the model with all four instruments and are statistically significant at 10% level. Instrument using share of protected areas yields lower magnitude and is not statistically significant on conventional levels.

[72] Similarly Glaeser and Ward (2009) show for Boston area that individual municipalities are very close substitutes as the regulation affects quantity of new construction but not prices when demographic characteristics are controlled for.

forward. It seems plausible that in the case of single family houses, which are typically being built on natural or agricultural land, the building permit process assessment is rather binary - whether new development of detached houses negatively affects environment or not, with less of attention paid to the size of houses themselves. Contrary to that, in dense urban areas where apartment buildings are built, their size and height likely affect to what extent they would pose negative effects on their surrounding, such as shading existing buildings or exploiting local amenities.

It has been shown earlier there are vast areas in the Czech Republic where residential real estate prices do not reach actual construction costs and as a consequence housing supply should be almost perfectly inelastic there following prediction of the kinked housing supply function. Implication for the models presented so far should be a negative effect of the appeal rate on new construction only in areas where real estate prices exceed construction costs and where new construction is profitable. In areas where real estate prices are below construction costs the appeal rate should have no effect because there is no systemic demand for new construction and therefore any level of building permit stringency should not be binding[73].

To allow for heterogeneous effects of the appeal rate on new construction, it is interacted with a dummy variable *constrained*, which has a value 1 for boundaries where property prices are above construction costs at least on one side of the boundary and is equal to 0 elsewhere. The estimation equation 3.4.5 is below:

$$\ln\left(H^R_{t,if}/H^R_{t-1,if}\right) = \beta \ln\widehat{(AR)}_i * constrained_{if} + \phi_f + \varepsilon_{if} \qquad (3.4.5)$$

The results for specifications of the main interest - intensive and extensive margin for the period between 2011 and 2011 - are shown in the table 3.4.3. For single family houses, the extensive margin effect of the appeal rate on growth rate of new construction is indeed on average larger for areas with property prices above construction costs, approximately one-and-half times, but the result is not statistically significantly different from the effect for areas with prices below construction costs.

For apartment buildings the intensive margin effect for areas above construction costs is approximately one-half larger in magnitude compared to the

[73]This prediction is consistent with stylised theoretical model of the kinked supply function. However, in reality, all areas exhibit some amount of new construction, either because some plots even in otherwise cheap locations have outstanding amenities and are profitable to be developed, or development is driven by some idiosyncrasies of investors. Also by definition of the explanatory variable of interest - the appeal rate - some development activity is necessary so that building permit applications are filed and appeals against decisions are raised. This section uses simple concept of the kinked housing supply function while more elaborate approach is taken in the quantitative model section.

previous results reported in the table 3.4.2[74]. In areas where real estate prices exceed construction costs increasing the appeal rate by 10% decreases average size of an apartment building by almost 4%, but at the same time in areas that are below construction costs increasing appeal rate by 10% is associated with on average larger apartment buildings by 9%. While the effect for the areas above construction costs is aligned with theoretical assumptions, there does not seem to be any reasonable explanation for the opposite effect found for areas below construction costs. However, apartment buildings are by large built in cities where property prices are above construction costs and therefore the result for places bellow construction costs is likely driven by few specific observations.

	Detached houses		Apartment buildings	
	# Bldg 2001-2011	Bldg size 2001-2011	# Bldg 2001-2011	Bldg size 2001-2011
log(AR)	$-0.040^{\cdot}$	-0.026	-0.022	0.646^{**}
	(0.024)	(0.047)	(0.040)	(0.249)
log(AR)*c.	-0.063	-0.086	0.062	-1.127^{***}
	(0.045)	(0.085)	(0.056)	(0.305)
boundary FE	✓	✓	✓	✓
1.S. F-stat	346.213	346.213	346.213	346.213
R^2	0.000	0.001	0.000	0.002
Adj. R^2	-0.144	-0.215	-0.338	-0.475
Num. obs.	12423	8446	4813	1677

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are aggregates of elementary statistical units.
Observations include administrative areas of Building permitting offices with non-zero appeal rate and boundaries with non-zero size of housing stock in the initial period.
Robust standard errors clustered at the boundary level reported in parentheses.

Table 3.4.3: Effect of appeal rate on new construction with kinked supply curve, BDD

This section has brought evidence of negative effects of the appeal rate on housing supply. The results support expectations that more stringent building permit processes reduce construction and do suggest, although not conclusively, this effect is stronger for markets where prices are above construction costs and which experience systemic demand for new construction.

The results also show different effects for single family houses and apartment buildings. While the effect on single family houses is on extensive margin through number of new units built, the effect on apartment buildings is on intensive margin with smaller size of buildings being built.

Effects of zoning plans

In this part the aim is to estimate the effect of available zoned developable gross floor areas on new development. It is assumed the more land is zoned for development at higher allowed development densities, the more development would be likely seen in a given municipality.

[74] Evaluating the effect in constrained areas as + 0.65 - 1.13

The left-hand side of the estimation equation 3.4.6 has the same outcome variables as the first three models in the previous section: for the first two models log difference between number of buildings built in the two periods 2001-2011 and 2014-2020 and the number of existing buildings at the beginning of the respective periods. The third model have as a left-hand variable the mean size of buildings completed in the period 2001-2011.

On the right-hand side of the equation 3.4.6 is a variable D/C which measures ratio between zoned developable gross floor areas D and existing stock of gross floor areas C as of 2011. This variable therefore measures municipal development potential relative to its current real estate stock. Measurement of the variable D, developable gross floor areas, is however problematic and contains measurement error. The zoned developable land data collected by Maier et al. (2016) do not cover the whole Czech Republic and methodological definition of developable land differs for regions and ORPs which collect and report data from individual municipalities[75]. Although the data were cleaned to make them consistent across administrative areas, they additionally only include information about developable land without permitted developable intensity. To overcome this issue, gross development density of buildings built in the period 1991 to 2011 in each municipality was calculated and taken as an expected developable intensity of areas zoned for development.

Then remaining regressors are controls of municipal population in the form of a polynomial of a fourth degree to take flexibly into account potential differences in growth patterns based on municipal size. The last term ϕ is a regional fixed effect.

$$\ln\left(H^R_{t,if}/H^R_{t-1,if}\right) = \beta \ln\left(D/C\right)_{if} + f(population_{if}) + \phi_r + \varepsilon_{if} \qquad (3.4.6)$$

Results for both single family houses and apartment buildings are reported in the table 3.4.4. Similar to effects of appeal rate on new construction, results are statistically significant and with expected signs in case of extensive margin (number of units built) for single family houses. Increasing capacity of zoning plans by 10% on average increases new construction by 0.1%. Results for intensive margin and for apartment buildings are however insignificant.

The model specification according to the equation 3.4.6 however suffers from several issues: first of all, there is the already mentioned measurement error in dependent variable which is expected to attenuate results toward zero. Another problem is potential endogeneity of the variable measuring relative development potential regulated by zoning plans. First of all, it could be only growing municipalities or municipalities willing to attract new development which adopted zoning plans and other municipalities would not be represented

[75] Administrative subdivision and data processing are described in detail in Appendix.

in data[76]. Then the direction of causality is initially unclear: either more of zoned land could attract more development, or existing demand and construction could call for more zoned areas for development. As it has been shown earlier, zoning seems to be persistent for larger municipalities above 5 or 10 thousand inhabitants, but not for smaller ones. To the contrary, municipalities bellow 1,000 inhabitants seemed to be more responsive to new demand in their zoning which is raising concerns of endogeneity.

	Detached houses			Apartment buildings		
	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011
log(dev/cur)	0.009^{***}	0.013^{***}	0.002	0.000	0.002	0.013
	(0.003)	(0.001)	(0.003)	(0.003)	(0.002)	(0.019)
population.c.	✓	✓	✓	✓	✓	✓
region FE	✓	✓	✓	✓	✓	✓
R^2	0.006	0.040	0.000	0.004	0.001	0.191
Adj. R^2	0.002	0.036	−0.004	−0.002	−0.004	0.176
Num. obs.	4379	4390	4274	3217	3361	967

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Robust standard errors clustered at the regional level reported in parentheses.

Table 3.4.4: Effects of zoned developable areas on development

These issues are addressed with the instrumental variable approach. Specific feature of the Czech local public finance from the beginning of the 2000's is exploited to instrument relative amount of developable gross floor areas in zoning plans. Municipalities are financed primarily with state transfers based on a per-capita formula. Over a period of seven years in early 2000's, there were fourteen size categories of municipalities and transfers per capita were stepwise increasing with municipal size category creating discrete jumps in overall size of transfers (Provazníková, 2015)[77]. As a result, municipalities were motivated to exceed population thresholds to qualify for higher per-capita transfers, especially if their population was slightly below these thresholds. This setting provides a good boundary discontinuity design, especially because these boundaries are evenly distributed along the range of municipal population sizes.

The first stage of the model predicting relative development capacity of zoning plans is defined by equation 3.4.7. Binary variable *thr* has a value of 1 if the municipality population is close to the cut-off thresholds from below. The size of the interval 'being close to the threshold' has been defined as the upper third from one threshold cut-off to the next one. Alternative specifications were tested with similar quantitative results, but usually with higher standard errors.

The distance to the cut-off threshold is used as a running variable in two

[76]Municipalities are not required to have a zoning plan, but they have been incentivised over time to procure it.

[77]More details regarding the local public finance in the Czech Republic and its development since the early 1990's is provided in Appendix.

alternative functional forms: either as a second degree polynomial or as a natural logarithm. The function of running variable is interacted with the *thr* variable to allow for different trends on the both sides of the boundary. Finally, the function controlling overall population effect is included as a control, either as a fourth-degree polynomial or as a natural logarithm, and regional fixed effects are included.

$$\ln(\widehat{D/C})_{if} = \pi_a thr_{if} + f(dist.bnd_{if}) * thr_{if} + f(population_{if}) + \phi_r + \varepsilon_{if} \quad (3.4.7)$$

The results of the first stage are reported in the table 3.A.4 in Appendix. All five alternative model specifications yield reasonably similar results with expected signs, but some of the tested specifications are not statistically significant. The alternative specifications include only municipalities above 300 inhabitants (>300, the second column), municipalities in population range between 300 and 20,000 only (>300 <20,000, the third column) and the last two models use alternative functional form of distance to threshold and population controls. The preferred specification in the first column shows that municipalities below the cut-off threshold do have on average 15% more zoned developable gross floor areas.

The second stage of the model is defined by the equation 3.4.8. Results of the model are reported in the table 3.4.5. None of the results but one are significant. Surprisingly, the effect on number of detached houses is negative and significant. Discussion of the potential reasons of this result is provided later in this section.

$$\ln(H^R_{t,if}/H^R_{t-1,if}) = \beta \ln(\widehat{D/C})_{if} + f(population_{if}) + \phi_r + \varepsilon_{if} \quad (3.4.8)$$

	Detached houses			Apartment buildings		
	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011
log(dev/cur)	-0.075^*	0.011	-0.141	-0.086	0.072	-0.101
	(0.032)	(0.017)	(0.090)	(0.127)	(0.090)	(0.377)
population.c.	✓	✓	✓	✓	✓	✓
region FE	✓	✓	✓	✓	✓	✓
F-stats.	13.49	13.49	13.49	13.49	13.49	13.49
R^2	0.005	0.040	0.000	0.000	0.000	0.173
Adj. R^2	0.001	0.036	-0.004	-0.006	-0.005	0.158
Num. obs.	4379	4390	4274	3217	3361	967

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Robust standard errors clustered at the regional level are reported in parentheses.

Table 3.4.5: Effects of zoned developable areas on development, IV

As it has been shown earlier, there is a good evidence of property prices being in some places below construction costs and elsewhere above them. Implications of the kinked housing supply curve predict different effects of amount of zoned developable gross floor areas for these two types of locations. Limiting new development with low provision of developable land should be constraining in places where demand for new construction is sufficient which are places with property prices at or above construction costs. On the other hand, in municipalities where construction costs are larger than property prices, no systemic new development should occur and therefore any kind of regulation of new construction should not be binding. This is introduced into the estimating equation 3.4.9 by interacting the variable of interest $(\widehat{D/C})_{if}$ with a dummy variable denoting whether property prices within a municipality are above construction costs.

Remaining terms in the equation 3.4.9 are the same as in the equation 3.4.8.

$$\ln{(H^R_{t,if}/H^R_{t-1,if})} = \beta \ln{(\widehat{D/C})_{if}} * constrained_{if} + f(population_{if}) + \phi_r + \varepsilon_{if} \tag{3.4.9}$$

The results shown in the table 3.4.6 indeed confirm different effect of zoning plans' capacity on new construction depending on relation between local property prices and construction costs. With an exception of the effect on number of detached houses in the period 2001-2011, all effects in areas below construction costs are insignificant and even magnitudes of the coefficients in the four specifications out of six are rather small.

Conversely, resulting extensive margin effects on number of units built are significant and of similar magnitudes for both periods in the case of detached houses and for later period in the case of apartment buildings. On average, increasing amount of zoned developable gross floor areas by 10% in municipalities where property prices are above construction costs leads to 9.2% to 15.3% faster growth rate of new construction, both for detached and apartment housing.

The reason, why the result is not statistically significant for number of built apartment buildings in the period 2001-2011, could be slow building permit processes. As it was noted earlier, building permit processes for apartment buildings are very lengthy in the Czech Republic - 5.1 years on average in Prague according to Deloitte (2021). Taking into account also longer construction time, it seems possible that not so many apartment buildings initiated at the time of relaxing zoning plans in early 2000's could have been completed by early 2011 when the first analysed period ended.

The negative and significant effect of zoned developable gross floor areas on detached houses construction is puzzling. One plausible, but rather weak, explanation could be intentional expansion of developable land in areas with low demand. Areas below real estate construction costs should not see systemic new development. It might however be the case that municipalities right below the population cut-off which had poor prospects of future growth purposefully expanded amount of developable gross floor areas in their zoning plans to try to attract new investment. Such behaviour would explain the obtained negative effect.

Unlike effects on extensive margin, there does not seem to be any effect on the intensive margin - the amount of zoned developable capacities does not affect size of buildings themselves.

	Detached houses			Apartment buildings		
	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011	# Bldg 2001-2011	# Bldg 2014-2020	Bldg size 2001-2011
log(dev/cur)	$-0.096^{\cdot}$	0.007	-0.152	-0.068	0.040	0.003
	(0.050)	(0.018)	(0.095)	(0.127)	(0.052)	(0.334)
log(dev/cur)*c.	0.206^{**}	0.081^{**}	0.120	-0.143	$0.102^{\cdot}$	-0.253
	(0.068)	(0.025)	(0.087)	(0.102)	(0.056)	(0.396)
constrained	0.377^{***}	0.148^{***}	$0.173^{\cdot}$	-0.045	0.150^{*}	-0.108
	(0.092)	(0.035)	(0.100)	(0.110)	(0.066)	(0.460)
population.c.	✓	✓	✓	✓	✓	✓
region FE	✓	✓	✓	✓	✓	✓
F-stats.	13.49	13.49	13.49	13.49	13.49	13.49
R^2	0.007	0.061	0.000	0.006	0.004	0.188
Adj. R^2	0.003	0.057	-0.005	-0.001	-0.002	0.171
Num. obs.	4379	4390	4274	3217	3361	967

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Robust standard errors clustered at the regional level are reported in parentheses.

Table 3.4.6: Effects of zoned developable areas on development with kinked supply curve, IV

This section has brought convincing evidence that both building permit processes and capacities of zoning plans affect growth rates of new development. While in the case of zoning plans it is the extensive margin effect affecting areas above real estate construction costs, for building permit processes the effect is present for all places with weak evidence it is stronger in areas with prices above construction costs. Unlike effects of zoning plans, effects of building permit processes vary for the two studied types of housing: detached houses are affected on the extensive margin while apartment buildings are affected on the intensive margin.

Despite these differences, the overall conclusion is that more restrictive building permit process and lower capacities of zoning plans impede new residential development.

3.5 Quantitative spatial model

The aim of this part is to model spatial development of the economy on the national level in the period between 1991 and 2011 within a general equilibrium framework with a special focus on planning and building permit process stringency affecting local housing supply. Obvious difficulty of doing so is lack of data at a sufficient geographic detail. Real estate prices are not available for the beginning of the study period and wages are not available at a sufficient geographical level at all.

To overcome the data limitations, simplified quantitative spatial model based on Ahlfeldt et al. (2015), Heblich et al. (2020) and Monte et al. (2018) is used to recover wages from commuting patterns in 1991 and 2011, and then rents using observed data, size of housing stock and expenditure shares on housing. Model calibrated on available data is then used to predict counterfactual scenarios. Unlike a model of one city embedded in a wider economy as in Heblich et al. (2020) or Ahlfeldt et al. (2015), in this chapter a system of municipalities covering the whole country is modelled, resembling in this respect Monte et al. (2018) who model interactions among US counties with daily commuting, trade and migration. Unlike them, I do not model trade between spatial units and in this respect the model is more similar to the two previously mentioned papers.

As the primary objective of the analysis are housing supply constrains, a novel housing supply function is proposed. The function explicitly includes variables that are expected to affect housing supply price elasticity: amount of physically developable land, share of land zoned for development, building permit process stringency and locally allowed development density. Key structural parameters are estimated from equilibrium conditions using instrumental variable approach and the housing supply function is then calibrated to match observed stock and new construction between 1991 and 2011.

The framework of the quantitative spatial model is then used to simulate counterfactual scenarios in which the three types of constraints are relaxed one by one or in combinations. Additionally, alternative scenario with imperfect durability of housing capital is simulated. The key outcomes of these scenarios are alternative distributions of population across space, change in wages and rents and change in households' indirect utility.

Workers and firms

The economy consists of discrete exogenously defined locations - municipalities $\mathbb{I}$ that are both home to workers and where jobs are located. Workers can either work in the location of their residence i or they can commute to any other location which becomes their workplace denoted by j. Number of workers living in i is denoted by N_i^R and number of workers working in j is denoted by N_j^J. The total number of workers in economy is $\mathbb{N}$ with $\mathbb{N} = \sum_i^I N_i^R = \sum_j^J N_j^J$.

Workers do have the same preferences given by the utility function, but choices of even observationally same workers do differ as each worker has a randomly distributed taste shocks for each residence-workplace pair. Worker's indirect utility is defined by the equation 3.5.1 and depends on his or her residence i and workplace j. Utility increases with wage w_j earned at a workplace j and decreases with commute costs d_{ij} separating workplace and residence, and with rents Q_i given by a place of residence. Parameter α defines expenditure share on consumption of goods other than housing. Rents are collected by an absentee landlord. Each worker o draws idiosyncratic utility shifter for a particular residence-workplace pair z_{ijo} that has a Fréchet distribution with a dispersion parameter ε and a scale parameter governed by B_i^I and B_j^J. B_i^I captures the mean utility derived from amenities in residence i. The term B_j^J captures the mean utility derived from working in j. However, unlike in Heblich et al. (2020), wage component w_j and utility component B_j^J are empirically inseparable, so all benefits of working in j are assumed to be capitalized into wages w_j.

Within a residential location i, workers also value quality of prospective land for development θ_{il}. This term is normalized to 1 for already developed properties for which local quality is fully captured in their market price. Demand for quality of land θ_{il} is the same for all workers and it is perfectly elastic, so the quality of land is fully offset by higher price of developed properties Q_{il} which is a product of local market level rents in existing properties $\widetilde{Q_i}$ and price shifter $\widehat{q_{il}}$ which is equal to the value of θ_{il}. The term $(\theta_{il}/Q_{il})^{1-\alpha}$ could be therefore simplified to $\widetilde{Q_i}^{1-\alpha}$ where $\widetilde{Q_i}$ is a rent level in existing buildings. The role of θ_{il} and assumptions about its distribution are described in more detail in the section regarding housing supply.

$$V_{ijol} = \frac{z_{ijo} w_j}{d_{ij}} \left(\frac{\theta_{il}}{Q_{il}} \right)^{1-\alpha} \qquad Q_{il} = \widetilde{Q_i}\widehat{q_{il}} \tag{3.5.1}$$

$$F(z_{ijo}) = e^{-B_i^I B_j^J z_{ijo}^{-\varepsilon}}$$

The economy produces one homogeneous good using Cobb-Douglas production technology with constant returns to scale expressed in the equation 3.5.2. Production of good X in location j depends on labour size N_j and capital input M_j which is fully mobile across space and available at the same price. Consumption good is freely and costlessly traded across space and its price is normalized to one everywhere. Implication of the production function is that production does not need commercial real estate which is omitted in the model altogether and as a result jobs are mobile across space and follow the workforce. Productivity in each location j is adjusted by an exogenous local production amenity A_j^J. Constant share of inputs into production function is governed by parameters β^L and β^M which sum to one.

$$X_j = A_j^J N_j^{\beta^L} M_j^{\beta^M} \qquad \beta^L + \beta^M = 1 \tag{3.5.2}$$

The key feature of the model is the relationship between wages, commuting costs and probability of commuting between pairs of workplaces and residences defined in the equation 3.5.3. Probability of commuting from a residence i to a workplace j conditional on living in i $\pi_{ij|i}$ is equal to a wage earned in j divided by commuting costs d_{ij} to the power of Fréchet dispersion parameter ε. The numerator is also called a bi-lateral resistance between residence and workplace. The numerator is divided by the sum of all wages and commuting costs to the power of ε for all accessible locations, which is called a multilateral resistance between residence and all accessible workplaces. The probability of commuting is observable as a volume of individual commute flows from i to j relative to a number of workers residing in i in the data.

Commuting costs are modelled as in Ahlfeldt et al. (2015) as an exponential function with arguments of commuting time τ_{ij} in minutes between a residence i and a workplace j and estimated commuting probability semi-elasticity ν.

$$\pi_{ij|i} = \frac{(w_j/d_{ij})^{\varepsilon}}{\sum_{s=1}^{S}(w_s/d_{is})^{\varepsilon}} \qquad d_{is}^{\varepsilon} = e^{-\tau_{is}\nu} \tag{3.5.3}$$

The link between wages by workplace w_j and wages by residence w_i^R is expressed in the equation 3.5.4. A wage by residence w_i^R in a location i is a weighted mean of wages by workplace w_j weighted by commuting probability from i to j.

$$w_i^R = \sum_{j}^{J} \pi_{ij|i} w_j \tag{3.5.4}$$

The constant expenditure feature of the Cobb-Douglas utility function imply the share of workers' expenditure on housing is always $1-\alpha$ of their wages by residence. Therefore that fraction of workers' income has to be equal to a rent Q_i times quantity of housing H_i in all locations $\mathbb{I}$ in equilibrium. Income shifter A_i^I controls for unobserved parts of income in location i not coming from estimated wages, such as retirement benefits or capital income which are not captured by the model. This term is assumed to be constant over time. Empirically, this term balances both sides of the equation (3.5.5) as housing price and quantity on the left-hand side are observed, and on the right-hand side residents N_i^R are observed, while wages are inferred from the model and parameter α is constant across municipalities[78].

$$Q_i H_i = A_i^I (1-\alpha) w_i^R N_i^R \tag{3.5.5}$$

The level of utility achieved in the economy is expressed in the equation (3.5.6) where $\Gamma(\cdot)$ is the Gamma function.

$$V = \Gamma\left(\frac{\varepsilon-1}{\varepsilon}\right)\left[\sum_{i}^{I}\sum_{j}^{J} B_i^I B_j^J \left(d_{ij}\widetilde{Q}_i^{1-\alpha}\right)^{-\varepsilon}(w_j A_i^I)^{\varepsilon}\right]^{1/\varepsilon} \tag{3.5.6}$$

[78]Inclusion of the income shifter A_i^I is practically identical to the approach of Heblich et al. (2020) who use equivalent rent-clearing condition to solve for wages directly

Housing supply

I propose a housing supply function featuring within-municipality variation in land amenity value that is motivated by empirical observation of new construction even in places where simple theory would not predict any new investment. Theoretical implication of the kinked supply curve (Glaeser and Gyourko, 2005) is no construction if property prices decrease below costs of new construction. In that region the housing supply curve is perfectly inelastic[79]. Figure 3.2.2 shows that large portion of the Czech Republic is actually in the region of property prices well below construction costs.

Despite prices being well below construction costs, we hardly see any place without at least some new development as it is shown on the figure 3.5.1. However, this observation contradicts the prediction of the simple kinked housing supply function theory, because we should not observe any new development in areas with property prices below construction costs. It worth to add the kinked supply theory is a powerful concept and it can be amended to take into account local idiosyncratic reasons for development even in locations where simple theory would not predict any development at all. To link the theory to observed data and justify new construction, distribution of plot-level amenity shifters θ_{il} is assumed. This localised amenity effect might capture quality of neighbourhood, environmental qualities, accessibility or other features[80].

To link this concept to the observed data, residual variation in property prices σ_i from an auxiliary hedonic model is used to measure dispersion in local within-municipality amenities. As could be seen on the figure 3.5.2, there are almost everywhere at least some properties that are valued above construction costs. While some portion of price of high-value properties could be explained by property-level characteristics or overall local property prices level, remaining portion could be attributed to local plot-level unobserved features which are not explicitly modelled and therefore enter the error term.

Each municipality is endowed with initial amount of housing stock $\widetilde{H_i}$ which developers could increase with new construction. Housing is produced by perfectly competitive developers who use optimal amount of developable land L_i^* acquired at price of unit land p_{Li}. They always develop plots at constraining maximum permitted density ρ_F with total development costs c_i^* per unit of housing. The resulting amount of housing H_i^* is sold at price $\widetilde{Q_i}\overline{\theta_i}$ corresponding to the price of existing housing stock $\widetilde{Q_i}$ multiplied by premium $\overline{\theta_i}$ capturing higher amenities of the new development compared

[79] Or almost perfectly inelastic if changes in use of existing buildings are allowed - for instance utilising vacant buildings, or converting recreational properties into residences.

[80] An alternative approach shown for instance by Gechter and Tsivanidis (2020), which is more appealing because it does not include θ_{il} in the utility function, assumes scattered land ownership among land owners-developers who each have idiosyncratic shock to profitability developing their piece of land. In their setting equivalent of θ_{il} enters the housing supply function only. However, to link the distribution of θ_{il} to observed data in my case, I have to use observed dispersion of property prices which I could relate to underlying local amenities. I do not observe data to do the equivalent with developers' idiosyncratic construction costs

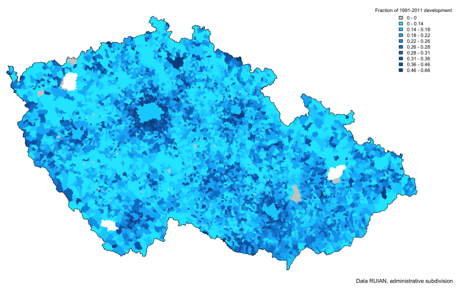

Figure 3.5.1: Fraction of new development to 1991 stock

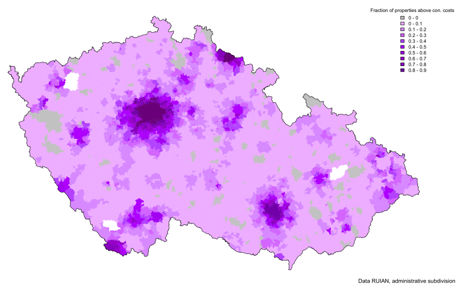

Figure 3.5.2: Fraction of properties above constr. costs

to the existing stock. This is expressed in the profit function (3.5.7) and the resulting equilibrium condition (3.5.8) relating housing prices and development costs when developers' profits are zero.

$$\Pi_i = H_i^* \widetilde{Q}_i \overline{\theta_i} - L_i^* \rho_{Fi} c_i^* - L_i^* p_{Li} = 0 \tag{3.5.7}$$

$$H_i^* \widetilde{Q}_i \overline{\theta_i} = L_i^* \rho_{Fi} (c_i^* + p_{Li}/\rho_{Fi}) \tag{3.5.8}$$

Land plots available for development within a municipality differ in their amenity they provide to prospective users. Within a municipality i there are land plots l with a random quality θ_{il} drawn from a Fréchet distribution with a scale parameter equal to one and municipal-specific dispersion parameter ς_i.

$$F(\theta_{il}) = e^{-\mu_i \theta_{il}^{-\varsigma_i}} \tag{3.5.9}$$

Only plots with amenity value sufficiently large to ensure price of new development to be weakly higher than construction costs would be developed. Fraction of land worth development within a municipality is therefore defined as a survival function $[1 - e^{-(\mu_i c_i^* / \widetilde{Q}_i)^{-\varsigma_i}}]$ as for these plots worth development holds $\theta_{il} > c_i^* / \widetilde{Q}_i$, or in a re-arranged form $\theta_{il} \widetilde{Q}_i > c_i^*$: plot amenity value multiplied by local property values of endowed housing stock is higher than construction costs and therefore profitable to develop.

The mean value of $\overline{\theta_i}$, which determines relative price of new development to price of endowed stock, is an expectation of a random variables drawn from a truncated Fréchet distribution. The expected mean is calculated using the equation (3.5.11) following Abid (2016) where $\Gamma(\cdot)$ is the upper incomplete Gamma function and Ω approaches infinity[81].

$$\overline{\theta_i} = \mathbb{E}[\theta_{il} | \theta_{il} > c_i^* / \widetilde{Q}_i] \tag{3.5.10}$$

[81] Ω approaches infinity because quality of land is not truncated from above and all possible randomly drawn values up to infinity are considered.

$$\overline{\theta_i} = \frac{\mu_i^{1/\varsigma}}{e^{-\mu_i \Omega^{-\varsigma}} - e^{-\mu_i (c_i^*/\widetilde{Q_i})^{-\varsigma}}} \left[\Gamma\left(1 - \frac{1}{\varsigma}, \mu_i \Omega^{-\varsigma}\right) - \Gamma\left(1 - \frac{1}{\varsigma}, \mu_i (c_i^*/\widetilde{Q_i})^{-\varsigma}\right) \right] \tag{3.5.11}$$

Since density of new development is regulated and regulation is assumed to be binding in all cases[82], the only choice variable developers have is the amount of land to be developed. Equation (3.5.12) expands the optimal amount of land used L_i^* and construction costs per unit.

The construction cost per unit consists of c_i which includes hard and soft costs and varies by location according to the share of apartments to single family units developed there during the study period. These costs are adjusted by the cost shifter of local stringency of building permit process $\rho_{Pi}^{\omega_P}$ where ρ_{Pi} is a share of appeals against Building permit authority's decision and ω_P governs to what extent a change in appeal rate changes overall cost of construction. The rest is a contribution of land to cost per unit of housing.

The land used for development is expanded into overall amount of physically developable land $\widetilde{L_i}$ excluding water bodies, woods[83] and land at slopes over 15% following Saiz (2010). $\rho_{Li}^{\omega_L}$ is a share of physically developable land that actually could be developed. ρ_{Li} measures the fraction of developable land that was zoned for development and ω_L captures to what extent more of formally zoned land increases the supply of land available for actual development. The survival function capturing a fraction of land to be profitably developed is in the brackets. κ_i is a municipal-specific housing productivity shifter that captures all unobserved factors affecting local housing supply. This parameter is calibrated using observed data.

$$H_i^* \widetilde{Q_i} \overline{\theta_i} = \underbrace{\kappa_i \widetilde{L_i} \rho_{Li}^{\omega_L} \left[1 - e^{-(\rho_{Pi}^{\omega_P} c_i / \widetilde{Q_i})^{-\varsigma_i}} \right]}_{\text{Land used}} \rho_{Fi} \underbrace{(\rho_{Pi}^{\omega_P} c_i + p_{Li}/\rho_{Fi})}_{\text{Cost per unit}} \tag{3.5.12}$$

From the equilibrium condition (3.5.8) resulting from the developers' zero profits, price of new development has to be equal to construction costs. Prices and costs could be therefore eliminated from both sides of the equation result-

[82] Compared to other countries, Czech cities are relatively low rise. Average height of a building there is 1.75 floors and only 1.5% of all buildings are taller than 5 floors. According to Ahlfeldt and McMillen (2018), elasticity of construction costs with respect to building height is rather low for low-rise buildings at 0.25 compared to super tall buildings with elasticity of construction costs with respect to density of 1.7. They also report there is no negative effect of building height on share of rentable space on gross floor space for buildings up to five floors. This suggests that height regulation is likely within the range where increasing developed density does not increase significantly construction costs and therefore building up to the limits is rational, compared to situations when binding limits would be too high and it would not pay-off to developers to build up to the limit.

[83] Woods in the Czech Republic enjoy special protection and their conversion into developable land would be very complicated.

ing into the housing supply function (3.5.13).

$$H_i^* = \kappa_i \widetilde{L_i} \rho_{Li}^{\omega_L} \left[1 - e^{-(\rho_{Pi}^{\omega_P} c_i / \widetilde{Q_i})^{-\varsigma_i}} \right] \rho_{Fi} \tag{3.5.13}$$

Equation (3.5.14) is the housing market clearing condition. The mean rent Q_i multiplied by the local size of housing stock H_i has to be equal to the constant share $(1 - \alpha)$ of the households' income consisting of wage and non-wage component. The size of housing stock could be alternatively expressed as a portion of endowed stock $\lambda \widetilde{H_i}$[84] and a portion of new development H_i^* with its higher amenity value $\overline{\theta_i}$ and these two portions are multiplied by price of endowed housing $\widetilde{Q_i}$ to obtain overall rent collection.

$$Q_i H_i = \widetilde{Q_i}(\lambda \widetilde{H_i} + H_i^* \overline{\theta_i}) = (1 - \alpha) w_i^R A_i^I N_i^R \tag{3.5.14}$$

The overall housing stock H_i in the equation (3.5.15) is a sum of endowed housing stock $\lambda \widetilde{H_i}$ and new units constructed by developers. If housing stock is perfectly durable and all endowed stock endures, then coefficient λ is equal to one. Perfect durability is a reasonable assumption for the case analysed, but in some counterfactual scenarios this is relaxed and only a fraction of endowed housing capital survives. In such cases $\lambda < 1$.

The housing supply function is limited from above by maximum physical development capacity of a municipality defined as $\widetilde{L_i} \rho_{Fi}$ which is the maximum fixed area of physically developable land multiplied by maximum allowed developable density. If the housing supply reaches this limit it becomes perfectly inelastic.

$$H_i = \lambda \widetilde{H_i} + \min\left(\kappa_i \widetilde{L_i} \rho_{Li}^{\omega_L} \left[1 - e^{-(\rho_{Pi}^{\omega_P} c_i / \widetilde{Q_i})^{-\varsigma_i}} \right] \rho_{Fi},\ \widetilde{L_i} \rho_{Fi}\right) \tag{3.5.15}$$

Recovering wages and rents

In the first step, the model is used to predict wages by workplace and residence for all municipalities and for both time periods, and to predict rents for the first period.

First, wages have to be found. As rental prices of real estate are known only for the second period and to make wage estimation consistent for both periods, wages are not calculated from the equation 3.5.5 as in Heblich et al. (2020), but from the equation 3.5.3 as in Ahlfeldt et al. (2015). Probability of commuting to j conditional on residing in i is directly observable for both periods in the data in the form of commute flow volumes relative to overall out-commuting from each municipality i. Travel costs d_{ij}^{ε} for each commute flow are calculated from observed mean commuting time for each commute flow and

[84] Unless explicitly stated, the share of surviving endowed housing stock λ is assumed to be 1 omitting any depreciation.

estimated commuting probability semi-elasticity ν. Commuting probability semi-elasticity is estimated for each period with the gravity equation 3.5.16, where τ_{ij} stands for commuting time in minutes between a residence i and a workplace j and R_i, W_j are residence and workplace fixed effects.

$$\ln \pi_{ij} = \nu \tau_{ij} + R_i + W_j + \epsilon_{ij} \tag{3.5.16}$$

Models are estimated for both time periods for all commute flows and then for commute flows with more than 10 commuters, because commute flows with few individuals are likely to contain larger proportion of undesirable misreporting, such as very long commutes that are actually not taken on a daily basis.

	$\ln \pi_{ij}$			
	1991 all	1991 10+ commuters	2011 all	2011 10+ commuters
$\tau_{ij}[minutes]$	-0.008^{***} (0.000)	-0.008^{***} (0.000)	-0.019^{***} (0.000)	-0.027^{***} (0.001)
Residence and workplace fixed effects	✓	✓	✓	✓
R^2	0.023	0.021	0.084	0.079
Adj. R^2	0.023	0.021	0.084	0.078
Num. obs.	104529	21987	117943	20290

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Table 3.5.1: Estimation of commuting probability time semi-elasticity

The first two columns of the table 3.5.1 show the same results for the year 1991 for both specifications. The columns three and four for year 2011 yield different results with smaller magnitude of semi-elasticity of -0.019 for all commute flows compared to -0.027 for commute flows above 10 riders. Due to the concern of misreporting described above, the second value is therefore used later in the model.

It also worth mentioning the magnitude of semi-elasticity increased substantially over the period of 20 years. One possible explanation could be increased costs of commuting as either opportunity cost of time, or costs of transportation, or both increased. Alternative explanation could be high frictions either on labour or on housing markets that did not allow efficient residence-jobs allocation and forced workers to undertake relatively long commutes during the period of planned economy.

With calculated commute costs d_{ij}^{ε} for $i-j$ pairs, the system of n equations (3.5.3) where n stands for number of non-zero commute flows between all residences i and workplaces j can be calibrated with a unique vector of wages w_j such that number of residents and number of workers in each workplace and residence matches the data and squared error of predicted and observed size of commute flows is minimized with an iterative algorithm searching for the vector w_j^{ε}.

To find the vector of relative wages w_j, parameter ε governing the dispersion of idiosyncratic taste shock has to be set. This Fréchet dispersion parameter was chosen to be 5, to lay somewhat in between of calibrated values in related literature: 5.25 in Heblich et al. (2020), 6.83 in Ahlfeldt et al. (2015) and 2.7 and 3.2 in Bryan and Morten (2019).

With the vector of wages by workplace w_j and commuting probabilities, wages by residence w_i^R are calculated according to the equation (3.5.4).

While the model is designed to be based on flow variables, in the case of residential real estate only sales asking prices are observed instead of rents. To get equivalent monthly rental figures, asking prices are multiplied by 0.06 discount rate and divided by 12 months.

Housing supply function parameters

The three key policies affecting housing supply that are studied in this chapter are amount of zoned developable land ρ_L, stringency of the building permit process ρ_P and maximum allowed development density ρ_F. The last one mentioned is however thought to be always binding and therefore its actual effect on development is not subject to analysis to what extent it is binding unlike the other two.

Stringency of the building permit process is proxied in the same way as in the reduced form part with the share of appeals against decisions of Building permit authorities. The amount of zoned developable land is however modelled differently to fit better the proposed housing supply function. For each municipality a share of all physically developable land is calculated. Physically developable land includes not yet developed land excluding woods and slopes over 15%[85].

The building permit process stringency $\rho_{Pi}^{\omega_L}$ enters the cost part of the profit function and survival function governing share of land to be developed since the cost shifter effectively increases baseline costs of real estate construction c_i. Baseline construction costs are otherwise almost identical across space due to small geographic size of the country, same regulatory requirements on construction, mostly similar building materials and building tradition. The only variation in construction costs is caused by proportion of single family units to multifamily units built over the study period as the former have lower construction costs. Parameter of interest ω_P then governs to what extent increased permitting stringency increases construction costs.

Magnitude of parameter ω_P is estimated from an equilibrium condition resulting from the profit function and zero profit condition and perfect competition under which housing prices should be equal to production costs of housing: $Q_i = \rho_{Pi}^{\omega_L} c_i + \frac{p_{Li}}{\rho_{Fi}}$ where ρ_{Fi} is a local development density. This

[85] The slope threshold follows Saiz (2010), but it is not particularly binding for most of the Czech Republic.

condition is re-arranged and used as an empirical specification:

$$\ln(Q_{if} - \frac{p_{Lif}}{\rho_{Fif}}) - \ln c_{if} = \omega_{Pif} \ln(\widehat{\rho_{Pif}}) + \epsilon_{if} \tag{3.5.17}$$

	OLS	IV 1	IV 2
log(ρ_P)	0.086***	0.010	0.008
	(0.014)	(0.067)	(0.052)
log(ρ_P)*C_+	0.023	0.193	0.216*
	(0.043)	(0.139)	(0.108)
C_+	0.505**	1.178*	1.162**
	(0.175)	(0.560)	(0.429)
County FE	✓	✓	
ORP FE			✓
1st st. F-test:			
log(ρ_P)		74.095	75.627
log(ρ_P)*C_+.		105.623	138.109
R^2	0.180	0.153	0.092
Adj. R^2	0.166	0.138	0.051
Num. obs.	4591	4487	4487

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Observations are individual municipalities for which amount of zoned land and appeal rates are observed. Robust standard errors are reported in parentheses.
ORP stands for 206 administrative areas of Municipalities with extended powers.
Initial specification with counties fixed effects is preferred as counties are sufficiently large to typically cover more commuting areas. As argued in Glaeser and Ward (2009), within smaller areas where individual municipalities are close substitutes, planning regulation does not result in price differences, but differences in quantity of new development. Although ORP administrative areas are smaller in scale, using this spatial unit as a fixed effect does not change results substantially and results are statistically significant on conventional levels.

Table 3.5.2: Effects of appeal rate

In this specification standard costs of construction (hard costs, soft costs and expected development profit offsetting risk) are subtracted from housing prices and residual value is then regressed on a measure of local building permitting stringency. However, land values are not observed and omitting their subtraction from rents on the left hand side will introduce measurement error in the dependent variable. Because the appeal rate ρ_P is endogenous, instrumental variable estimation is used with the same set of instruments as in the reduced-form section. Results of the estimation are reported in the table 3.5.2 below. Similarly as in the reduced form part, the model is estimated separately for municipalities where property prices are above and below construction costs. Municipalities with prices above construction costs are labelled C_+.

Estimated magnitude of the parameter ω_P is approximately 0.20 for places that are above construction costs and 0 otherwise. This coefficient could be interpreted similarly as the estimates in the reduced form part. Results here are approximately twice larger than those in the reduced form part where magnitudes were between 0.06 and 0.10.

Effects of amount of zoned developable land. To estimate parameter ω_L, equilibrium condition $(1-\alpha)N_i w_i^R = \chi_{Li}\bar{L}_i\rho_{Li}^{\omega_L}\rho_{Fi}Q_i$ is used, re-arranged and in the form of difference between the periods 2011 and 1991 it is taken as an empirical specification:

$$\ln\left(\Delta\left[(1-\alpha)N_{if}w_{if}^{R}\right]\right)-\ln\left(\Delta Q_{if}\right)=\omega_{Lif}\ln(\widehat{\rho_{Lif}})+\omega_{\bar{L}if}\ln\bar{L}_{if}+\omega_{Fif}\ln(\rho_{Fif})+\vartheta_{if} \quad (3.5.18)$$

$$\vartheta_{if}=\omega_{\chi_{L_i}}ln(\chi_{L_i})+\epsilon_{if}$$

	OLS	IV 1	IV 2
$\log(\rho_L)$	0.116***	1.693***	1.763***
	(0.016)	(0.134)	(0.169)
$\log(\rho_L)*C_+$	−0.045	−0.501	
	(0.051)	(0.439)	
$\log(\rho_F)$	0.910***	0.285	0.246
	(0.120)	(0.222)	(0.234)
$\log(\bar{L})$	0.917***	1.348***	1.391***
	(0.049)	(0.076)	(0.091)
C_+	0.402	−2.338	
	(0.267)	(1.600)	
County FE	✓	✓	✓
1st st. F-test:			
$\log(\rho_L)$		15.057	27.992
$\log(\rho_L)*C_+$		8.796	
R^2	0.387	0.092	0.085
Adj. R^2	0.376	0.076	0.069
Num. obs.	4591	4591	4591

$^{***}p<0.001$; $^{**}p<0.01$; $^{*}p<0.05$; $^{\cdot}p<0.1$

Observations are individual municipalities for which amount of zoned land and appeal rates are observed. Robust standard errors are reported in parentheses.

Table 3.5.3: Effects of share of zoned developable land

The actual share of available land used for development χ_L is not observed, remains on the right hand side and enters the error term. This would be a problem for ordinary least square estimator as χ_L is highly likely negatively correlated with the share of zoned developable land. For that reason and also because amount of zoned developable land is endogenous and suffers from measurement error, instrumental variable approach is used with the same population-size discontinuity design as in the reduced form part. Estimates of the equation (3.5.18) are presented in the table below.

The key parameter of interest ω_L has a value of roughly 1.7 for both areas above and below construction costs. Column 2 suggests the value could be actually lower by 0.5 for areas above construction costs, but the estimate is not statistically significant on conventional levels and for that reason estimate of 1.7 is used later in the analysis. Although remaining parameters are not of primary interest, ω_F and $\bar{L}$ should be equal to 1 to be consistent with the theoretical model. However, if these two coefficients are constrained to be equal to 1, ω_L is equal to 2 without interaction or 1.55 in case of $\omega_L * C_+$. These results are statistically significant on conventional levels and do not differ substantially from the unconstrained estimation shown in the table 3.5.3. Unlike the estimate of ω_P, ω_L cannot be directly compared with results from the reduced form section, where availability of zoned developable land was modelled differently.

Municipality-specific dispersion parameter ς_i of the survival function is based on a separate hedonic price model in which log of housing prices per square meter are regressed on a set of building-specific characteristics and proximity to a centre of a regional capital if a place falls within its vicinity. The model is run for each individual municipality and includes 300 most proximate observations. Standard deviation of residuals shown on figure 3.5.3 proxies for variation in underlying localized amenity effect of individual plots.

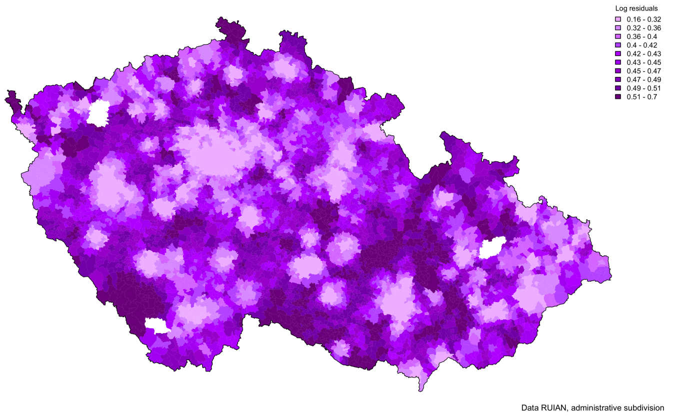

Figure 3.5.3: Standard deviation of residuals from hedonic model

The aim is to find dispersion parameter ς_i of the Fréchet plot-level amenity distribution such that standard deviation of random draws from the distribution would approach standard deviation of residuals from the hedonic model. To do so, property of the Fréchet distribution standard deviation $\sigma_i = \sqrt{\Gamma(1-2/\varsigma_i) - [\Gamma(1-1/\varsigma_i)]^2}$ was used and for each municipality the ς_i was found.

Housing supply price elasticity

Having all the key parameters of the housing supply function estimated or calibrated, the function could be evaluated for all levels of prices in each city. This is shown for the ten largest cities in the Czech Republic on the figure 3.5.4 with equilibrium as of 2011 marked with a points. The plot also highlights the range of common total construction costs in light purple colour.

Supply functions do have the expected smooth shape unlike the standard kinked housing supply function. While for property prices deep below construction costs housing supply is very inelastic, it smoothly flattens as prices increase closer to construction costs. The curve becomes more elastic as more plots even with lower amenity value start to be profitable to be developed. At some point the pool of available land is exhausted and the supply curve either smoothly starts increasing its slope or run into the hard border beyond which is not plotted[86].

The plot also support expectations that three out of four largest cities (with exception of Ostrava located in a former mining region undergoing structural transformation and population decline) are rather inelastic compared to second-tier regional capitals.

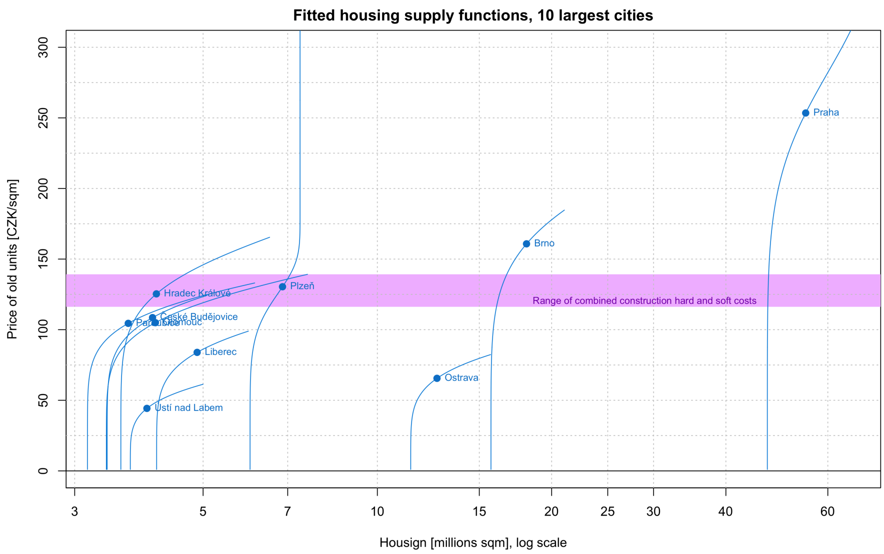

Figure 3.5.4: Evaluated housing supply functions

Using housing supply functions calibrated for all municipalities, reduced-form housing supply price elasticities could be numerically calculated. Resulting elasticities for individual municipalities are shown on the figure 3.5.5. The map reveals some expected spatial patterns: the largest urban areas are in general more price elastic than rural hinterlands and within functional urban areas core cities are less elastic than surrounding suburban municipalities.

In overall, mean supply price elasticity is 0.64 or 0.69 when municipalities are weighted by population. The interquartile range spans from 0.39 to 0.77[87]. Results are comparable with reduced-form evidence from central Europe by Caldera and Johansson (2013) who report long-run elasticities of 0.44 for Poland, 0.43 for Germany and 0.23 for Austria. Their estimate for the US is 2.01 and 0.40 for the UK.

As housing supply elasticity depends on a local price level, an alternative case is shown on the figure 3.5.6 where rents in all municipalities are set equal

[86] Which one of the two options would occur depends in particular on a parameters of a given city. The reason why not all cities have smooth supply curves is the parameter κ which controls productivity of the construction industry in a city such that the model fits the data. This however causes that supply functions with large κ predict more housing than physical constrains allow in the limit.

[87] Values are roughly twice larger when compared with results from the earlier version of the paper in which "reduced-form" elasticities using long difference in prices and quantities were used with resulting interquartile range from 0.14 to 0.36. Lower estimated elasticities using this approach are sensible as mean elasticity over the whole period is estimated. Relatively high construction costs during 1990's and low property prices likely cause lower price elasticity in the first half of the period. In contrast, currently reported values are for the end of the study period in 2011.

to 110 CZK per square meter which is at the lower bound of construction costs. As it could be seen on the map, many places which currently do have low supply price elasticity would be actually quite elastic if property prices were higher there. Current low supply price elasticity in these places is not caused by overly stringent planning and regulation, but by low property price levels. In this alternative scenario, mean supply price elasticity is 3.25 or 2.6 when municipalities are weighted by population. These values are not that much larger than results reported by Saiz (2010) for 95 US metro areas with elasticity of 2.5 and population weighted elasticity of 1.75. It should be also noted Saiz (2010) focuses on metro areas that are likely less elastic than all areas including rural ones as in my analysis.

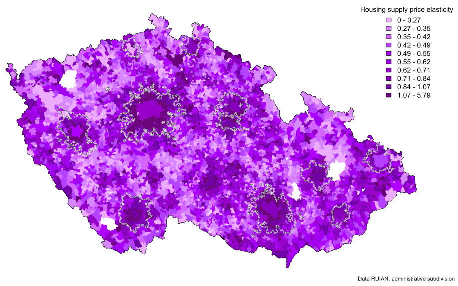

Figure 3.5.5: Reduced-form supply price elasticity

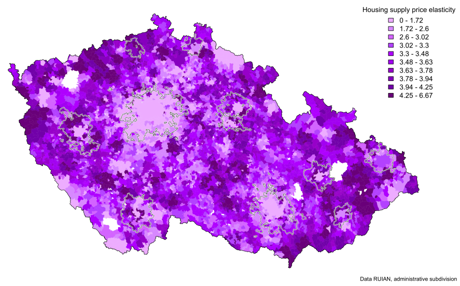

Figure 3.5.6: Supply price elasticity if price is kept the same

3.6 Counterfactual analyses

In this section several sets of alternative scenarios are simulated and compared with the baseline scenario which corresponds to the actual development from 1991 to 2011. All of the alternative scenarios assume some relaxation of stringent zoning and building permit process and they result into change in households' indirect utility, wages, rents and spatial distribution of residents when compared to the baseline.

To calculate new equilibria of considered scenarios, iterative algorithm based on Monte et al. (2018) is used. First, new wages by residences relative to the original wages in equilibrium are calculated using adjusted relative commuting flows. Second, relative new population by residence is calculated from adjusted commuting flows. Third, several steps are taken to predict new construction and real estate prices: new construction is calculated and then used to update calculation obtained in the previous iteration. Then new prices of all and old housing stock are solved for using new population and amount of development. Finally, premium of new buildings over existing stock is calculated and updated from the previous iteration. Fourth, using predicted property prices, new relative commuting flows are calculated and used to adjust the previous iteration. At this point the algorithm stops if standard deviation of difference between calculated commuting flows in the last and the previous iteration is lower than $5 * 10^{-5}$. The whole procedure is described in more detail in Appendix 3.A.

To run counterfactual scenarios, following parameters are used. First, two parameters used in utility and production functions are values commonly used in literature. The cost of commuting semi-elasticities ν_{91} and ν_{11} are estimated from gravity equations. Parameters $\xi^H, \xi^\theta, \xi^\pi$ control adjustment steps from one iteration to a next one in an algorithm computing counterfactual scenarios.

parameter	value	method
α	0.7	sel.
ν_{91}	0.008	est.
ν_{11}	0.027	est.
ω_L	1.7	est.
ω_P	0.2	est.
ε	5	sel.
ξ^H	0.95	sel.
ξ^θ	0.9	sel.
ξ^π	0.8	sel.

Table 3.6.1: Parameters' overview

Change of one variable at a time

Counterfactual scenarios are based on changes of planning stringency related variables - the share of zoned developable land ρ_L, the stringency of building permit processes ρ_P and maximum development density ρ_F.

In the scenario 1, amount of zoned developable land is increased by 50% in all municipalities and capped at 100% of physically developable land. In the scenario 2, the building permit processes stringency (measured as the appeal rate against Building permit authorities' decisions) is set at the first pentile of national distribution for all municipalities above that threshold. In the Scenario 3, maximum density of new development (FAR ratio) is increased by 50% in all municipalities.

The effect of these three policies on housing supply price elasticity, when adopted independently, is shown on the figure 3.6.1 for the 10 largest cities. All three policies increase housing supply price elasticity and the biggest impact on most cities is achieved by reducing building permit processes' stringency, which is plotted in purple dotted line. Increasing FAR plotted in purple dashed line has an effect on shifting hard border of maximum developable capacity to the right since more housing could be built on the same amount of land.

Full equilibrium counterfactuals are presented on maps showing new distribution of population relative to the baseline scenario corresponding to the actual population distribution in 2011. All scenarios have the same colour scale to make them comparable.

The three maps that follow in figures 3.6.2, 3.6.3 and 3.6.4 show spatial reallocation of workers in the three introduced counterfactual scenarios. Scenarios 1 and 3 have similar implications in terms of migration as areas around large cities, and some large cities as well, would attract more workers. Resulting changes in indirect utility (0.8% and 0.5%), wages (0.2% and 0.1%) and rents (-2.3% and -1.4%) are also comparable, although increasing amount of zoned developable land has somewhat larger effect.

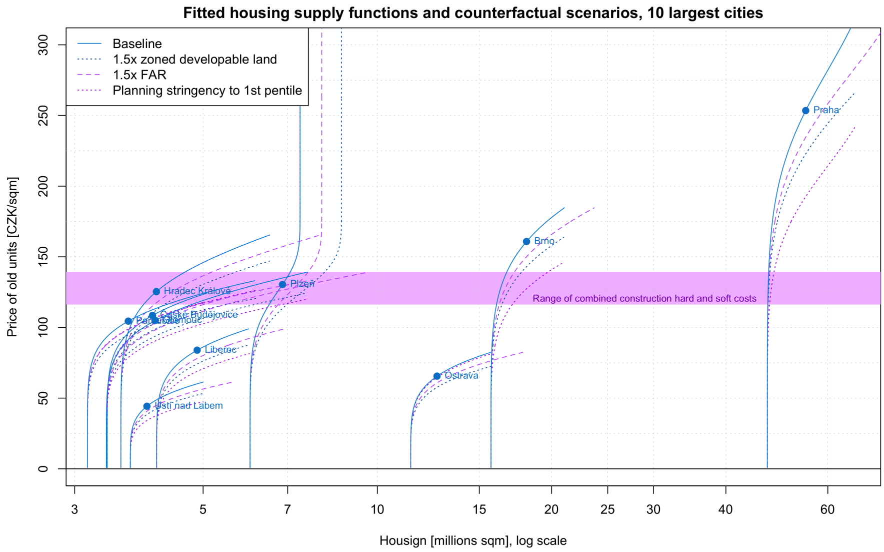

Figure 3.6.1: Evaluated housing supply functions with counterfactuals

Compared to the scenarios 1 and 3, the scenario 3 shows larger effect in terms of its magnitude. Migration of workers in this scenario is even more pronounced, but the migration destinations are more scattered as in this scenario even some remote locations decrease their building permit process stringency and therefore construction costs decrease there and they attract new population. The indirect utility of households increases by sizeable 2.8%, wages increase by 1.1% and rents decrease by 5.6%. When taking policy interventions separately, decrease in building permit processes' stringency has by far the largest effect. But it should be also noted this intervention is unlike the remaining two, which are uniform across space. Instead, decreasing building permit processes' stringency has rather larger effect in cities where this regulation is on average more stringent now.

Combinations of policy changes

The scenario 4 is a combination of the two previous scenarios - assuming increased amount of zoned developable land and lowered building permit processes' stringency. Scenario 5 also features lower building permit processes' stringency, but it is combined with increased maximum FAR by 50%. These two scenarios could be considered as counterfactuals of primary interest.

Both scenarios 4 and 5 increase indirect utility by almost identical 3.9%. They do however differ in amount of induced migration which is more than

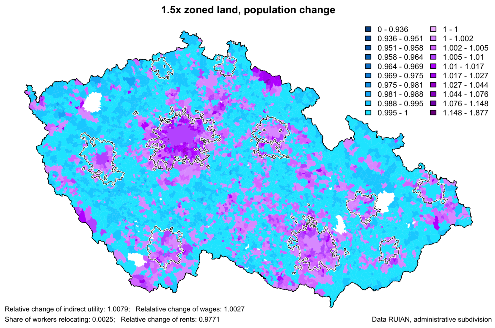

Figure 3.6.2: Counterfactual scenario 1

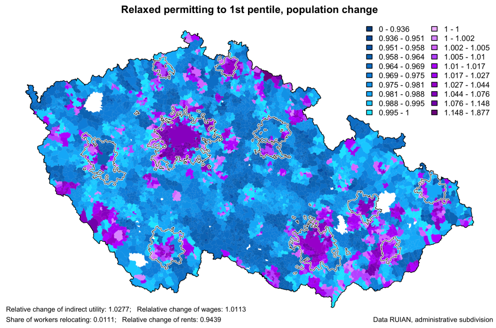

Figure 3.6.3: Counterfactual scenario 2

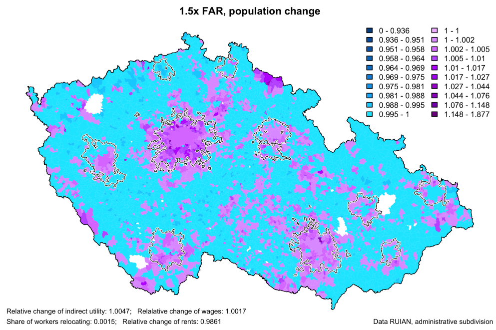

Figure 3.6.4: Counterfactual scenario 3

50% higher in the scenario with increased FAR with 1.7% of all workers moving elsewhere compared to the baseline. This scenario also achieves higher wages (1.9% increase compared to 1.1%) and slightly lower rents (-8.1% compared to -7.2%). The reason why resulting indirect utilities are almost identical despite higher magnitudes of wage and rents change is because more of workers move and they end up in places for which they have lower idiosyncratic taste given by their individual utility shock.

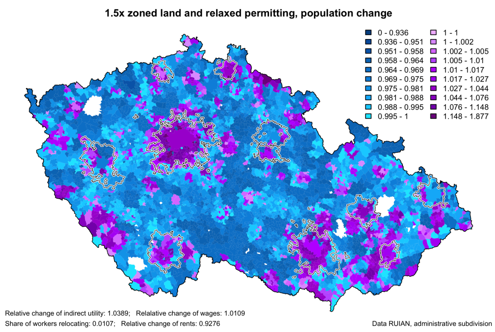

Figure 3.6.5: Counterfactual scenario 4

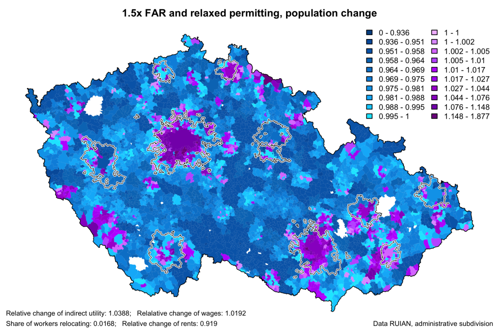

Figure 3.6.6: Counterfactual scenario 5

Spatially non-uniform policy changes

The scenario 6 also sets building permit stringency at the first pentile of national distribution and expands amount of zoned developable land by 50% as in the scenario 4, but the zoned developable land is allocated proportionally to the wage growth in levels squared for each municipality. This thus allocates developable land to locations where productivity increased the most. The scenario 7 which is based on the scenario 5 is defined similarly with FAR limits distributed proportionally to the wage growth squared.

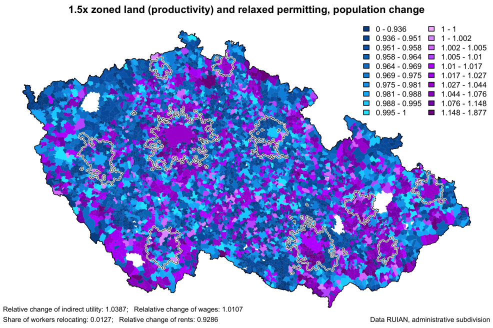

Figure 3.6.7: Counterfactual scenario 6

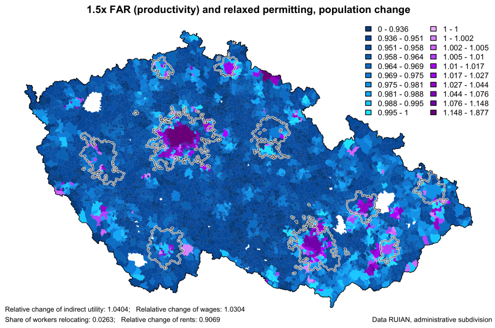

Figure 3.6.8: Counterfactual scenario 7

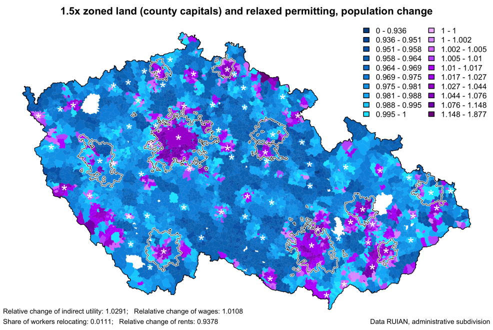

Figure 3.6.9: Counterfactual scenario 8

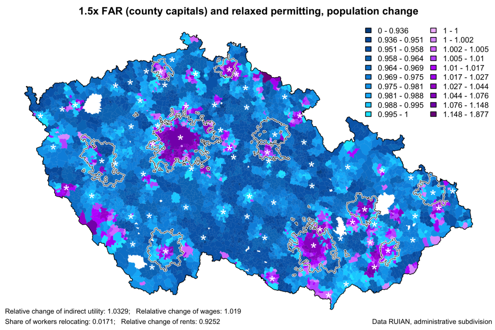

Figure 3.6.10: Counterfactual scenario 9

Results do resemble the scenarios 4 and 5. Allocation of land based on productivity growth does not seem to affect results much. Increase in indirect utility in the two scenarios is 3.9% and 4% respectively, wages increase by 1.1% and 3% and rents change by -7.1% and -9.3%. Notably, 2.6% of workers migrate in particular into large cities in the scenario 7. Although increase in wages and decrease in rents is significant in this scenario, relatively large displacement of workers to places for which they have smaller utility due to their idiosyncratic taste shocks decreases overall welfare improvement.

The scenarios 8 and 9 also set permitting stringency at the first pentile and then apply either 50% increase of zoned developable land of 50% increase of FAR, but policy change is done only to the county seats which are marked with the white asterisks on the maps. Both scenarios are rather similar. Their increase in indirect utility is 2.9% and 3.3% respectively, wages increase by 1.1% and 1.2% and rents change by -6.2% and -7.5%.

Scenarios with imperfect durability of housing

The last set of counterfactuals consider possibility of imperfect durability of housing. Until this point, housing was assumed to be perfectly durable. The question is, to what extent workers would migrate and prices of housing would change if a fraction of housing depreciates and has to be replaced elsewhere - likely in more productive places.

The scenario 10 does not differ from the baseline in any parameter except of coefficient λ which defines what fraction of endowed housing endures. In this scenario, λ is set to 0.74 which is equivalent to a hypothetical cumulated depreciation at 1.5% over 20 years of the study period. The result shows that under this condition overall indirect utility would decline by 5.4%, rents would increase by 21%. However, wages would increase by 1% because 1% of workers would move to more productive places. This scenario shows peculiar implications of durable housing: economic output of the sector producing consumption goods could be increased by removal of part of the housing stock, but it has a negative effect on households' utility.

The scenario 11 also sets λ to 0.74, but on top of that sets building permit stringency at the first pentile of national distribution and increases FAR by 50%. Surprisingly, the resulting effect on utility is still negative with 1.3% decline.

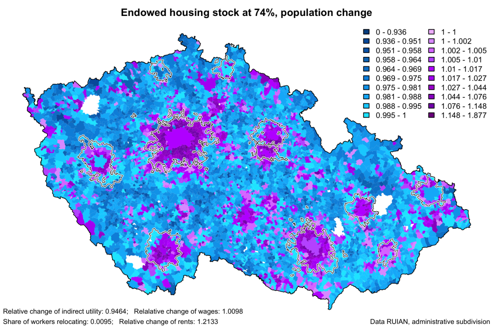

Figure 3.6.11: Counterfactual scenario 10

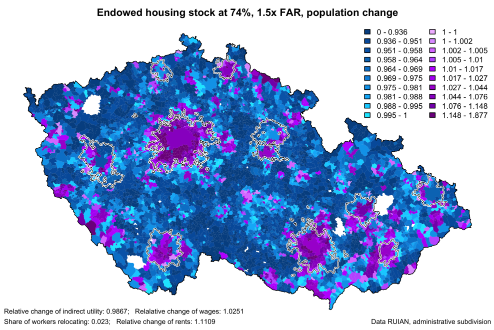

Figure 3.6.12: Counterfactual scenario 11

To summarise the results, out of the three planning policies considered, decreasing building permit processes' stringency to the first pentile of national distribution would have the largest effect. When considering combining other policies with this policy, increasing FAR seems to lead to larger improvements including larger wage increases and rent decreases that are on the other hand partly offset by induced higher migration response when workers end up in places which they value less due to their idiosyncratic preferences. Additionally, decreasing Building permit offices' stringency is a complementary policy to either relaxing zoning plans or increasing FAR since combining these two together more than proportionally increases households' indirect utility.

The results seem to be aligned with findings from existing literature. Cheshire and Sheppard (2002) estimated net costs of planning including some of its benefits in Reading, a heavily regulated city in the UK. They end up with an effect equivalent to a 3.9% tax on income. Their estimate is in terms of magnitude comparable with my findings for the whole Czech Republic, although I do not model benefits of planning. Additionally, only partial relaxation of planning regulation is considered here with potentially larger effects if the planning were to be abolished altogether. The results also do not depart much from the earlier versions of this chapter where effects in the closed-city model were estimated with resulting decline of rents by 6.9% that is equivalent to an increase in indirect utility by 2%[88].

3.7 Conclusions

Spatial planning and building permission processes have had a profound effect on the spatial distribution of economic activity across the Czech Republic following the 1989 revolution and subsequent transition from a planned to a market economy. While growing competitive industries were predominantly urban, persistent planning has not reflected the change in spatial patterns of demand and did not ease development in large urban regions to accommodate this pent-up demand.

When focusing on the stringency of the building permission process, which is one channel through which new construction is constrained, analysis using boundary discontinuity design at the administrative boundaries of the building permission offices reveals that an increase of stringency in the permission process by 10% decreases growth of new single family homes by approximately 0.6%. For apartment buildings, increasing the appeal rate by 10% leads to a decrease in the size of apartment buildings by 3.3%. Additional specification suggests that these effects are stronger for places with property prices above construction costs and weaker for areas where property prices are below construction costs. Negative effects of zoning plans measured by amount of zoned developable gross floor areas could only be found in areas where property prices are above construction costs. Increasing the amount of developable space there by 10% roughly increases development growth by 1%. These results confirm

[88] In the earlier version of the chapter, change in rents was calculated assuming fixed population. Two regions with the highest declines of rents were the two largest cities - Prague and Brno and their suburban hinterlands. In overall, the decrease of rents in municipalities weighted by their population was 6.9%, but the distribution was highly concentrated. In fact, approximately only 10% out of more than 6,200 municipalities experienced a rent decrease in the counterfactual scenario.

that both stringent construction permissions and a limited amount of zoned developable land limit new development.

Housing supply price elasticity and counterfactual scenarios are analysed within a quantitative spatial model framework based on Ahlfeldt et al. (2015), Heblich et al. (2020) and Monte et al. (2018) within which is embedded a realistic housing supply function featuring the concept of a "kinked housing supply curve"(Glaeser and Gyourko, 2005) and further explicitly integrating planning and permission stringency related variables. First, the core parameters governing the extent to which planning affects housing production are estimated. Second, the housing production function is then calibrated on the observed data and several sets of alternative counterfactual scenarios are simulated.

Estimated housing supply price elasticities for all municipalities in the Czech Republic have a mean value of 0.64 and an interquartile range spanning 0.39 to 0.77. However, if all municipalities had the same property prices at the lower bound of construction costs, mean housing supply price elasticity would increase to 3.25, suggesting many places do have low supply price elasticity, not because of stringent planning policies, but because of very low property prices.

Counterfactual scenarios analysing the lifting of regulations generally predict higher population growth in the two largest cities. When comparing the relaxation of each of the three regulation policies, the largest effect is achieved by decreasing the stringency of the building authorities' permission processes to the first pentile of the national distribution. This alone would increase indirect utility of households by 2.8%. Further, combining this policy with increasing the permitted developable density by 50% would increase households' indirect utility by 3.9%.

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3.A Appendix

Extensions

Local opposition to development

Fischel (2005) identifies multiple channels why communities might demand more stringent planning regulation. In his ’Homevoter hypothesis’ he claims the homeowners who are at the same time voters in local government elections are motivated to protect "their single most valuable asset" that is their residential real estate against uncertain outcomes of new development. As a result they are in favour of more stringent planning reducing risk of new development that could potentially lead to decrease in local area real estate values. He further mentions several other channels through which local communities might be willing to limit new development: larger share of undeveloped land could positively capitalize into property values as a green open space amenity, lower densities could prevent local congestion and are valuable by its own right, more stringent regulation might keep poorer households out of a community, and ultimately less of new development will not increase local supply leading to property appreciation.

The later motives would likely hold for all property owners, both homeowners and larger residential-stock owners. But it does not have to be true for the first point of protecting their assets in face of uncertainty. Fischel (2005) claims homevoters cannot unlike larger property owners diversify their portfolio and therefore they have to take other actions to mitigate risks endangering their real estate assets, such as voting for more stringent regulation. Glaeser et al. (2005) use the same argument and propose that 10 percentage point increase in home ownership in the US in 40 years until 2000’s could in part explain more pronounced opposition toward new development.

Although the homevoter hypothesis is appealing, it cannot fully explain observed trends. Strictly interpreting the hypothesis, all municipalities with at least some homeowners would be willing to impose more restrictive development policies that does not seem to be the case. Hilber and Robert-Nicoud (2013) propose more complex ’Influential landowner hypothesis’ that take into account opposing interests of owners of developed and undeveloped land. While the first group as in the homevoter hypothesis tend to protect their real estate assets by resisting new development, owners of undeveloped land welcome development opportunities so they can sell their land profitably. As a result, more stringent planning policies are likely to arise as community is being built-up and share of homeowners is exceeding share of owners of undeveloped land. The authors show evidence for this pattern on data from the US MSAs. Similar result, although achieved with different theoretical framework, is reported by Saiz (2010). He shows evidence that US cities with scarcer land tend to impose more restrictive development policies.

While above mentioned literature shows the planning stringency is determined by local circumstances, some notes have to be made to what extent this apply for the context of the Czech Republic as the institutional context there is much different from the US investigated in all four articles mentioned earlier. The major difference is nationalized system of local public finance (described in more detail in section 3.A).

Real estate supply in growing and declining regions

Difference between a growing and a declining region in terms of real estate supply is conceptualized with a kinked supply curve. For any real estate price level bellow the construction (reproduction) cost P_{con} the supply curve is (almost) perfectly inelastic. When price reaches construction cost, then supply curve starts to be upward-sloping with its slope being dependent on multiple factors, such as construction costs with respect to development density or local specific natural and artificial construction constraints. When demand once decreases from D to D^0, the equilibrium price drops bellow the construction costs. In the next periods, when demand recovers and starts to grow again, there is no new construction until the demand reaches again the level of D. Until then the only equilibrium adjustment is only through price.

The size of the negative demand shock caused by the the economic transition seem to be so large that the demand hasn't recovered in 20 years after the revolution. It could be illustrated with the figure 3.2.2 which plots local residential prices to residential construction costs. Areas plotted in red have their residential prices above construction costs and blue are bellow construction costs. The map reveals how large is a fraction of the country where residential real estate prices are significantly deep bellow the construction costs.

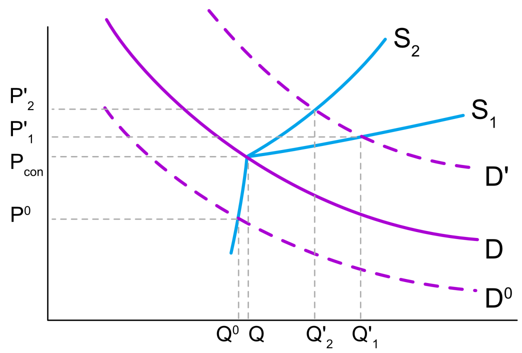

Figure 3.A.1: Kinked supply curve

The modernist movement

Underlying principle of the modernists' housing was relation between individual apartment and landscape. "It was a system in which the clear distinctions between the natural and the artificial and between the public and the private had disappeared, or were at least greatly suppressed and lost their original meaning" (Kohout et al., 2016, p. 47).

Kohout et al. (2016) claim the modernists' disdain for cities was not solely pragmatic as the inter-war development, still rooted in the traditional urbanism, was able to accommodate most of the contemporary needs the city faced. They added two more ideological reasons: The first is negation of the traditional distinction between built-up artificial settlement and nature. Instead, they proposed mixture of both. Second, modernists saw traditional city as a physical representation of the social structure and its denial was part of their intended social reform.

As Josep Lluis Sert, who attended the sail to Athens, admitted in the foreword, the Athens charter is mainly a product of architects who miss other perspectives - economic among them. Nonetheless, as he adds, the charter was quite influential in urban planning after the Second world war (Le Corbusier and Eardley, 1973).

While the theory of the modernist development has been formed during the inter-war period, its practical implementation did not occur until mid-1950's (Kohout et al., 2016).

The Czech context

Subdivision and public administration of the Czech Republic

The Czech Republic has a three-level system of elected governing bodies: national level, 13 regions plus the capital of Prague and 6,258 municipalities[89]. Both regions and municipalities have elected assemblies (with proportional representation electoral system) which then elect members of a council (governing body) from the assembly members. The council then elects the mayor (in case of municipalities) or governor (hejtman in Czech; in case of regions) from council members.

Public administration in the Czech Republic is a so called mixed-system, or Central European system (Provazníková, 2015). Some state agendas are administered by special offices with their local branches. These for instance include tax collection office or cadastral office. Other state administration is transferred to regional and municipal offices that are obliged to administer these agendas, such as registry offices and many others. State administration is not transferred to all municipalities, but rather to larger of them which serve wider areas.

There exist several administrative areas for the purpose of the state public administration. Two of them are 206 Administrative areas of municipalities with extended powers (abbreviated as ORP in Czech) and 393 Administrative

[89]The city of Prague has at the same time competencies of a municipality and region; the number of municipalities also include 4 military districts managed by the army

areas of municipalities with authorized offices (abbreviated as POU in Czech). Municipal offices of these areas execute some of transfered powers of the state administration and they are subordinated to the regional offices.

Building permit offices have their own 740 distinct administrative areas that could actually cross ORP and POU boundaries.

Specific administrative areas are 13,077 cadastral areas used predominantly by the Cadastral office. These cadastral areas are based on the original land surveys done during the period of Austro-Hungarian empire and roughly capture delineation of past village and town structure.

The Czech Republic used to be subdivided into 77 counties, but after the public administration reform in 2002 county offices have been mostly abolished and their competencies were either transferred to larger regions or devolved to smaller ORPs. However, former county subdivision is still being used for instance for data reporting.

For the purpose of statistical data reporting, all above mentioned subdivisions are used, although some of them (such as Building permit authorities areas or cadastral areas) are used predominantly to report data for their own agenda only. Specific additional spatial unit used for statistical purposes only are 22,654 elementary statistical units (abbreviated as ZSJ in Czech, or ESU in English). They are defined to capture roughly similar population so their size varies significantly.

Spatial pattern of industrial transition

As Durdík (2019) notes, the Czech Republic has been undergoing major shift in industrial structure since 1990 after the revolution, whereas similar transitions in western countries (and possibly at slower pace) had occurred earlier, such as in Western Germany already in 1960's.

Spatial distributions of occupation shares by municipalities in 1991 and 2011 are shown on the next 8 pairs of maps. The first 4 pairs show most expanding industries by number of workers and the second 4 pairs show industries in which employment declined the most[90].

[90]Information services have not been yet explicitly defined as a category in 1991 and for that reason no distribution across space is shown.

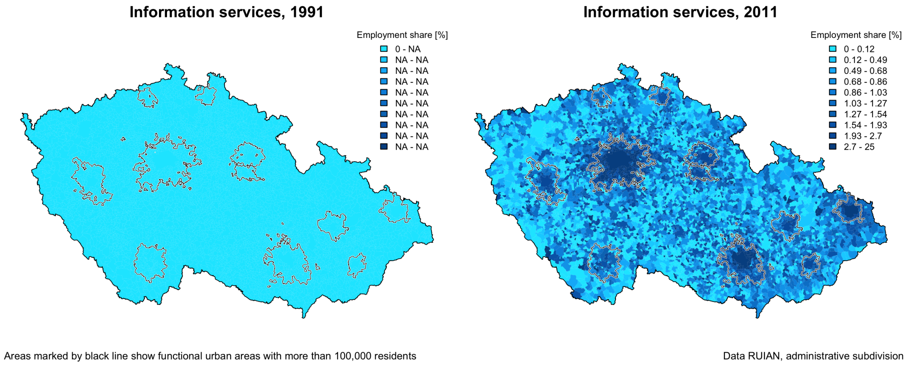

Figure 3.A.2: Economic transition - 1st most expanding industry

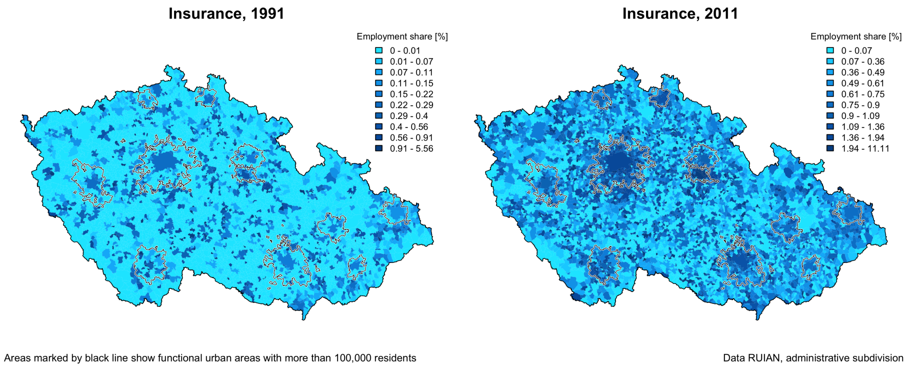

Figure 3.A.3: Economic transition - 2nd most expanding industry

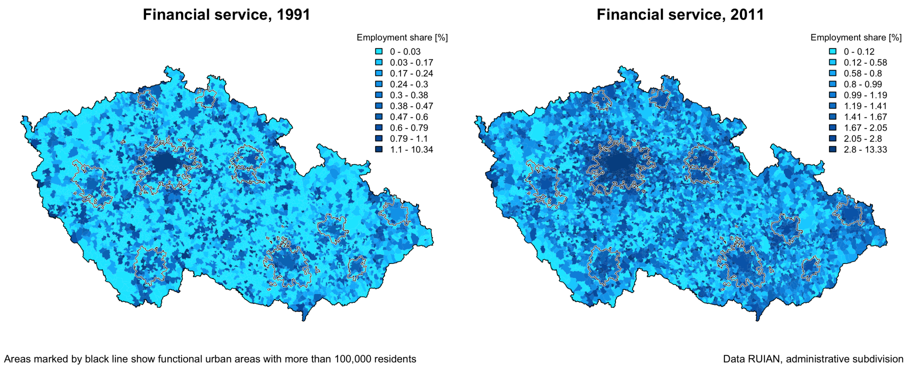

Figure 3.A.4: Economic transition - 3rd most expanding industry

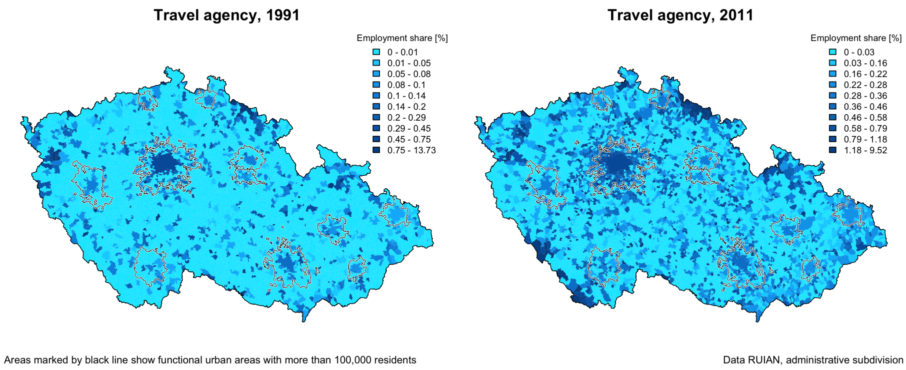

Figure 3.A.5: Economic transition - 4th most expanding industry

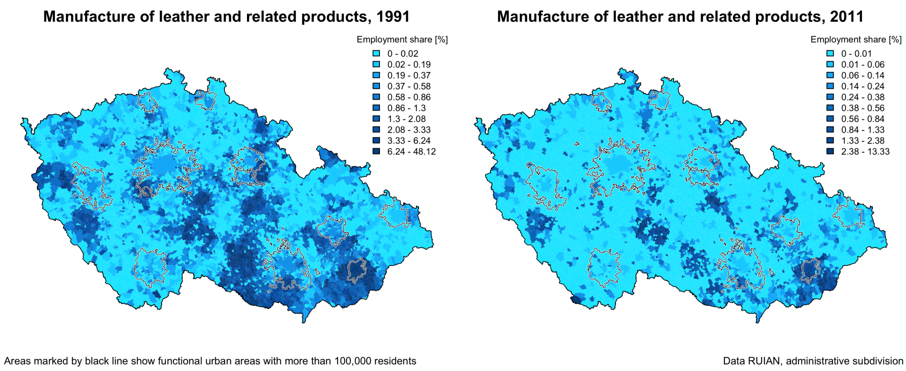

Figure 3.A.6: Economic transition - 1st most declining industry

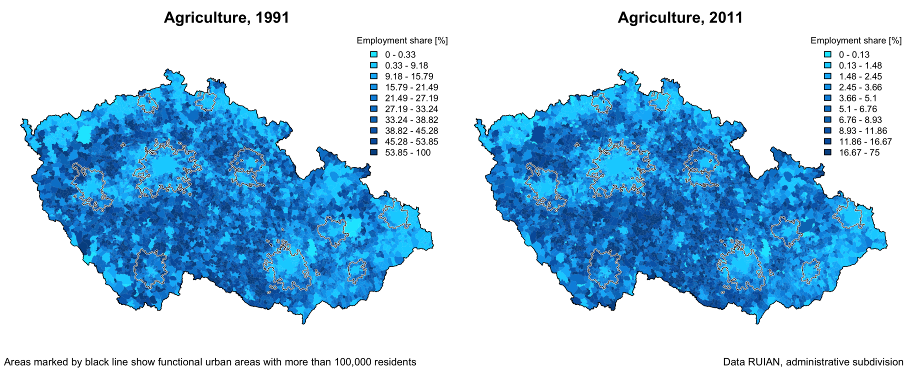

Figure 3.A.7: Economic transition - 2nd most declining industry

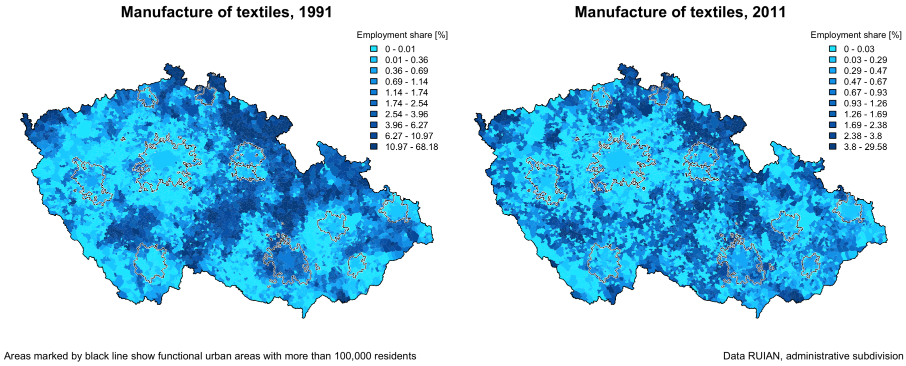

Figure 3.A.8: Economic transition - 3rd most declining industry

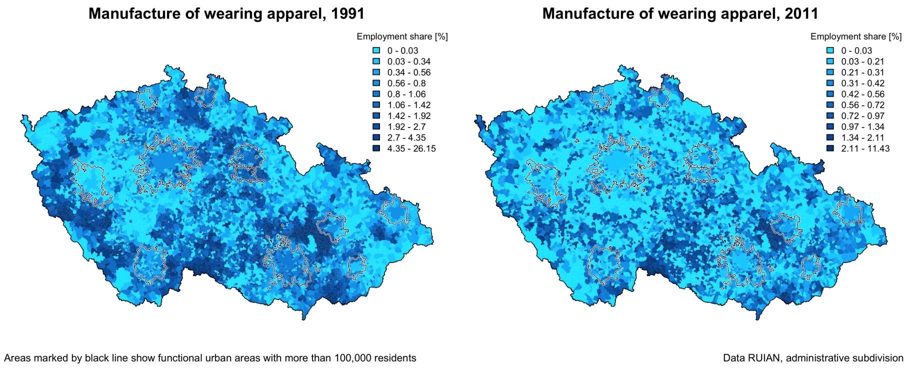

Figure 3.A.9: Economic transition - 4th most declining industry

Spatial planning and Building permitting in the Czech Republic

Development of the spatial planning - Town and city development in Czechia following the Second world war differed from development in the neighbouring countries for several reasons: the housing stock remained almost intact by war and as a consequence of the war itself and following eviction of Germans the population size in Czechia has shrunk by 1947 approximately by one third (Körner, 2020).

Regarding the legal framework, spatial planning had been introduced in the Czech legal system for the first time in 1949 with the Act no. 280/1949 Col. Within that regulation spatial planning was part of the national economic planning and its role was to allocate projects defined in the national economic plan. In 1958 had been adopted the new Act on spatial planning no. 84/1958 Col. and the Building Act no. 87/1958 Col. Major change in spatial planning is its distinct definition from national economic planning, its emphasis on consistency and alignment with economic plan. New tool of regional plans was introduced and process of zoning permit was included. Process of building permit and approval for use were distinct for socialist sector (production), for which both permits were issued by industry-sectoral ministries, while Building permit authorities permitted mostly residential development. New regulation started to be prepared during more liberal 60's, but its completion was affected and delayed by the invasion of the Soviet army in 1968 so the act has been adopted in 1976 as the Building Act no. 50/1976 Col. The Act integrated several by that time separate laws, such as the Building Act, the Act on spatial planning or the Expropriation Act[91]. It has also shown progressive attitude to the environmental protection that has originally appeared already in the Building Act from 1936 (Haganbart and Ebel, 2015). The Act also defined 3 spatial scales of planning documentation: large areas, municipal areas and zones, and three types of plan's level of detail (Durdík, 2019).

Regarding the actual development of towns and cities, almost none has lost population between 1950 and 1990, however, majority of cities grew in the later period after 1970 when large-scale apartment construction was unfolded (Körner, 2020).

Development of spatial planning following the revolution in 1989 is summarized by Maier, 2019. Previous aim of the spatial planning formulated in the 1975 Building Act as 'general development of socialist society and economy' has become obsolete after the revolution in 1989, but no general consensus on aim of planning was reached in 1990's[92]. While planning at that time was under pressure from neo-liberal proponents of the free market, it was upheld by those newly elected representatives who saw it as a tool that could be used to improve damaged environment. On the municipal level planning became a tool largely within competencies of self-governing municipal bodies. In the 1990's, two-tier governance system was implemented (with national level and self-governing municipalities, and counties that were units of regionalised state administration). In this setting, regional planning in the early 90's did not have succeeding authority derived from the elected body so it was largely abolished and planning remained only at the municipal level and focused predominantly on functional zoning.

After experiencing economic regional divergence in the late 1990's and following European Commission's critique regarding missing regional policy, new regional governance has been established in the form of introduction of regions as self-governing bodies and together with it regional economic policy which became a parallel system to the existing spatial planning. The new Building Act from 2006 defined new hierarchical structure of spatial planning documentation on the national level, regional level and municipal level, but municipal spatial plans remained the key planning documents as upper-level plans have practically limited tools to affect municipal plans. Regional plans were defined

[91]The legacy of these areas of construction regulation and spatial planning integrated within one act remains in the Czech legal system until nowadays even after two major reforms in 2006 and 2021.

[92]The lack of consensual agreement on the desirable future spatial and urban development and role of planning itself seem to remained unresolved. Koucký (2017) has admitted he was not aware of any agreed vision of city development neither among political representation, nor general public when he has initiated works on the new Prague zoning plan in 2012.

in a way not to interfere with municipal planning competencies. Durdík (2019) noted the regional planning became limited only to supra-local systems. As a result of lack of regional planning, the country saw massive suburbanization beyond administrative limits or larger cities. However, predominant planning on the municipal level is becoming obsolete in the face of large functional areas that have formed around core cities.

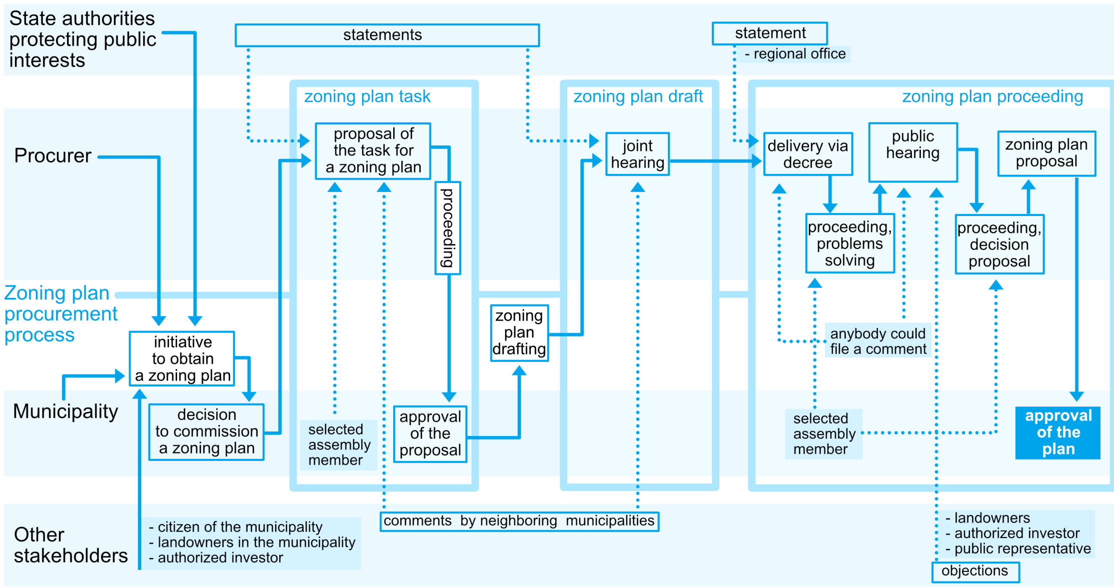

Figure 3.A.10: Zoning plan procurement and approval process diagram

The lack of general consensus about the role and goals of spatial planning in the new context could be further exemplified by significantly different interpretation of the post-1990 evolution of the spatial planning. Durdík (2019) criticizes relatively less involved state authorities in the second half of the 90's which lead to rather bottom-up approach to search for goals and new methods in planning and resulted into very scattered practice across the country which has become hard to harmonize in 2000's. Plos (2010) instead values the former approach as expression of local political will embedded into the planning documentation to fit the local context and conversely criticizes development in the 2000's as a state attempt to constrain performance of self-governing powers. Various attitudes to the current system lead to quite different opinions how the system could be reformed. This is for instance expressed by (Koucký, 2006, p. 23) who argues for much deeper reform than is commonly assumed: "All contemporary attempts to 'adjust' spatial planning, and especially in our country, are based on completely false assumption that everything is fine and it is necessary just to tweak, modify 'it', and then the right 'document' will be created. The contrary is true. We have to depart from the fact the current legislation and practice are wrong and morally obsolete and that it is necessary to define completely new system from the scratch and without prejudices".

There seems to be a contradictory critique of the current planning prac-

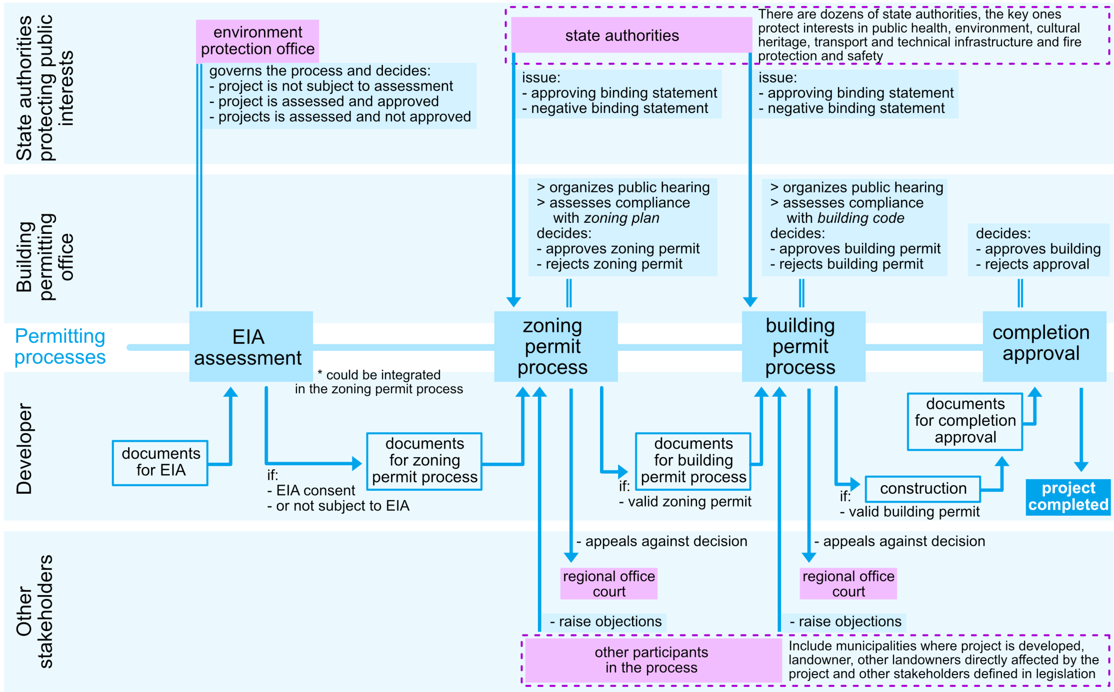

Figure 3.A.11: Building permitting process diagram

tice. Maier (2019) on one hand criticizes planners for non-critical acceptance of pro-development intentions of municipal governments, but at the same time criticizes planners for a top-down planning approach without involving requirements of civil society. Similarly questionable is critique by Durdík (2019) regarding new definition of a spatial plan in 2006 Building Act as a measure of general nature[93] which, according to the Czech administrative code, could be reviewed by the court. In principle this new definition of the planning documentation should especially provide more security against undue processes or violations of one's rights. However, it could be admitted the court review has still some shortcomings such as formal approach to spatial plans' review that have been expressed by stakeholders in spatial planning (Deloitte, 2021).

Maier (2019) also admits due the persistence of spatial planning it might not be possible to address new challenges we are facing - he explicitly names demographic development and rising regional disparities, increasing size of functional units beyond administrative areas of municipalities and emerging agenda of climate crisis and landscape planning. I would argue the same persistence has been already impeding potential development following the transition to market economy in the past 30 years. This persistence brings wery different outcomes to planning in the standard political economy model of spatial planning where local residents would vote for representatives who select policies and planners in their favour and as a result planners answering to the demand of municipal governments would as a consequence answer to

[93]Until 2006, municipal spatial plans were issued as a municipal decree and were not subject to the Administrative court review.

the demand of local communities.

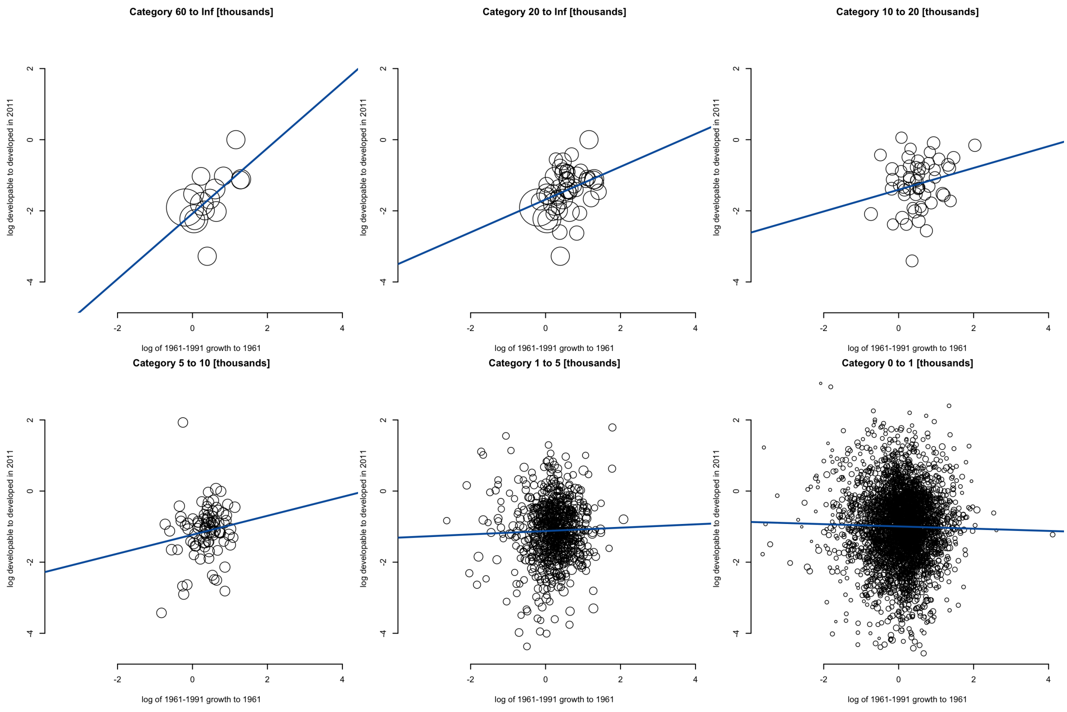

Figure 3.A.12: Relation between municipal growth between 1961 and 1991 and current developable gross floor areas

Amendments to the 2006 Building Act between 2010 and 2020 - in this period for which survey data from Building permitting authorities are analysed the Building Act has been amended in total 18 times, almost twice a year on average (Zákony pro lidi, 2022). However, only six amendments are directly focused on the Building Act or are highly related to it, while the remaining ones primarily amended different laws and amendments to the Building Act were likely done only to coordinate updated legislation with the existing Building Act.

Act no. 350/2012 Col. amending the Act on town and country planning and building code (Building Act), effective from the 1st January 2013. According to Plos (2013) it is the major amendment addressing almost two thirds of provisions of the Act. In the area of municipal planning it was explicitly stated both spatial plan and evaluation of impact on environment should not contain details appropriate for more detailed regulation plan or building permit (decision). Regarding the process of procuring municipal spatial plan, the step of concept of the plan has been abolished. Instead, proposal is drafted and presented at public hearing and when it is required it is re-designed and re-submitted for public hearing.

Regarding the building permit decision-making, new process has been introduced: instead of standard two-stage processes of zoning permit and building permit new options of integrated zoning and building process and alternative zoning and building agreements[94] were introduced.

The reform also limits range of stakeholders who are statutory stakeholders in the building permit proceeding, especially targeting NGOs. After the reform, only entities defined by specific legislation and if they represent public interests, participate in the process.

Act no. 39/2015 Col. amending the Environmental Impact Assessment Act (the EIA Act), effective from 1st April 2015. The amendment also updates 41 articles of the Building Act. Updates likely affected spatial planning and decision-making and focused on regulation plans and projects requiring EIA. It includes new provision that regulation plan cannot substitute zoning permit in cases when project requires EIA. If the task for procuring regulation plan is not formulated in a spatial plan, it could be proposed by a procurer. Regulation plan should contain complex justification for a proposed design.

For projects requiring EIA, the Building permit authority may request public hearing while public hearing will be called for every project in an area without spatial plan. Projects requiring EIA cannot be approved via announcement permit process, public contract or authorized inspector.

Act no. 225/2017 Col. amended the Building Act and was effective from 1st January 2018. Key changes are discussed in Fialová and Vodný (2017). It is assumed to affect duration or stringency of permit and decision-making processes. Key features are described below.

The amendment defines new alternative shortened process of spatial planning documentation for cases when alternative designs are not considered. This shortened process skips several steps and should allow for more timely plan update. Another change intended to speed up especially supra-local infrastructure proposed in regional and national plans allows to override municipal spatial plans if these do not allow to build regionally and nationally planned projects. After the amendment the spatial document of 'land study' could be obtained and financed by an investor while definition of its objectives and its approval are still within competencies of the state authority.

Regarding the building permit processes, State offices of spatial planning were authorized to issue binding statements regarding compliance with spatial planning documentation and goals of spatial planning. Until the amendment the offices issued only non-binding opinions. As Durdík (2019) notes, increased extent of the agenda was not met by increasing number of officers leading to the offices' overload.

Act no. 169/2018 Col. on Fast-tracking the Construction of Transportation, Water and Energy Infrastructure and E-communication Infrastructure, effective from 1st August 2019. The act affects only strategic infrastructure and makes compulsory purchase and land survey easier for these projects as well as simplifies some parts of the building permit process regarding inform-

[94] Agreement processes are simplified alternatives of the standard processes for uncontroversial and typically small development projects

ing participants of the process. Additionally, for motorways, roads, railways and selected infrastructure for water and air transport listed in the annex of the Act interim decision could be issued and on its ground land compulsory purchase for these projects could be initiated (Deloitte, 2019).

Act no. 312/2019 Col. effective from 1st February 2020 updates three articles of the Building Act and adds requirement of approval for use of water-engineering facilities and requirements for project documentation for these facilities.

Act no. 47/2020 Col. effective from 1st July 2023 and *Act no. 403/2020 Col.* effective from 1st January 2021. Although these two amendments were approved within the period for which survey data were used, they did not become effective during this period and therefore are of lesser relevance for this study. The first amendment focus predominantly on definition of new national geoportal and the second one on some new planning tools and national development plan being one among them.

Permit stringency proxy. Building permit stringency γ is not directly observed and it is being proxied by observed appeal rate p^O_{ap} against decisions of Building permit authorities (AR in empirical specifications and ρ_P in the quantitative spatial model). The conceptual model derived below proves the observed appeal rate is a monotonous function of the true permitting stringency γ. The model is inspired by Glaeser et al. (2005) and takes into account potential gains and losses of developers and local communities regarding new development. The model indeed shows this monotonicity holds under rather weak restriction that developers would always file an appeal if their proposal is not approved in the first stage. Given relative costs of appeal and potential gains for developers, this assumption seems to be reasonable.

The probability of filing an appeal p^O_{ap} is given by a probability of either local community or developer appealing. On the community side, probability of filing an appeal is given by the probability of obtaining building permit p_{a1}, which is itself a decreasing function of permitting stringency γ and potential other factors, and probability of filing an appeal p^R_{ap}, which is increasing in planning stringency γ and further depends on a probability of appeal being successful $p^{+\to-}_{ch}$ and cost of an appeal C^R. Developer is assumed to file an appeal whenever the project is not approved which is $1 - p_{a1}(\gamma, \cdot)$.

$$p^O_{ap} = \underbrace{[p_{a1}(\gamma, \cdot) \times p^R_{ap}(\gamma, p^{+\to-}_{ch}, C^R, \cdot)]}_{\text{residents, activists}} + \underbrace{[1 - p_{a1}(\gamma, \cdot)]}_{\text{developer}} \tag{3.A.1}$$

Taking a derivative of the equation (3.A.1) yields:

$$\frac{\partial p^O_{ap}}{\partial \gamma} = p_{a1}(\gamma, \cdot)'\gamma' p^R_{ap}(\gamma, p^{+\to-}_{ch}, C^R, \cdot) + p_{a1}(\gamma, \cdot) p^R_{ap}(\gamma, p^{+\to-}_{ch}, C^R, \cdot)'\gamma' - p_{a1}(\gamma, \cdot)'\gamma' \tag{3.A.2}$$

Rearranging the equation (3.A.2):

$$\frac{\partial p_{ap}^{O}}{\partial \gamma} = \underbrace{p_{a1}(\gamma,\cdot)'\gamma'}_{\text{negative}} \times \underbrace{(p_{ap}^{R}(\gamma, p_{ch}^{+\to-}, C^{R},\cdot) - 1)}_{\text{non-positive}} + \underbrace{p_{a1}(\gamma,\cdot)p_{ap}^{R}(\gamma, p_{ch}^{+\to-}, C^{R},\cdot)'\gamma'}_{\text{positive}} > 0 \tag{3.A.3}$$

$p_{a1}(\gamma,\cdot)'$ is by assumption negative, second term cannot be positive as 1 is subtracted from probability p_{ap}^{R} and $p_{ap}^{R}(\gamma, p_{ch}^{+\to-}, C^{R},\cdot)'$ in the third term is by assumption positive.

Local public finance

The Czech Republic has very centralized fiscal system with limited local tax differentiation. The only pure local tax is the property tax which is however set nationally and then could be adjusted by municipal coefficients, which are again regulated by the national government[95]. On top of that the tax collection from the property tax on the overall tax collection is very low by standards of developed countries with 0.4% of GDP in 2019 (while the OECD average was 1.8%) and 1.1% of overall tax collection, whereas in the OECD property taxes account for 5.5% of tax collection (OECD, 2021). As a result, Czech municipalities are mostly dependent on transfers from the national government.

The system of municipal financing undergone several major reforms since early 1990's when local self-governing municipalities were re-established. According to Provazníková (2015) the three key periods could be defined as 1993-1995, 1996-2000 and after 2001. In the first period municipalities were largely financed by personal income tax collection. Municipalities received all tax collection from self-employed individuals by place of their residence and for employees the tax revenue on county level by workplace location was shared between counties and municipalities within a county. This system lead to large cross-county tax-income differences depending on local labour markets and also to competition for self-employed. Reform effective from 1996 was supposed to address these drawbacks, but it was not successful. The aim was to integrate more local budgets with the state budget so 40% of the county employment income tax was redirected to the state budget (for 4 largest cities only 30%) and at the same time 20% of the national corporate income tax was distributed among municipalities. The reform implemented in 2000 has brought a significant change. Since 2000 the only purely locally collected tax (aside of local fees) remained the property tax and corporate income tax of municipality-owned firms. Personal income tax, corporate income tax and

[95] There are nationally set tax rate correction coefficients adjusting the tax up with increasing size of a municipality (while municipality can adjust its coefficient 3 levels down or one level up) and additionally there are local coefficients which allow municipalities to increase overall tax rate up to 5 times more compared to the baseline rate (Provazníková, 2015)

value added tax are collected nationally and then redistributed among municipalities. Specific role has personal income tax of self-employed out of which 30% belongs to a municipality by place of residence and remaining 70% are redistributed nationally. The method of redistribution has changed several times since 2000.

Initially from 2000, tax redistribution for each municipality was based on municipal population and transfers per capita were increasing with population size. The reasoning was based on higher devolution of state powers to municipalities with their increasing size. The implementations has however turned problematic. Fourteen discrete municipal size bins were defined, each having adjusting coefficient to define tax-transfer per capita. This incentivized municipalities right below the threshold to attract new residents to overcome the threshold of their respective bin. For instance some municipalities provided one-off payments to individuals for registering permanent residency within a municipality (Provazníková, 2015). This shortcoming has been fixed with an amendment implemented in 2008 when number of size bins decreased to 4 and tax transfer calculation changed such that only marginal payments for inhabitants in a given size bin do change and as a result the function of tax-payments per capita is continuous with kinks at the boundary of size bins where slope of the function increases.

Despite the method of tax redistribution between 2000 and 2007 has proven to be problematic, it provides a good case of policy that could be used in the econometric analysis as an instrument capturing exogenously determined motivation of municipalities for population growth.

Data processing

Developable land data processing

Developable land data as defined in municipal zoning plans are collected on quadrennial basis (used to be collected on a biannual basis until 2016) by ORP offices. ORP offices then provide data to regional offices. Individual regions have more or less binding and detailed methodologies how to classify developable land. As these differ from region to region (and occasionally from ORP to ORP) data cleaning of the raw data was necessary. Examples of different methodologies include incorporation of planned transport and technical infrastructure into developable land, in some cases as relatively thin lines and in others as quite wide buffers. Another methodological difference is inclusion of already developed land into developable land, or its exclusion.

To clean the data, first all developed land from CORINE 2012 land cover was subtracted from the dataset too keep only undeveloped land. Then long and narrow features of transport and technical infrastructure were removed if their ratio of circumference to square root of area exceeded 20. After this step manual cleaning in GIS software has been done to keep observations of

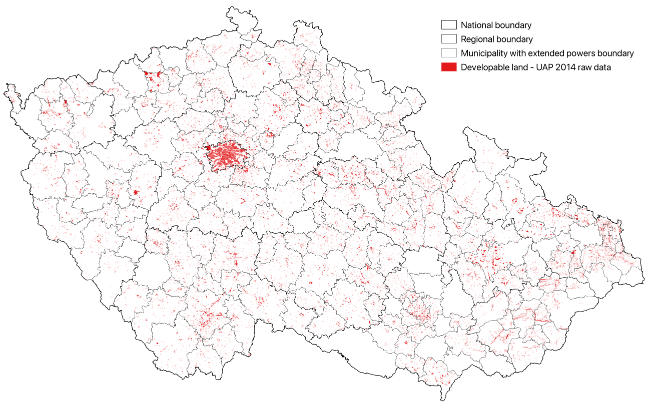

Figure 3.A.13: Raw data of developable land, mostly 2014

reasonable shape that are likely to be developable as some kind of real estate.

Building permit offices survey data processing

Offenses against Building Act - In the period between 2011 and 2017 the survey contained questions how many decisions regarding individuals' offences against Building Act were issued (according to the article 178 of the Building Act) and how many decisions regarding firms' or entrepreneurs' of offences against Building Act were issued (according to the article 180 of the Building Act).

The Building Act explicitly defines a wide range of offences that could be committed by both individuals, entrepreneurs, firms, construction managers (article 179) and developers (article 181). In case of individuals, entrepreneurs and firms, the offences are not only limited to construction, refurbishment or other adjustments of property, but also cover usage of property. These entities could breach the law if they for instance use a property in a way violating approved usage (Plos, 2013).

Terrain slope

To calculate terrain slopes, data by GISAT (2007) with elevation measured for the whole territory of the Czech Republic in a 100 meter grid are used. From the elevation grid data slope of an each grid cell is calculated. Following Saiz (2010), grid cells with slopes steeper than 15% are considered hard to develop and along with all water bodies and woodlands are excluded from otherwise developable land.

Building-level data processing

Individual-level building data are created by merging two distinct data sources: Czech Statistical Office's information about buildings reported at the entrance

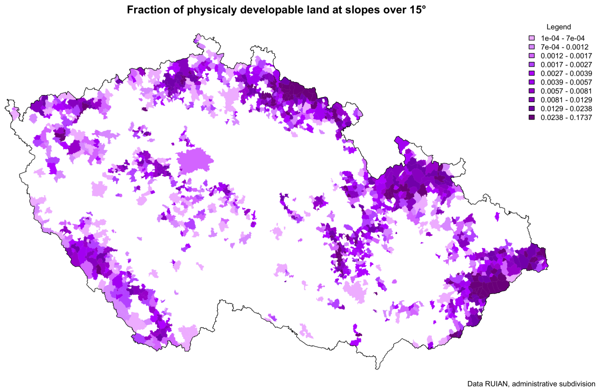

Figure 3.A.14: Fraction of physically developable land at slopes over 15

into a building level (further called 'Entrance data') with 2,911,562 point entries, and Cadastral Office's buildings' footprint data obtained from the digital cadastral maps.

While all essential information but buildings' size or footprint are provided in the Entrance data, this dataset had to be merged with building footprints provided as a polygon geometry in cadastral maps. Individual buildings in both datasets contain a common ID so these two data sources were easy to join.

Out of 2,911,562 Entrance entries, 52,561 are missing ID and when aggregated from the entrance level to the building level, the dataset has 2,795,924 observations.

Age of buildings was aggregated into discrete categories by decades starting in 1960. Previous age groups are somewhat longer due to the data limitations and the category of oldest buildings consist of all buildings built before 1920. As the Entrance dataset is based on the 2011 Census, it does not contain additional information about buildings built after early 2011. However, age of buildings built after 2011 was inferred from a time stamp of individual data points. Mode of the time stamp of individual buildings in almost all cadastral areas is 2013 marking likely the year when the database was created. Buildings with a time stamp of 2014 and newer are assumed to be completed in that year when these observations entered the database.

There are two sources of information about floor count of a building, one from the 2011 Census with discrete bins of number of floors, and second from the building administrative data with integer value. Data inspection has revealed there are some mistakes in the administrative data (for instance reporting 70 floors tall building, approximately twice taller than the currently tallest building in the country) so validation algorithm was used. For each building minimum and maximum floor count was defined based on the Census category and if value from the administrative data was within this range it was confirmed as a true floor count. If administrative data value did not fall within the range, lower bound from the Census was used as a true floor count.

For further analysis buildings were divided into residential and non-residential. Residential buildings have their reported functional category of "Buildings for housing" (general category for housing), "Apartment buildings" or "Single-family unit[96]".

Individual-level Census data processing

1991 Census

Commuting flows are aggregated from individual-level data. 91 Elementary statistical units (0.5% of all) where 17,867 workers resided (0.3% of all) were not matched with recent geography used and were therefore dropped[97].

Within the resulting sample, only 1.7% of workers have unknown place of residence or place of work and these observations were dropped.

2011 Census

Workers by place of residence are perfectly matched to the recent geography of elementary statistical units. Then only 1.2% of workers filled-in they are commuting, but destination of their commute is unknown, a similar figure as in 1991.

However, significantly less workers filled-in the question regarding daily commuting. For that reason commuting behaviour of workers who did not filled it in was implied from other workers in the same municipality. When this has been done, shares of commuters in years 1991, 2001 and adjusted share in 2011 were very similar, suggesting the adjustment is reasonable.

For both periods, commuting time for individuals was provided in discrete bins of 15 minutes up to an hour, then one bin covering time from 60 to 90 minutes and last bin for commutes longer than 90 minutes. These bins were assigned numerical value in the middle of their respective ranges, with exception of the first bin that was assigned 10 minutes and the last bin assigned with 105 minutes.

Software and methods used

Majority of the data management and analysis was done in R software (R Core Team, 2019) and source codes are available upon request. Data in Excel were uploaded using 'readxl' package (Wickham and Bryan, 2019). Data manipulations were done using 'dplyr' package (Wickham et al., 2019) and 'stringr' package (Wickham, 2019). Spatial data manipulations and visualizations were

[96]Single-family units according to the Czech law could include buildings with up to 3 apartments if they have up to 2 floors, attic and basement. Single-family units with 2 apartments were particularly popular until 1989, so called "Two generations detached house" designed for co-living of a middle-age family and one couple of their aging parents.

[97]Elementary statistical units could have been modified, merged or divided and some are no longer in use with the same code.

done with 'sp', 'sf' and 'rgdal' packages (Pebesma and Bivand, 2005, Pebesma, 2018, Bivand et al., 2019). Two stage least square models were estimated with 'AER' package (Kleiber and Zeileis, 2008) and model results were exported into Latex with 'texreg' package (Leifeld, 2013).
Spatial data were, when needed, adjusted in QGIS.

Instrumental variables

Instrumenting appeal rate

Number of Building permit office clerks relative to agenda. Building permitting agenda is within the state competencies (although it is a part of the state transferred powers devolved to local governments) and state contributes on financing this public service. As being part of the state administration, it is likely the state is using some simple rule how to allocate number of office clerks in individual regions. Such a simple rule could be number of inhabitant within an area that is easy to obtain from administrative data. The table 3.A.1 below shows it is indeed the case: the column one uses only geographical area and population to explain number of building permit office clerks and it turns out these two regressors explain 84% of the variation in the data. In the column (2) average size of agenda measured as a number of square meters of new buildings to be approved is used instead (that seems to be much more appropriate metric to allocate building permitting workforce) and it explains only 57% of the variation in the data. In column (3) all variables are used jointly and it could bee seen adding size of agenda to specification (1) increases explanatory power of the model only by some 2.4 percentage points. As a result, it could be concluded number of office clerks is by majority determined simply by number of residents in the area without much consideration of local demand for their services.

	Equivalent number of clerks		
	(1)	(2)	(3)
(Intercept)	1.291^{***}	2.525^{***}	1.180^{***}
	(0.120)	(0.148)	(0.112)
area_ths_sqkm	-0.306		0.219
	(0.811)		(0.753)
ths_residents_2011	0.239^{***}		0.199^{***}
	(0.004)		(0.005)
mil_sqm_permits_year		28.917^{***}	8.270^{***}
		(0.962)	(0.775)
R^2	0.836	0.567	0.860
Adj. R^2	0.836	0.566	0.859
Num. obs.	692	692	692

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Equivalent number of clerks refers to sum of equivalent full-time employment. Ordinary standard errors are reported in parentheses.

Table 3.A.1: Determinants of number of clerks at Building permitting authorities

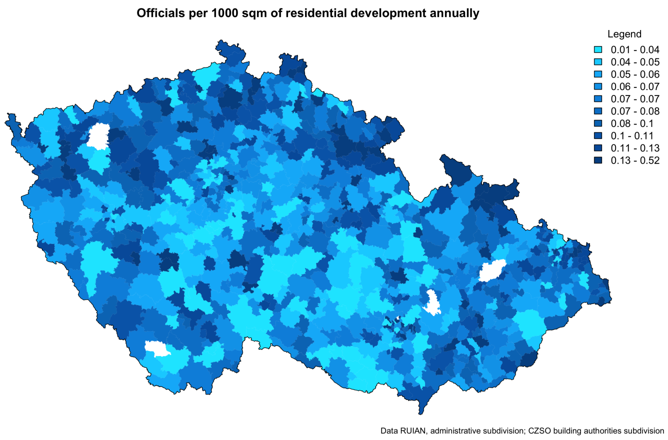

Figure 3.A.15: Number of officials relative to the local size of annual development

Share of exemptions

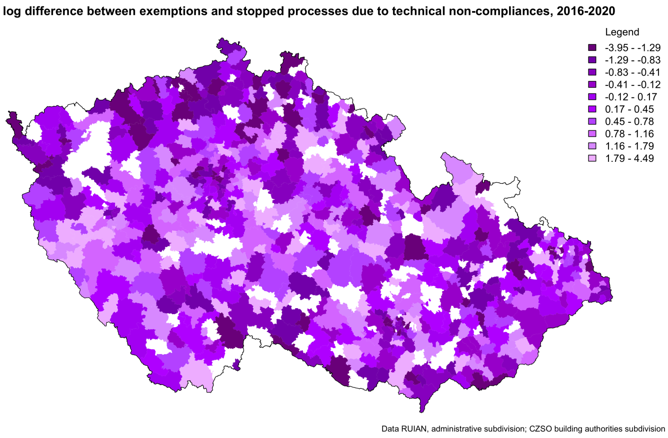

Figure 3.A.16: Relative number of granted exemptions to stopped permitting processes due to the technical non-compliance

Share of protected area

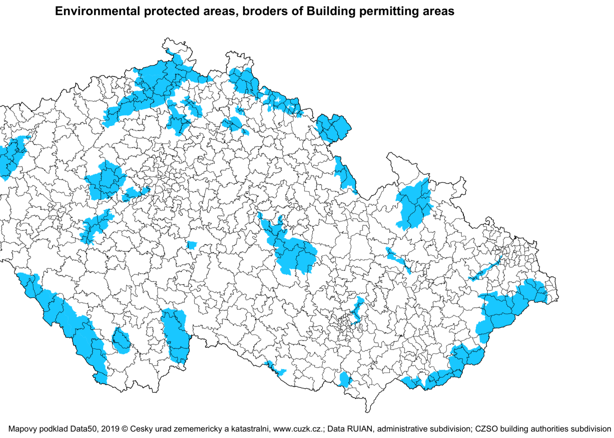

Figure 3.A.17: Share of area under environmental protection

Change in appeal rate after Building Act reform

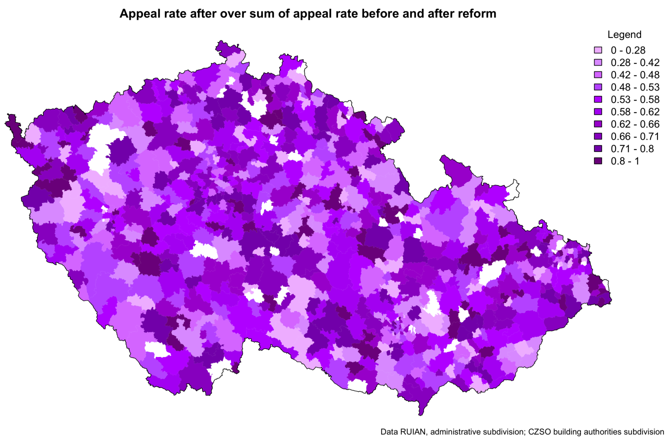

Figure 3.A.18: Change in appeal rate following Building Act reform in 2012

Reduced form estimates

Effect of appeal rates on new construction

		BDD - log(appeal rate)			
	(full)	(a)	(b)	(c)	(d)
appeal_rate_1st_ch	0.615^{***}	0.621^{***}			
	(0.118)	(0.101)			
exemp._to_offenses	-0.067^{***}		-0.074^{***}		
	(0.016)		(0.016)		
offi_per_ths_dec	3.631^{***}			2.690^{***}	
	(0.538)			(0.516)	
prot_frac	0.314^{**}				0.366^{***}
	(0.118)				(0.109)
boundary FE	✓	✓	✓	✓	✓
1.S. F-stat	346.213	562.216	254.541	310.505	136.865
R^2	0.103	0.041	0.020	0.022	0.010
Adj. R^2	-0.032	-0.096	-0.126	-0.114	-0.128
Num. obs.	13894	15132	14048	15463	15463

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Robust standard errors clustered at the boundary level reported in parentheses.

Table 3.A.2: First stage, boundary discontinuity design

Alternative estimates of the effect of appeal rate on growth of detached houses construction in period 2001-2011 are reported in table 3.A.3. The table shows estimates using individual instruments separately. All models yield results of similar magnitude (statistically not different one from another) and three out of four models are significant on 10% level.

Single family houses / log difference of number of houses in 2011 and 2001

	BDD - IV (full)	BDD - IV (a)	BDD - IV (b)	BDD - IV (c)	BDD - IV (d)
log(AR)	-0.058^{**}	$-0.059^{\cdot}$	$-0.075^{\cdot}$	$-0.065^{\cdot}$	-0.034
	(0.021)	(0.032)	(0.045)	(0.036)	(0.041)
boundary FE	✓	✓	✓	✓	✓
1.S. F-stat	346.213	562.216	254.541	310.505	136.865
R^2	0.000	0.000	0.000	0.000	0.000
Adj. R^2	-0.161	-0.151	-0.160	-0.148	-0.148
Num. obs.	13101	14312	13244	14631	14631

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Individual observations are aggregates of elementary statistical units.
Robust standard errors clustered at the boundary level reported in parentheses.
(a) Change in appeal rate following Building Act amendment in 2012 instrument
(b) Log ratio of exemptions to stopped processes due to technical non-compliance instrument
(c) Number of Building permitting authority officials per volume of development instrument
(d) Fraction of administrative area under environmental protection instrument

Table 3.A.3: Effect of appeal rate on quantity of new construction, instrumental variables individually, BDD

Share of developable GFA - 1st stage results

	log(developable/current)				
	all	>300	>300 <20,000	all	>300
bellow threshold	0.142^{***}	0.134^{*}	0.097	0.115	0.170
	(0.040)	(0.052)	(0.069)	(0.095)	(0.155)
2nd d.pol. fr. cut-off	✓	✓	✓		
4th d.pol. population	✓	✓	✓		
log dist fr. cut-off				✓	✓
log population				✓	✓
region FE	✓	✓	✓	✓	✓
thr F-stats.	13.49	5.6583	1.8348	1.6765	1.2103
R^2	0.082	0.106	0.106	0.084	0.105
Adj. R^2	0.077	0.099	0.099	0.081	0.100
Num. obs.	4390	2849	2801	4390	2849

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Robust standard errors reported in parentheses.

Table 3.A.4: Fist stage - effects of population thresholds on zoned developable areas

Quantitative model

Counterfactual simulation algorithm

The algorithm is based on approach in Monte et al. (2018).

Initial values are set as follows:

$$\hat{w}_i^{R(t)} = 1 \qquad \hat{\pi}_{ij}^{(t)} = 1$$

$$\hat{\tilde{Q}}_i^{(t)} = \widetilde{Q}_i \qquad \hat{c}_i^{(t)} = c_i \qquad \hat{\bar{\theta}}_i^{(t)} = \bar{\theta}_i$$

$$\hat{H}_i^{(t)} = \min\left(\kappa_i \widetilde{L}_i \rho_{Li}^{\omega_L} \left[1 - e^{-(\rho_{Pi}^{\omega_P} c_i / \widetilde{Q}_i)^{-\sigma_i}}\right] \rho_{Fi},\ \widetilde{L}_i \rho_{Fi}\right) \tag{3.A.4}$$

$$\xi^H = 0.95 \qquad \xi^\theta = 0.9 \qquad \xi^\pi = 0.8$$

Iterative calculation:

$$\hat{w}_i^{R(t)} = \frac{\sum_j^J \pi_{ij} \hat{\pi}_{ij}^{(t)} w_j}{\sum_j^J \pi_{ij} w_j} \tag{3.A.5}$$

$$\hat{N}_i^{R(t)} = \frac{\mathbb{N}}{N_j} \sum_j^J \pi_{ij} \hat{\pi}_{ij}^{(t)} \tag{3.A.6}$$

$$\hat{H'}_i^{(t)} = \min\left(\kappa_i \widetilde{L}_i \rho_{Li}^{\omega_L} \left[1 - e^{-(\rho_{Pi}^{\omega_P} \hat{c}_i^{(t)} / \hat{\tilde{Q}}_i^{(t)})^{-\sigma_i}}\right] \rho_{Fi},\ \widetilde{L}_i \rho_{Fi}\right) \tag{3.A.7}$$

$$\hat{H}_i^{(t+1)} = \xi^H \hat{H}_i^{(t)} + (1 - \xi^H) \hat{H'}_i^{(t)} \tag{3.A.8}$$

$$\hat{Q}_i^{(t)} = \frac{(1-\alpha) N_i^R \hat{N}_i^{R(t)} w_i^R \hat{w}_i^{R(t)}}{\lambda \widetilde{H}_i + \hat{H}_i^{(t+1)}} \tag{3.A.9}$$

$$\hat{\tilde{Q}}_i^{(t)} = \frac{\hat{Q}_i^{(t)} (\lambda \widetilde{H}_i + \hat{H}_i^{(t+1)})}{\lambda \widetilde{H}_i + \hat{\bar{\theta}}_i^{(t)} \hat{H}_i^{(t+1)}} \tag{3.A.10}$$

$$\hat{\bar{\theta}}_i'^{(t)} = \mathbb{E}[\theta_{il} | \theta_{il} > \rho_{Pi}^{\omega_P} \hat{c}_i^{(t)} / \hat{\tilde{Q}}_i^{(t)}] \tag{3.A.11}$$

$$\hat{\bar{\theta}}_i^{(t+1)} = \xi^\theta \hat{\bar{\theta}}_i^{(t)} + (1 - \xi^\theta) \hat{\bar{\theta}}_i'^{(t)} \tag{3.A.12}$$

$$\hat{\pi'}_{ij}^{(t)} = \frac{(\hat{Q}_i^{(t)1-\alpha})^{-\varepsilon}}{\sum_r^R \sum_s^S \pi_{rs} (\hat{Q}_r^{(t)1-\alpha})^{-\varepsilon}} \tag{3.A.13}$$

$$\hat{\pi}_{ij}^{(t+1)} = \xi^{\pi}\hat{\pi}_{ij}^{(t)} + (1-\xi^{\pi})\hat{\pi'}_{ij}^{(t)} \tag{3.A.14}$$

The algorithm stopping role is:

$$\hat{\pi}_{ij}^{(t)} - \hat{\pi}_{ij}^{(t+1)} < 5 * 10^{-5}$$

Algorithm converges to the solution in approximately 100 iterations.

The evaluation of change in indirect utility between scenarios is done according to equations (3.A) and (3.A.15) where $\Gamma(\cdot)$ is the Gamma function.

$$\hat{V}^{(s)} = V^{(s)}/V^{(0)}$$

$$V^{(s)} = \Gamma\left(\frac{\varepsilon-1}{\varepsilon}\right)\left[\sum_{i}^{I}\sum_{j}^{J} A_i^I \left(d_{ij}Q_i^{(s)1-\alpha}\right)^{-\varepsilon}(w_j A_j^W)^{\varepsilon}\right]^{1/\varepsilon} \tag{3.A.15}$$

Calibrated wages

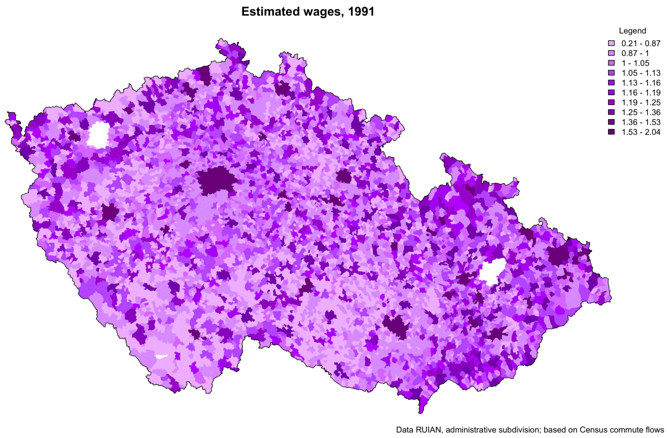

Figure 3.A.19: Relative wages in 1991

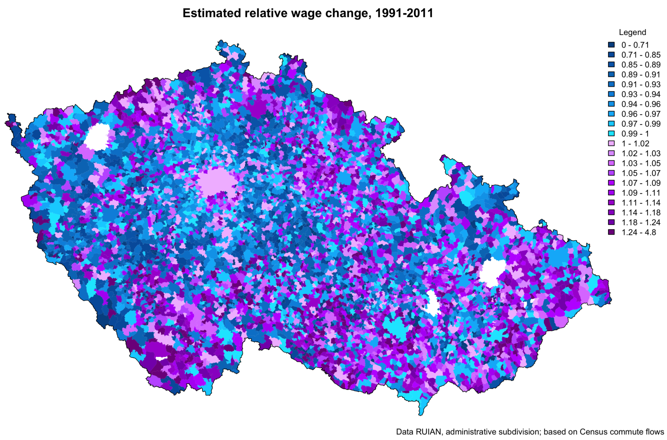

Figure 3.A.20: Relative change of wage by workplace

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4 The Impact of Noise on Open Space Amenity Value: Evidence from Cross-Sectional and Quasi-Experimental settings in Prague

Abstract

In this chapter, I investigate the effects of noise on the amenity value of urban open green spaces using a hedonic pricing model exploiting cross-sectional and quasi-experimental variation in the apartment price data from the city of Prague.

The effect of noise within open green areas is dependent on the distribution of green spaces. While for locations where all accessible green areas are concentrated into one single space, one additional decibel of noise in such green spaces decreases nearby property values by up to 1.6%. The effect, however, diminishes when green areas are distributed in more separate spaces.

The main contribution of this chapter is the evidence of the indirect effect of noise on residential real estate through the channel of open space green amenities. Additionally, this paper adopts a multi-dimensional conceptualisation of the characteristics of green spaces including the notoriously hard-to-measure quality of open green spaces, which is inferred from a quantitative spatial model. The results also contribute to the literature on the complementarity of public goods, specifically complementarity of open green space provision and low noise levels. The paper additionally provides some new insights into the indirect negative effects of transport on residential real estate via the channel of recreation areas' value, as transport is the main source of urban noise. (JEL R31, R41, R52)

4.1 Introduction

Provision of public open green areas is traditionally very important in urban planning, and empirical evidence shows that people are indeed willing to pay to reside in closer proximity to urban green areas and in places providing more green space.

Many studies have focused on the value of urban green spaces according to their size, type and proximity to residents, but a limited number of them have analysed the perceived value of open green areas with respect to their location in a city and other factors affecting their attractiveness for local residents. In this chapter, attention is paid to the effect of noise on the value of urban open

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green spaces. Both the provision of green spaces and low noise at the place of residence are well documented public goods that households are willing to pay for, but low levels of noise in recreation areas are rather unstudied.

Although there is literature looking at the problem of noise in urban parks, there do not yet seem to be any studies that use a revealed preferences approach to infer the magnitude of the negative effect of noise on the value of open green space.

Among the literature dealing with noise and sounds in green and natural areas is, for example, Merchan et al. (2014), who investigated stated willingness to pay to mitigate noise in Peñalara Natural Park in Spain and estimated that visitors would be willing to pay 1€ in entrance fees if a noise mitigating programme were introduced. Carles et al. (1999) tested the effects of various sounds combined with different settings from natural to urban by playing them to 75 respondents, who were asked to order them according to the pleasure they brought. Among their findings, they reported that natural sounds, such as running water, improve the overall perception of a place. Zannin et al. (2006) evaluated noise levels in six urban parks in Curitiba, Brazil, and the results have shown that more centrally located parks suffered from higher levels of noise, with a maximum of 67 dB in the Botanical Garden. The importance of green urban areas for urban residents who face excess noise is mentioned, for instance, in Jabben et al. (2015), who refer to a survey conducted in Rotterdam, in which 57% of respondents answered that visiting parks helped them to deal with noise.

The literature focusing solely on noise effects on property prices is relatively rich. For instance, Dekkers and van der Straaten (2009) report results from seven reviews and meta-analyses, which estimated that one additional decibel of noise leads to a decrease in property value by 0.08% to 3.57%. Their own results from the Amsterdam area have shown an effect of 0.14% per decibel for road-caused noise. In an older overview Nelson (1982), the reported negative effect of one additional decibel of noise lay between 0.08% and 1.05%.

While experimental or quasi-experimental literature in this field is rather scarce, there is, for instance, an article by Ossokina and Verweij (2015) focusing on the negative effects of car traffic on property prices, which studies a change caused by opening a new urban road by-pass in The Hague. They measure the price elasticity of housing with respect to traffic volume rather than noise and find elasticity of -0.02. To make their results comparable with the existing literature, they evaluate the effect for a traffic decrease by 50%, which should increase property values by 1.4%. This should decrease noise by around 3 decibels, so the implied cost of noise is approximately 0.45% per decibel, well within the range of reported estimates.

As in the case of the effect of noise on real estate values, there is a relatively robust body of literature estimating the value of open green areas, typically considering size and proximity. Brander and Koetse (2011) did a meta-analysis of 12 studies using hedonic pricing models of the effects of the proximity of parks on property values and confirmed that proximity to parks increases property values by approximately 0.1% whenever the distance to open green space decreases by 10 metres. They also found that the value of open green spaces is higher in denser areas. The results from Panduro et al. (2018), who analysed Copenhagen[98], show that increasing the area of parks by 1 hectare within 1,000 metres of a property increases its value by 0.08%, and being closer to a park by 10 metres increases its value by 0.036%.

There are also a limited number of studies focusing on the city of Prague. Melichar et al. (2009) have found, in log-log specification, that a 10% increase in distance from an urban wood or park is associated with a 0.26% decrease in property value, or, in log-lin specification, a decrease by 0.02% when the distance from an urban wood increases by 10 metres. Their estimate of the effect of a parkâĂŹs size is surprisingly negative, which could potentially be driven by some omitted local specifics. Melichar and Kaprová (2013) estimate the effect of urban parks, forests and other types of green areas and find they have a positive effect on housing prices. Increasing green land use within a cadastral area by 1 percentage point is associated with property price appreciation by 0.1-0.2%. Their results would suggest that increasing land use by 1 hectare increases the property price by 0.002% to 0.004%; the upper bound is actually 20 times less than in Copenhagen in the case of parks. A recent paper by Vorel et al. (2022) adopting the difference-in-differences method based on Prague data suggests that the quality of open green land matters. They show that the renewal of an urban park increased rents in close vicinity to the park by 1% to 3%.

However, there is limited body of literature that uses hedonic models to analyse interactions between open green space amenities and other factors. Research has so far focused on interactions with crime or local urban characteristics such as density. Albouy et al. (2020) use cross-sectional and panel data to infer the effect of local crime on park values. They analyse Chicago, New York and Philadelphia over the period from 2001 to 2016. They show that omitting the effect of crime underestimates the value of the parks. They estimate that parks increase the value of homes in safe neighbourhoods by 2.5% to 2.7%, but the value of parks completely diminishes if homicide levels exceed 2.7 annually. Troy and Grove (2008) analysed the relation between the value of parks and crime rates in Baltimore and similarly concluded that high crime rates lower the value of urban parks. While in low-crime areas proximity to parks increases property prices, in high-crime areas proximity to parks decreases property values. Anderson and West (2006) analysed the relation between proximity to parks and crime rates in Minneapolis, and their results

[98] Applying 5% discount rate to convert annual rents to property values

are surprisingly different to the two above mentioned papers as effect proximity to most open spaces declines faster when crime rates are higher, but their results for most open space types were insignificant. Apart from interaction with crime, they also analysed interactions with density, distance to the CBD and share of population below 18. In the case of neighbourhood parks, they obtained the expected results that the value of parks decreases with distance from the CBD and increases with population density and share of population below the age of 18.

While crime might be a first-order problem regarding the recreational value of urban green spaces in the US, this is not so in Europe, or Central Europe at least. In the absence of crime, other factors such as noise and quality affecting the recreational value of green spaces might be relatively more important. The negative indirect effect of traffic-caused noise on residential property values via the recreational value of open green spaces is a yet unstudied negative externality of transport. Taking this externality into account could provide further rationale for regulating car usage in cities or imposing the currently considered 30 km/h maximum speed policies.

In this paper, I explicitly address the multi-dimensionality of open green spaces. Beyond their size and proximity, I consider other characteristics of green spaces that are expected to affect their recreational value. I focus most of my attention on the noise in green spaces, but I also consider the spatial concentration of open green spaces - whether the accessible green spaces form a few large areas or comprise many smaller separate elements - quality of green spaces, which is inferred from a quantitative spatial model, accessibility of green spaces by public rail services, and finally provision of green spaces given local residential and job densities, which inform us about potential crowding.

The analysis is primarily based on cross-sectional apartment transaction data, and detailed land use maps are used to measure open green spaces. To measure noise, a modelled noise map covering the whole city is used. The main cross-sectional estimation is supplemented with a quasi-experimental approach using the opening of an urban underground bypass diverting a significant share of the traffic into a tunnel along its 5.5 kilometre length and changing traffic flows within the whole transport network and as a consequence affecting noise along streets.

The results show that complementarities between the attributes of open green spaces are particularly important, at least in the studied setting, in which open green spaces are abundant, but their quality and recreation potential is often questionable. Increasing the noise by one decibel in open green areas which are more spatially concentrated by 0.2 of the Herfindahl-Hirschman index (the same size of open green spaces is divided into two separate parks instead of into three) decreases local property values by 0.32%. The remaining results show that increasing the quality of parks by 10% increases the value of local residential properties by 0.16%, and while increasing the size of green spaces alone does not have an effect, increasing the green space provision per resident by 10% increases local property values by 0.24%.

In the following parts, a conceptualisation of the multidimensionality of the open green spaces and the theoretical model used to infer the quality of the green spaces are introduced first, then the empirical approach is described, followed by data description and construction of variables. Then follow estimates of models and a discussion of the results.

4.2 Conceptualisation of the characteristics of multi-dimensional open green spaces

The most common approach adopted in the literature is to measure the overall provision of open green spaces or some of their types, either measuring the area of green spaces within a given distance from a housing unit, or proximity to the nearest green space, or a combination of the two (such as, for instance, in Panduro et al., 2018). Alternatively, an area or a proximity is measured separately for various discrete types of green spaces (as in Anderson and West, 2006).

The primary interest of this paper is the effect of noise on the value of open green spaces, which could be considered one feature that green spaces could have. However, I will also parametrize other dimensions of open green spaces that are expected to be important for their perceived value. I consider commonly used open green spaces' accessibility and size, then size relative to number of residents and workers in their vicinity, their quality, scatteredness, which is also referred to as spatial distribution, noise, and accessibility from public transport.

Prague is a hilly city and not always well integrated with local walkway networks, so proximity to green spaces is measured on a walkway network from housing unit to open green spaces instead of taking simple euclidean distance. Accessibility is then measured in two alternative ways, either as all green spaces within 600 metres of the residence in the baseline models, or as all green spaces within 1,500 metres of the residence discounted by a spatial decay parameter capturing decreasing utility from further located green spaces, which is, practically, a market potential applied to open green spaces.

Size. The area of accessible open green spaces is measured using a 100 by 100 metre grid. First, the sizes of the open green spaces under consideration are summed up within each grid cell. Second, each apartment is assigned to its respective grid cell and from these grid cells, accessible green spaces in other grid cells are calculated. This procedure largely reduces computational complexity, as there are tens of thousands of individual apartments and approximately one hundred thousand open green spaces, and calculating network distance between them for all combinations of these features would be intractable. Two measures of green space provision are therefore calculated. The first is a sum of green spaces within grid cells up to 600 metres away, and the second is open green spaces within grid cells grouped into bins of 100 metres up to 1,500 metres, and the area of green space in each bin is discounted with a separately estimated spatial decay parameter and then used in the model. It has also turned out that the implicit value of each additional hectare of open green space decreases, and therefore logs of green space areas are used instead of sizes in levels.

Quality. Measuring the quality of open green spaces with one continuous variable is not straightforward, unlike, for instance, measuring their size, as it is not clear what particular features make them valuable for their users, and at the same time, many potentially valuable features are not measured. I adopt two alternative approaches to proxy for quality. In supplementary models, the quality of open green spaces is proxied by four separate observable characteristics: provision of retail in and around green spaces, density of paths, scenic views, and density of public toilets. These four characteristics are assigned weights based on separate models. This quality proxy variable is labelled *gr_quality_n*.

An alternative approach is adopted for baseline models. To construct a continuous variable capturing the perceived quality of open green spaces, I use a quantitative spatial model framework based on Ahlfeldt et al. (2015). This class of model, allows us, among other things, to infer the unobserved 'attraction force' (quality, in this case, and wages in the original model) if the number of incomers and number of people by their place of residence are observed. I use this framework and, instead of inferring wages from commuting patterns, I infer the quality of open spaces from observed workers' places of residence and choice of open green spaces where they spend their free time, given network distances from residences to all accessible open green spaces. This quality variable is labelled *quality_model*.

The city is assumed to be monocentric with all workers earning wage w, paying commuting costs c_i to reach their workplace from their place of residence, where they pay rent r_i. Parameter $1 - \beta$ is expenditure share on housing. The simplifying assumption is that each worker chooses one open green space j (later referred to as a park) out of all the accessible parks J that he or she visits for recreation. Following Ahlfeldt et al. (2015) and Monte et al. (2018), the indirect utility of a worker o is given by size of park S_j, with μ which is parks' value elasticity with respect to their size and decreases with the time costs of walking to the park d_{ij} from a residence. Each worker has an idiosyncratic taste shock for amenities provided by a pairing of residence and park to go to for recreation z_{ijo}. Distribution of the taste shock follows Fréchet distribution with $F(z_{ijo}) = e^{-B_i Q_j^{-\varepsilon}}$ where B_i is a mean amenity value of place of residence, and Q_j is a mean amenity value of a park j. $\varepsilon > 1$ controls the dispersion of individual taste shocks. The larger is ε, the more homogeneous tastes are among residents.

$$V_{ijo} = \frac{z_{ijo} S_j^{\mu} w}{d_{ij} c_i r_i^{1-\beta}} \tag{4.2.1}$$

Following Ahlfeldt et al. (2015) and Monte et al. (2018), a discrete choice model of choosing a place of residence and a park with assumed distribution of idiosyncratic taste shock could be solved, so there is a probability π_{ij} of living in i and going to park j. As wages are constant for all residents, they drop out of the equation. The probability of living in i and choosing park j for recreation depends on the amenity value and rents in i, size and quality of park j, and the distance d_{ij} between them, which are all in the numerator (also called bi-lateral resistance) relative to all other options in the economy (multi-lateral resistance) in the denominator - which is the sum of the same term for all combinations of residences u and all parks v.

$$\pi_{ij} = \frac{B_i Q_j (S_j^{\mu}/d_{ij} c_i r_i^{1-\beta})^{\varepsilon}}{\sum_{u=1}^{U} \sum_{v=1}^{V} B_u Q_v (S_v^{\mu}/d_{uv} c_u r_u^{1-\beta})^{\varepsilon}} \tag{4.2.2}$$

Further, probability $\pi_{ij|i}$ of choosing park j conditional on living in place i simplifies the term as residence-specific terms in the numerator and denominator will cancel out:

$$\pi_{ij|i} = \frac{Q_j (S_j^{\mu}/d_{ij})^{\varepsilon}}{\sum_{v=1}^{V} Q_v (S_v^{\mu}/d_{iv})^{\varepsilon}} \tag{4.2.3}$$

The probability of choosing park j conditional on living in i can immediately be used to relate the number of park visitors N_j and number of residents N_i living in locations I, because the probabilities of choosing park j conditional on living in i multiplied by population in i sums up to the overall number of visitors of a park j: $N_j = \sum_{i=1}^{I} \pi_{ij|i} N_i$. Substituting in equation (4.2.3) yields:

$$N_j = \sum_{i=1}^{I} \frac{Q_j (S_j^{\mu}/d_{ij})^{\varepsilon}}{\sum_{v=1}^{V} Q_v (S_v^{\mu}/d_{iv})^{\varepsilon}} N_i \tag{4.2.4}$$

This expression in equation (4.2.4) states that the number of visitors N_j of a park j is a sum of probabilities $\pi_{ij|i}$ of recreating in a park j conditional on living in i multiplied by respective populations N_i of locations i. The fraction of population visiting a park j and living in i is given by the quality of a park Q_j and its size S_j to the power of μ, which captures the elasticity of value with respect to the park's size, divided by the cost d_{ij} of reaching j from i. The whole term is raised to the power of ε, a parameter that governs the dispersion of individual idiosyncratic preferences for combinations of places to live and places for outdoor recreation, which are assumed to be randomly drawn from the Fréchet distribution. The denominator is a summation of the same structure of all other accessible parks v, with their qualities Q_v, sizes S_v and proximities d_{iv} from i to v raised to the power of ε. Number of residents N_j, number of park visitors N_j, park sizes S_j and distances d_{ij} are measured and parameter μ is estimated in a separate model. The only unobserved variable in the equation (4.2.4) is a vector of open space quality $\mathbf{Q}$ with a length of J, number of parks. Ahlfeldt et al. (2015) show that there is a unique vector that solves the system of J equations (4.2.4); as long as one element of $\mathbf{Q}$ is normalised to one, the relative quality of parks is inferred.

The vector of park quality $\mathbf{Q}$ is solved numerically, so the model has to be brought to the data. The number of users of open green spaces N_j is proxied with data collected by Pánek et al. (2021), who in their public participation GIS project asked multiple questions regarding quality of life - for instance, which places are neglected, or which do not feel safe - and let participants select places on a map. I use particular entries labelled "This is where I spend my free time". Out of 15,989 entries in this category, 8,086 were geo-located within accessible open green spaces with recreation potential, as defined in this project. This shows that open green spaces are indeed important places for recreation. To be consistent with the theoretical model, and assuming each resident picks one open green space for recreation, the number of visitors in each open space is scaled up so that the sum of visitors matches the Prague population reported in the 2011 census.

Residential locations i consist of square grid cells with an area of one hectare (approximately the size of an urban block) for which population N_j is aggregated from the 2011 Census data reported on the building level. Lastly, the cost of reaching an open space j from a residence location i is given by $\tilde{d_{ij}}^{\tau}$, where $\tilde{d_{ij}}$ is the network distance between residence i and open green space j [99]. τ is the elasticity of probability of visiting an open space with respect to its proximity, and it is currently set to 5, following Heblich et al. (2020), who used the same functional form, but measured that elasticity in the case of commuting to work. ε measuring the dispersion of individual tastes for home locations and open spaces is set to the value of 5, similar to other literature (Ahlfeldt et al., 2015; Heblich et al., 2020) which models commuting to jobs. This application is, however, less sensitive to the choice of ε, which affects the variance of calculated vector $\mathbf{Q}$, but the ordering of individual parks by their inferred quality remains unchanged.

Open green space distribution captures the extent to which accessible green spaces are continuous or scattered as this is assumed to have an impact on the perceived value of green spaces. All else being equal, including the overall size of accessible open green spaces, contiguity of green spaces is expected to be valued by residents, providing more recreation opportunities

[99] The point of reference for residences i is always the centre of a grid cell. The same holds for small green areas that do not exceed one grid cell. For large open green spaces, the reference point is the nearest entrance into the open green space on a walkway network from i to j.

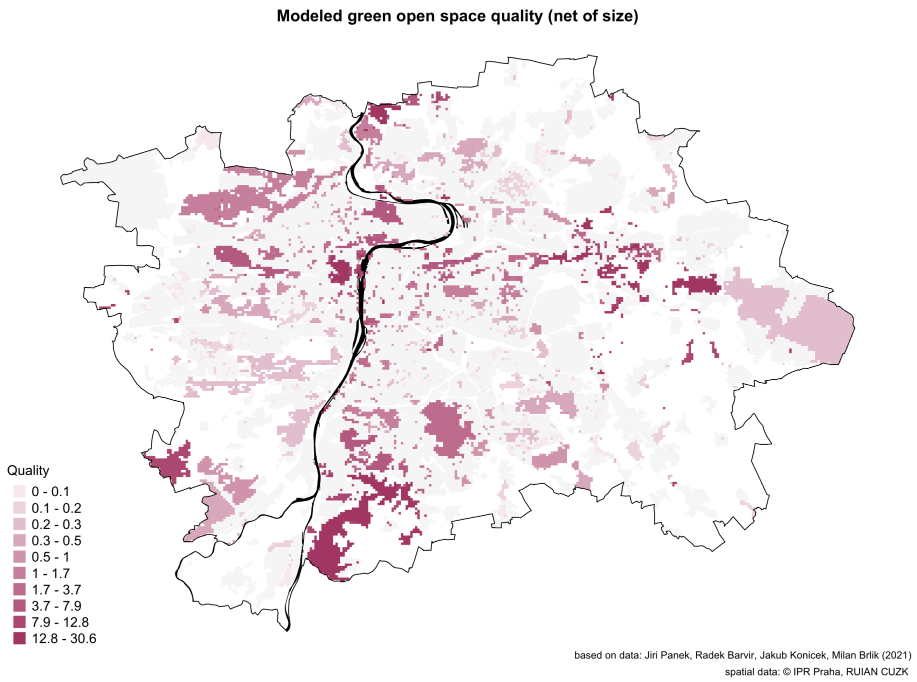

Figure 4.2.1: Quality of accessible green open spaces

within one larger open green space. The distribution is measured for individual green spaces within the 600-metre threshold distance from a residence using the Herfindahl-Hirschman concentration index (abbreviated as HHI). As a result, location has an index equal to 1 if all accessible green spaces form one continuous area, while the coefficient approaches 0 if green spaces are scattered into equally sized units and their number approaches infinity[100].

Public transport accessibility, surrounding densities and noise. A variable capturing proximity to public rail, underground and tram services from green spaces is used as another attribute that could affect their recreational value. Then, the sum of residents and jobs within 600 metres of the green spaces are calculated to construct variables of the number of jobs and number of residents per unit of open green space to measure the potential effect of crowding in green spaces.

The key variable of interest in this chapter is noise in open green spaces. To construct this variable, noise maps of the city of Prague are used, either a cross section in 2016, or the difference between 2014 and 2016. As noise maps are modelled for the whole area of the city (excluding areas occupied by buildings), noise within green spaces can easily be computed.

[100]Practically, the analysis aggregates green spaces to 100 times 100 metre grid cells (of 1 hectare each) that serve as the spatial unit at which spatial data are used. As a result, there is a maximum of 37 grid cells within 600 metres (when Euclidean distance is considered, but often it will be less due to the sparser walkway network), so it is also the maximum possible number of accessible green spaces. A detailed description of spatial data treatment is provided in the Data section

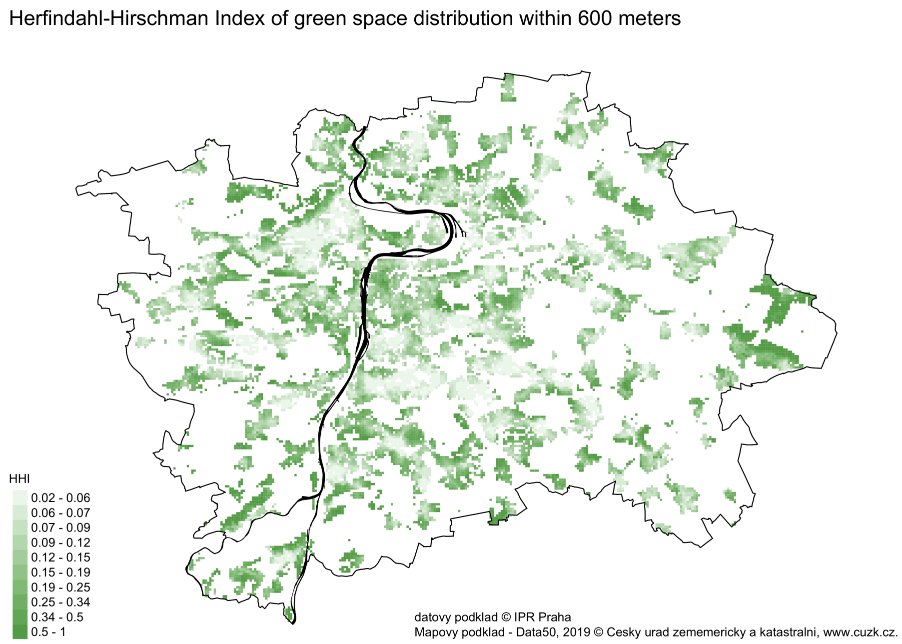

Figure 4.2.2: Distribution (concentration) of accessible open green spaces (Places of residence plotted on the map)

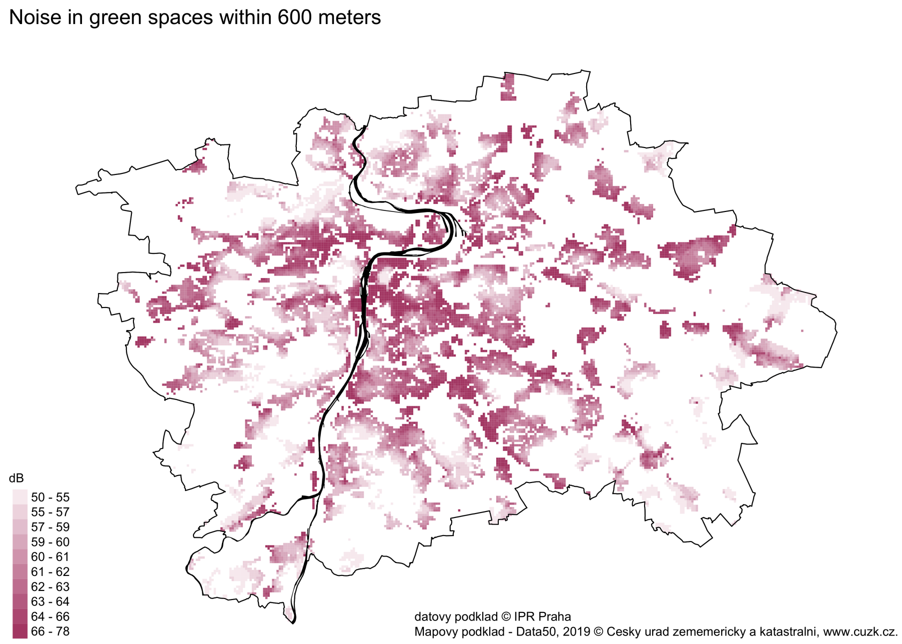

Figure 4.2.3: Noise in accessible green spaces

4.3 The Empirical Approach

The analysis utilises two identification strategies, both of them relying on the hedonic pricing model approach to infer implicit prices of green open spaces. The first approach investigates a cross-sectional variation in green open spaces and their characteristics, in particular noise that is of the main interest in this chapter. The second identification strategy explores variation in noise caused by a quasi-natural experiment of opening a new road tunnel bypass. The second strategy is described in more detail in the subsequent part.

Both approaches use individually recorded apartment transactions as observations. Each observation is exactly localized and contains set of apartment, buyer, building, time and location-specific characteristics. The dependent variable is a log of apartment transaction price and as explanatory variables of interest open green amenity features are used.

Cross-sectional analysis

The baseline model considers open green spaces accessible within 600 meters from a residence via walkway network. Implicit value of these open spaces' characteristics are estimated according to the following equation:

$$\begin{aligned}\log P_{iegct} &= \beta_1 \log(S_g^{pub}+1) + \beta_2 \log(S_g^{pri}+1) + \kappa_1 log(Q_g) + \gamma_1 \Gamma_g^{apart} \\ &+ \gamma_2 \Gamma_g^{green} + \kappa_2 T_g^{green} + \theta\ hhi_g + \omega_1 \log(C_g^{job}+1) + \omega_2 \log(C_g^{res}+1) \\ &+ \delta^{\beta_1,\kappa_1} \log(S_g^{pub}+1) \times log(Q_g) + \delta^{\beta_1,\theta} \log(S_g^{pub}+1) \times\ hhi_g \\ &+ \delta^{\kappa_1,\theta} log(Q_g) \times\ hhi_g + \delta^{\gamma_2,\theta} \Gamma_g^{green} \times\ hhi_g \\ &+ \boldsymbol{X_i \alpha_1} + \boldsymbol{D_e \alpha_2} + \boldsymbol{S_g \alpha_3} + \eta_c + \varsigma_t + \varepsilon_{iegct} \qquad (4.3.1)\end{aligned}$$

The dependent variable $\log P_{iegct}$ is a natural logarithm of price of an apartment i, located in an elementary statistical unit e, grid cell g, cadastral area c and sold in a year and month t. Variables S_g^{pub} and S_g^{pri} are sizes of accessible public and private green spaces within 600 meters respectively, T_g^{green} is a relative proximity from green open spaces to rail public transit, Q_g is a relative measure of open green spaces' quality inferred from the quantitative spatial model, Γ_g^{apart} and Γ_g^{green} measure equivalent daytime noise around a property and within the accessible green areas respectively. The hhi_g measures continuity (distribution) of green spaces within 600 meters using the Herfindahl-Hirschman index. C_g^{job} and C_g^{res} measure the size of green spaces per worker and per resident respectively so they control for potential crowding in green open spaces. Then interaction terms between the key variables of interest are included.

The vector X contains apartment and buyer specific controls including a log of apartment size, a property type (new, old), a construction type (brick, prefabricated panels), an age of building, connection to gas and a log of distance to the CBD. Buyer controls include the type of sale (developer to household, household to household), a dummy if buyer's age is known (unknown is for firms buying property), buyer's age and age squared, whether buyers are a married couple and if married whether they are in the age group 25 to 45.

The vector D contains demographic controls from 2011 Census available at the Elementary statistical unit level e and it contains a share of children below the age of 15, a share of residents above the age of 65, a share of college educated residents and a share of unemployed.

The vector S of local area controls on the level of apartments' grid cell g contains equivalent daytime noise, elevation, terrain slope, a dummy for the Southern slopes, a log of jobs within a grid cell, proximity to the metro or a train station, proximity to a tram or a bus stop, gross floor areas within 250 meter radius and a number of retail stores within 250 meter radius.

The last terms are η_c cadastral area fixed-effects, τ_t year and month fixed-effects and ε_{iegct} is a randomly distributed residual.

In the alternative specification, accessibility to green spaces is modelled differently - instead of treating all green spaces within 600 meters the same, the threshold for including green spaces is extended to 1500 meters and all green spaces are discounted with a distance decay function. To adopt this approach, the distance decay parameter must be estimated first using the non-linear least squares estimator according to the following equation (4.3.2):

$$\begin{aligned}\log P_{igt} &= \alpha_0 + \beta \sum_{n}^{\bar{N}} green\_public_n \cdot e^{\phi \cdot hundreds\_meters_n} \\ &+ \alpha_1 \log(size_i) + \alpha_2 \log(cbd\_dist_i) \\ &+ \alpha_3 noise_s + \tau_t + \varepsilon_{igt} \end{aligned} \tag{4.3.2}$$

The green public space size *green_public* is calculated for n 100 meter wide rings around each apartment transaction i. The model is estimated for *green_public* size both in levels and in logs. Sum of all green areas within a particular ring n is discounted by an exponential function driven by the parameter ϕ multiplied by a distance of a ring from an apartment i given in hundreds of meters. Additional control variables include the size of an apartment, distance to the CBD and noise in the grid cell where an apartment i is located.

Using the estimated distance decay parameter ϕ, proximity discounted open green areas are used in the subsequent models instead of size of green areas within 600 meters. It is also assumed the importance of noise outside an apartment could have similar spatial decay as value of green spaces, in other words noise immediately in the area of an apartment is perceived with higher weight compared to noise further away. Although particular magnitude of the coefficient could be questioned, the assumption seems to be reasonable as noise even further away from a residence could be considered as a nuisance, especially in neighbourhoods relying on walking and public transit. The following equation, where ϕ is estimated parameter and n represents concentric 100 metre wide rings, is estimated as an OLS model according to the following equation:

$$
\begin{aligned}
\log P_{iegct} &= \beta_1 \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \\
&+ \beta_2 \log(green\_private_g) + \alpha_1 \log(residents_g) \\
&+ \kappa_1 gr\_transit_g + \kappa_2 gr\_quality_g + \kappa_3 \log(gr\_job_g) \\
&+ \kappa_4 \log(gr\_resident_g) + \gamma green\_public\_noise_g + \theta hhi_g \\
&+ \delta_1 \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \times gr\_quality_g \\
&+ \delta_2 hhi_g \times \log(residents_g) \\
&+ \delta_3 hhi_g \times \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \\
&+ \delta_4 hhi_g \times green\_public\_noise_g \\
&+ \boldsymbol{X_i \alpha_2} + \boldsymbol{D_e \alpha_2} + \boldsymbol{S_g \alpha_3} + \eta_c + \tau_t + \varepsilon_{iegct} \qquad (4.3.3)
\end{aligned}
$$

Alternative to the equation (4.3.3), following specification further assumes proximity decay also imposed on open green spaces' quality and their noise. That means individuals are less sensitive to quality or noise in green spaces when these characteristics of green spaces are further away from their residence. Spatial decay parameter is again assumed to be ϕ and both variables are calculated as a weighted mean weighted by the proximity discounting exponential function:

$$
\begin{aligned}
\log P_{iegct} &= \beta_1 \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \\
&+ \beta_2 \log(green\_private_g) + \alpha_1 \log(residents_g) \\
&+ \kappa_2 \frac{\sum_{n=1}^{15} gr\_quality_{ng} \cdot e^{\phi n}}{\sum_{n=1}^{15} e^{\phi n}} + \gamma \frac{\sum_{n=1}^{15} green\_public\_noise_{ng} \cdot e^{\phi n}}{\sum_{n=1}^{15} e^{\phi n}} \\
&+ \kappa_1 gr\_transit_g + \kappa_3 \log(gr\_job_g) + \kappa_4 \log(gr\_resident_g) + \theta hhi_g \\
&+ \delta_1 \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \times \frac{\sum_{n=1}^{15} gr\_quality_{ng} \cdot e^{\phi n}}{\sum_{n=1}^{15} e^{\phi n}} \\
&+ \delta_2 hhi_g \times \log(residents_g) \\
&+ \delta_3 hhi_g \times \sum_{n=1}^{15} \log(green\_public_{ng}) \cdot e^{\phi n} \\
&+ \delta_4 hhi_g \times \frac{\sum_{n=1}^{15} green\_public\_noise_{ng} \cdot e^{\phi n}}{\sum_{n=1}^{15} e^{\phi n}} \\
&+ \boldsymbol{X_i \alpha_2} + \boldsymbol{D_e \alpha_2} + \boldsymbol{S_g \alpha_3} + \eta_c + \tau_t + \varepsilon_{iegct} \qquad (4.3.4)
\end{aligned}
$$

Quasi-experimental variation in noise

On the 19th September 2015, new underground highway segment of the Prague city inner-ring was opened. This new segment completed an alternative route to the existing South-North bypass going through the city centre and which until that time used to be the only major connection in that direction. The original thoroughfare runs through the central part of the city on a strip of land where former Western side of the baroque fortification used to be until the end of 19th century when it was demolished. As a consequence of opening the tunnel bypass, the road network experienced significant changes in the daily automobile traffic volumes. While the area above the new tunnel mostly experienced decrease of on-ground traffic, previously unconnected segments of the inner-ring, some radial arterial roads and some areas in the city centre experienced induced increase of automobile traffic. The event is assumed to be an exogenous shock to the noise in open green areas which is largely caused by car traffic.

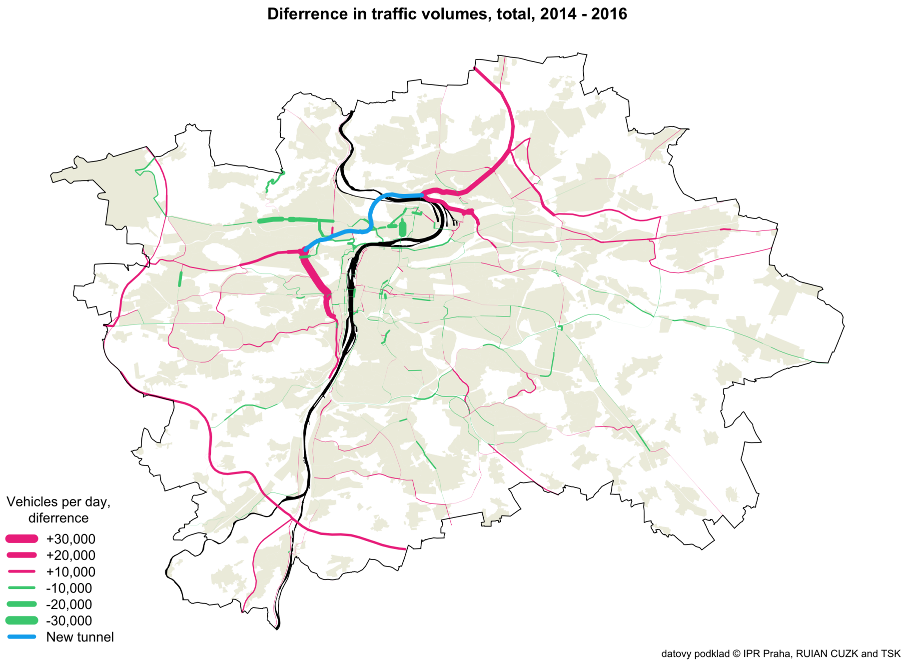

Figure 4.3.1: Traffic intensity change, 2014-2016

The link between change in traffic volumes and change in noise levels could be shown with three distinct data sources recorded before and after the opening of the inner-ring tunnel in 2015: with measured traffic volumes in 2014, 2016 and 2017, on-ground measured noise levels in 2015 (before opening the tunnel), 2016 and 2017 in 22 locations along the opened new route and adjacent arterial roads. The third dataset is modelled noise for the whole area of Prague for years 2014 and 2016.

The two sets of figures below show relationship between these three variables as changes over the time window between 2014 and 2016 on the left and between years 2014 and 2017 on the right. The horizontal axis plots change in noise at 22 observation points where noise was recorded. On the vertical axis in the first set of figures are log differences in observed traffic flows and in the second set of figures change in the modelled noise according to the noise maps is plotted on vertical axis. The noise change based on noise maps is calculated using three different methods. The original noise maps report noise levels in discrete 5dB bins and to convert it into a continuous variable alternative approaches to spatial smoothing are implemented. The first method calculates the mean noise within 15 meters from the measurement point (plotted in red colour), the second method reports noise level as a mean value for the whole grid cell (without considering built-up land) within which the measurement point is located (plotted in green colour) and the third method reports mean noise in the publicly accessible parts of the grid cell in which the measurement point is located (plotted in blue colour). As could be seen from the second set of plots, all three methods yield similar results no matter which one is chosen.

As expected, there is a positive relation between reduction of traffic flows and noise decrease which is plotted in the upper set of charts. Moreover, the slope of the fitted lines is similar for both considered periods and also the fitted lines in both cases almost intersects the origin, intuitively meaning no change in traffic flows is associated with no change in noise levels. Relationship between traffic volumes and noise shown on the plots are similar, although slightly smaller, to what Ossokina and Verweij (2015) report: halving traffic intensity (which is equivalent to the -0.69 log points difference) should be associated with 3 decibel of noise decrease.

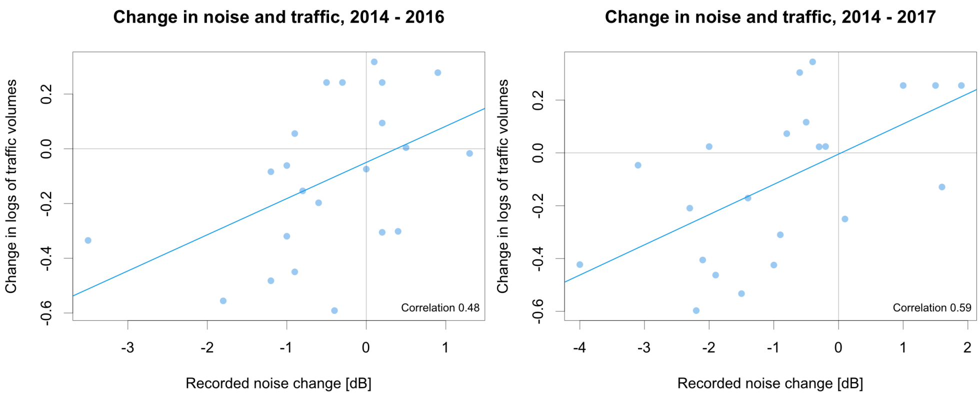

Figure 4.3.2: Relation between traffic intensity change and recorded noise change

The second set of charts also confirms expected positive correlation between measured and modelled noise, but reveals much lower slope of the fitted line than would be expected. On average, the change of 1 dB of measured noise data is associated with change of only 0.4 dB in the modelled data. Possible explanation for this inability to capture the true change in noise is some form of time lag as past noise levels are persistent due to modelling methods. In such case cross-sectional variation in noise should reflect real noise levels correctly, but changes of noise over time would be attenuated. If the measured noise levels were close to the true values, the estimation exploiting change over time based on the modelled data could overestimate the effect of noise by some 2.5 times that indeed seems to be the case, as it will be shown in the estimation part.

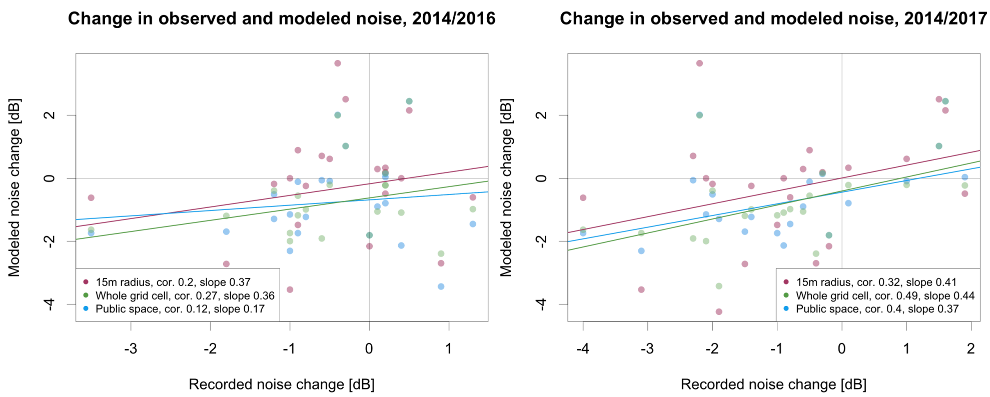

Figure 4.3.3: Relation between modelled and recorded noise change

The change of the noise between 2014 and 2016 based on the noise maps shows a lot of variation across the whole city without any clear pattern as it is shown on the map below where the blue colour marks relative decrease of noise. Conversely to the expectations, the area along newly opened underground bypass does not seem to experience significant decrease in noise compared to other areas in the city. This might be caused either by measurement error and random noise in the data, or by capturing wide range of events taking place in the period between 2014 and 2016, or both of these reasons could play some role. Another plausible explanation mentioned above is some kind of time lag in noise maps modelling that smoothed otherwise large noise decrease in the area affected by the new infrastructure opening.

Almost identical estimation equation as equation (4.3.1) is used to estimate the effect of noise using variation in the data caused by the quasi-experiment of opening the new urban tunnel bypass:

$$\begin{aligned}
\log P_{iegct} \;=\;& \alpha_0 \mathbb{1}(t > t^*) + \beta_1 \log(S_g^{pub} + 1) + \beta_2 \log(S_g^{pri} + 1) + \kappa_1 log(Q_g) \\
+\;& \gamma_1 \Delta\Gamma_g^{apart} \times \mathbb{1}(t > t^*) + \gamma_2 \Delta\Gamma_g^{green} \times \mathbb{1}(t > t^*) + \kappa_2 T_g^{green} + \theta \; hhi_g \\
+\;& \omega_1 \log(C_g^{job} + 1) + \omega_2 \log(C_g^{res} + 1) \\
+\;& \delta^{\beta_1,\kappa_1} \log(S_g^{pub} + 1) \times log(Q_g) + \delta^{\beta_1,\theta} \log(S_g^{pub} + 1) \times \; hhi_g \\
+\;& \delta^{\kappa_1,\theta} log(Q_g) \times \; hhi_g + \delta^{\gamma_2,\theta} \Delta\Gamma_g^{green} \times \; hhi_g \times \mathbb{1}(t > t^*) \\
+\;& \boldsymbol{X_i \alpha_1} + \boldsymbol{D_e \alpha_2} + \boldsymbol{S_g \alpha_3} + \eta_c + \varsigma_t + \varepsilon_{iegct} \qquad (4.3.5)
\end{aligned}$$

The explanatory variables used are the same as in the equation (4.3.1). The only difference is inclusion of an indicator variable $\mathbb{1}(t > t^*)$ which is equal to one for an apartment purchases done in time t after the opening of

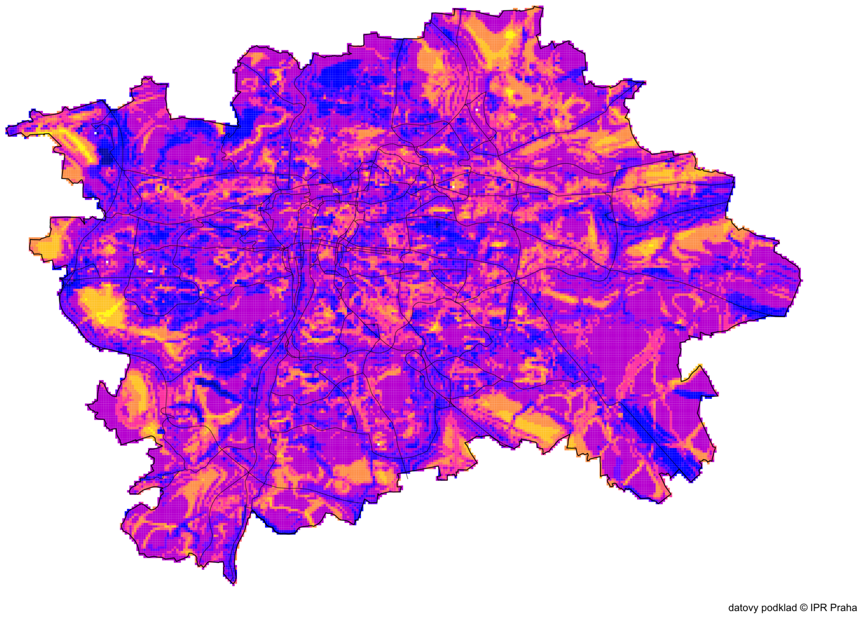

Figure 4.3.4: Noise change (based on noise maps), 2014-2016

the tunnel bypass on the 19th September 2015 (time t^*), and zero otherwise. Variable $\Delta\Gamma_g^{green}$ is in this specification the difference of noise levels between years 2016 and 2014. To measure the effect of noise change in open green areas resulting from the infrastructure opening both variables are interacted. Following previous specification in the equation (4.3.1) $\mathbb{1}(t > t^*) \times \Delta\Gamma_g^{green}$ is also interacted with *hhi*. Control variables do not differ from equation (4.3.1) except of noise within the grid cell of apartment which is again used alone and in interaction with $\mathbb{1}(t > t^*)$ variable to take into account direct effect of noise change.

4.4 Data Description and Processing

Data used in this project can be generally divided into three groups: spatial GIS vector data with high geographical detail provided by the city of Prague, apartment transaction prices and supplementary socio-demographic data from the 2011 Census.

Spatial data

For the purpose of tractability the whole area of the city of Prague is subdivided into a 100 by 100 metre rectangular grid (the size of a grid cell approximately matches one city block) with a total number of 50,587 grid cells. All the spatial data were then aggregated to these cells to make spatial analysis more efficient.

The main spatial data are obtained from the Prague Geoportal[101]. Detailed land-use vector dataset as of 2017 was used to measure size of 18 categories of open green spaces and aggregate them into the grid. Besides size, each green open space geometry feature has information about its public accessibility which was used in the later aggregation of publicly accessible green open spaces. The data were obtained in June 2017, therefore approximately in the first third of the period of recorded real-estate transactions used in the cross-sectional analysis.

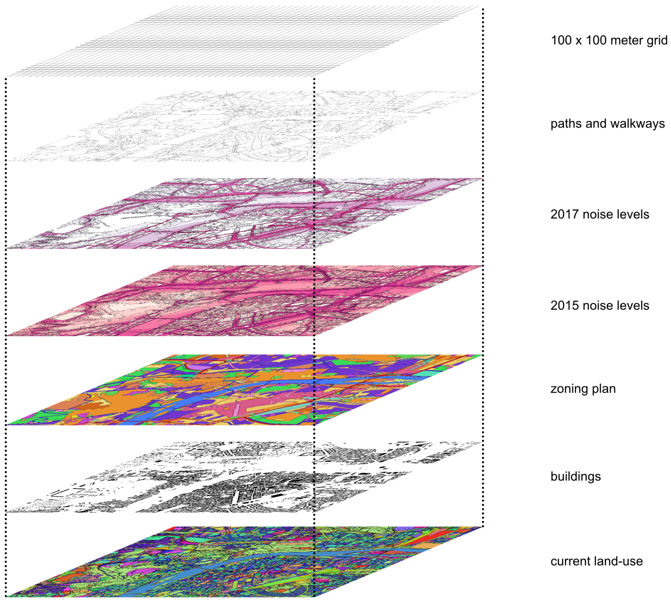

Figure 4.4.1: Spatial data

All permeable green areas including agricultural land are shown on the map below. The map reveals that the major share of Prague surface is actually undeveloped and the extent of open spaces provision is relatively high by European standards: The size of urban greenery per capita reaches 40 square metres in Prague, while Wien, Munich and Berlin have slightly above 20 square metres and Copenhagen and Budapest are slightly below 20 square metres per capita (IPR Praha, 2017).

The map shows all permeable green open space areas, but actually not all of them were included in the following analysis as some of these spaces are for instance not publicly accessible or they likely do not have any recreational amenity value at all. Green areas within airports and similar facilities serve as a good example.

One of variables of the primary interest is the size of green open space. The initial assumption is the perceived value of green open spaces is dependent on their size, accessibility, quality, distribution and noise. The accessibility is measured on a walkway network to reflect imperfect connectivity and existing obstacles to walking.

[101]https://www.geoportalpraha.cz/cs/data/otevrena-data/seznam

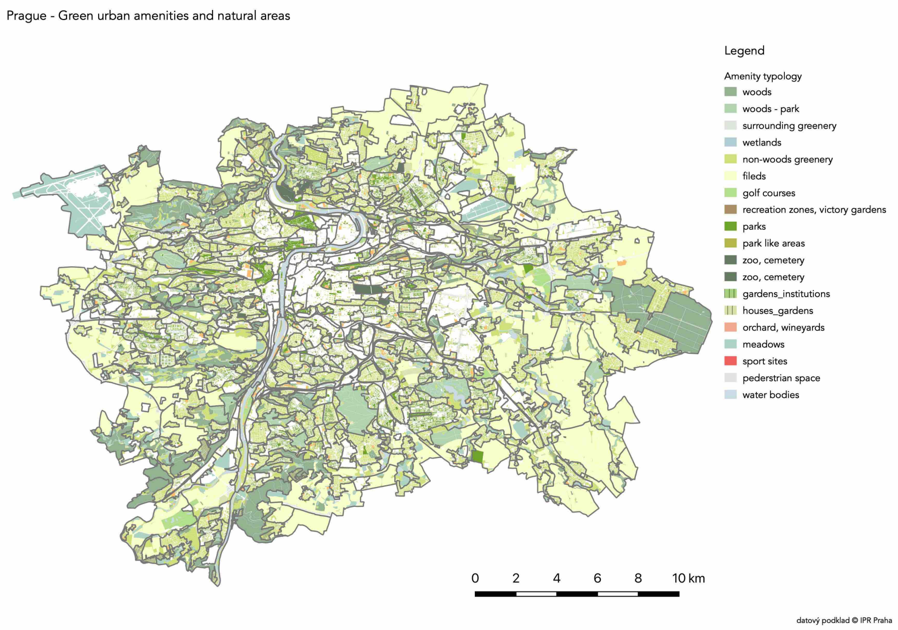

Figure 4.4.2: Permeable open green spaces in Prague

Open green spaces are divided into two categories - large and small ones. Large green open spaces consist at lest of two rook-contiguous grid cells (they share a common edge) with at least 50% of open green areas coverage each. For large green open spaces, proximity is measured as the shortest way on a walkway network from a grid cell centroid to the nearest access point of a large green area.

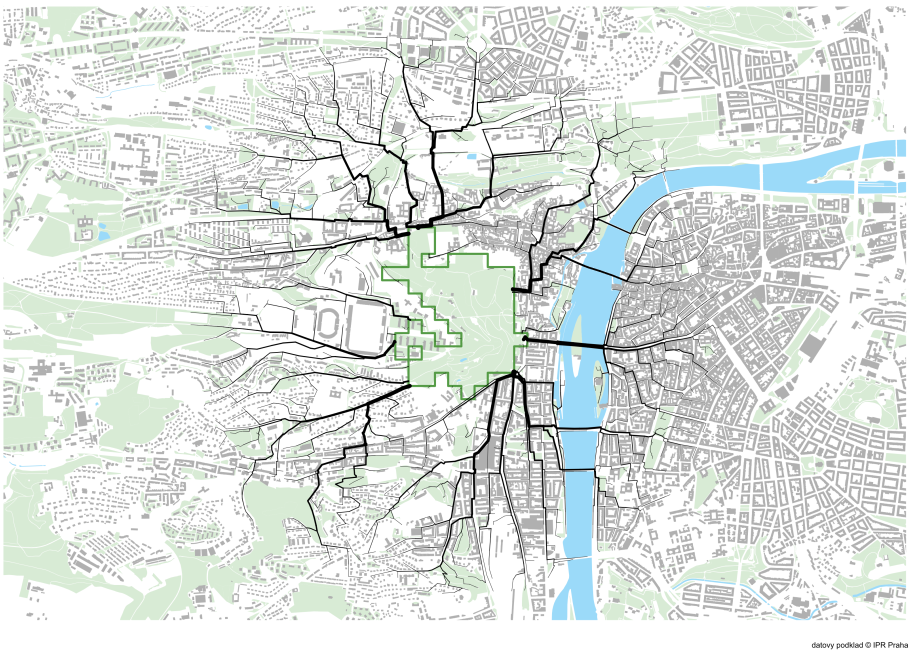

Figure 4.4.3: Example of park proximity network distance

Small green spaces are not spanning across multiple grid cells and each grid cell not integrated into a large green open space is simply assigned a size of its green open space. To measure proximity to these small green open spaces, network distance between centroids of grid cells is taken.

Example of a walkway network accessibility of one centrally located large park is shown on a map below.

Datasets essential for the analysis are noise maps. The dataset is a model for the whole area of the city provided as a vector polygon layer where each polygon represents an estimated equivalent daytime noise level with discrete steps by 5 dB. The noise dataset is constructed for years 2014 and 2016. The analysis is to some extent limited by the fact that for the later noise map the lowest defined noise level is 50dB, so to make both data sources consistent, noise levels lower than 50dB in the 2014 dataset are treated as equal to 50 dB. Although not being optimal, this noise level could be still considered as being below urban background noise that is 55dB according to Day et al. (2007) and the same value is mentioned by Nelson (2008) when reviewing existing literature.

The next map plots the noise data for 2016. High noise levels shown in bright colours clearly mark main arterial roads which are plotted in black. Another example of source of excessive noise is the main airport located in the North-Western corner of the city with its two easily identifiable runways.

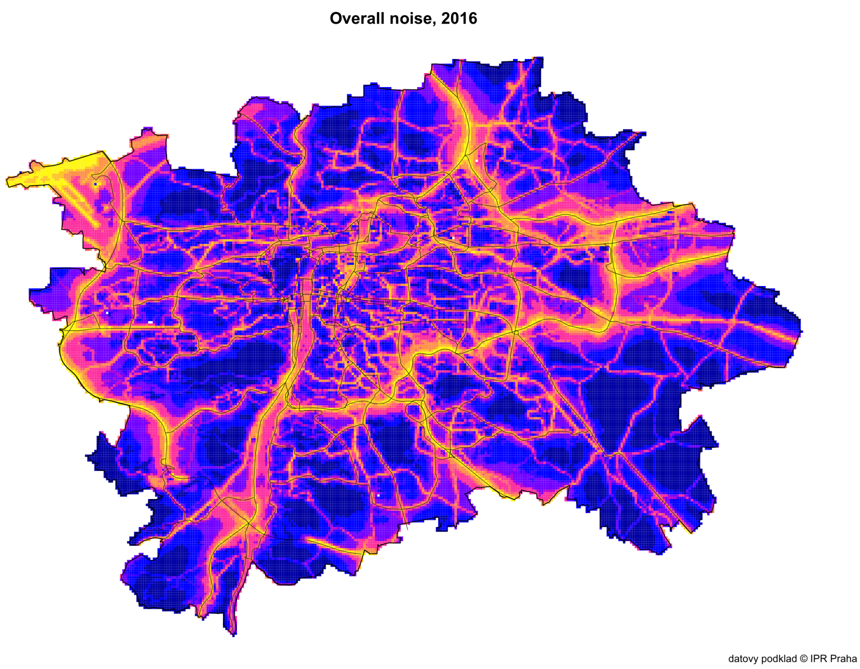

Figure 4.4.4: Noise levels in 2016, brighter colours refer to higher noise level

Additional data include demographic characteristics on the level of Elementary statistical units, public transit stations and stops, location of retail shops, public amenities such as public toilets and scenic vistas, gross floor areas of the building and estimated number of residents and jobs in each grid cell.

More information about these supplementary spatial datasets are provided in Appendix.

Real estate transaction prices

Two separate real estate transaction datasets are used, one for the cross-sectional analysis and the second one for the quasi-experiment. Both datasets are provided by Deloitte Real Estate Advisory Czech Republic together with Dataligence and contain all transactions of apartments in Prague registered by the Cadastral office which administers all real estate ownership transfers in the Czech Republic. The two datasets are very similar and the only differences are in time coverage and specific information about buyers. The time period of the first dataset for the cross-sectional analysis is from July 2016 to December 2019 and it contains in total approximately 60,000 observations. While observations for the whole year 2020 would be also available, specific circumstances of the covid pandemic might violate the assumption of a single housing market over time and therefore are not used in the analysis. The second dataset starts in 2014 and ends in December 2017. Six months period after the opening of the tunnel is dropped from the data as an adjustment period. That left one year and nine months of the data before and after the treatment. Both datasets are cleaned to contain only market-like transactions, excluding special cases such as subsidized sales of publicly owned apartments, property transfers within a family, ordered auctions and other non-standard transactions.

Each transaction is exactly localized with GPS coordinates, a day of processing at the cadastral office, size of an apartment, the real estate category (new development, buildings with brick load bearing structure, historic buildings and prefabricated buildings from 1960's to 1990's) and the sale category (first sale from a developer, resale between households).

Additional information about buyers are available in the cross-sectional data: whether buyer is a firm, individual or more individuals. If buyer is an individual or more individuals, an age category in 5-years bins is provided for each of them. For each person there is an indicator whether it is a Czech or former Czechoslovak citizen. Finally, there is an indicator if the property is bought jointly by a married couple.

Above is shown a plot of real estate apartment prices based on the cross-sectional data, and large green open areas. In red colours are plotted all grid cells that contain any residential use. Real estate prices are calculated for older properties and value for each grid cell is calculated as a mean of transactions if grid cell contains at least 15 entries, otherwise the value is a mean of 15 transactions in the closest proximity of the grid cell centroid. Green grid cells are the ones with at least 50% share of green open spaces.

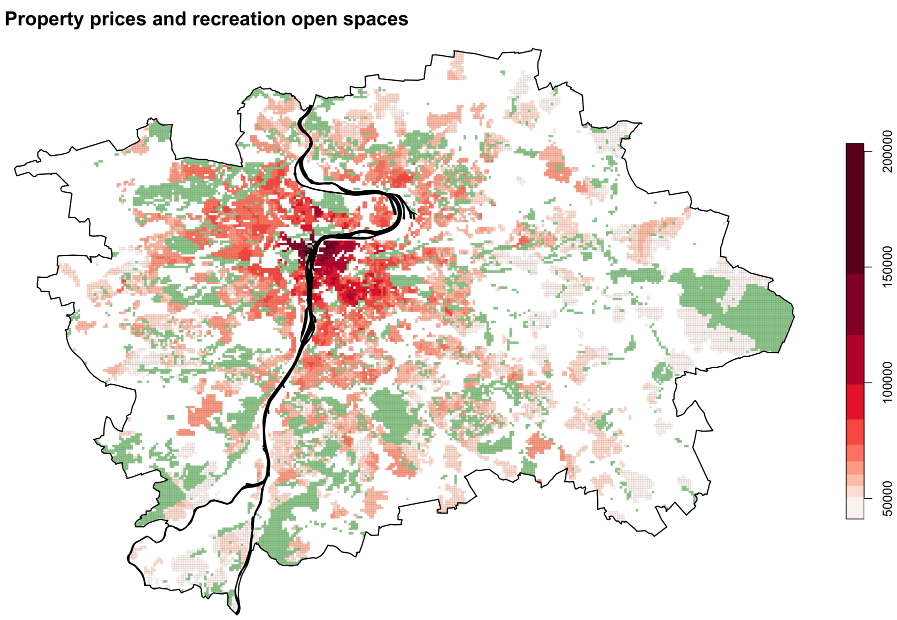

Figure 4.4.5: Apartment transaction prices and green open spaces

4.5 Estimates

In this section three sets of models are presented. The first are baseline models using cross-sectional variation in the data and as green spaces only those accessible within 600 meters from an apartment on a walkway network are used. The second set of models use also green spaces within 600 meters, but instead of relying on cross-sectional variation in noise, change in noise resulting from a quasi-natural experiment of diverting on-ground traffic into the underground highway bypass is used. The third approach exploits again cross-sectional data, but the accessibility and provision of open green areas is measured with a market potential-like variable which discounts more distant green spaces compared to closer ones.

Baseline estimates

The baseline models are all estimated according to the equation (4.3.1). The column (4) is the full model containing all terms in the equation while the columns (1) to (3) show results of simpler specifications with some variables and their interactions omitted.

The column (1) shows the most simple specification where apart of set of property-specific control variables logs of public and private (non-publicly accessible[102]) green spaces, their modelled quality are present. The results do have expected signs, but none of estimated coefficient is statistically significant on conventional levels. However, if quality is dropped from the model (see table

[102]These non-publicly accessible green open spaces contain only categories of parks, woods, park-woods, cemeteries, meadows and orchards

4.A.3 in Appendix), estimated elasticity of apartment prices with respect to open green spaces area is 1.8%. Alternative log-linear specification shows value of an additional hectare of green open spaces is 0.26% when overall provision of green spaces is low, but it declines sharply with overall size of green spaces. The result is not dissimilar in magnitudes from findings by Panduro et al. (2018), who find an additional hectare of parks in Copenhagen increases property values by 0.08%.

	(1)	(2)	(3)	(4)
log(green_public + 1)	0.0074	0.0070	−0.0056	-0.0262^{*}
	(0.0088)	(0.0088)	(0.0077)	(0.0118)
log(green_private + 1)	0.0196	0.0214	0.0168	0.0179
	(0.0183)	(0.0179)	(0.0191)	(0.0187)
log(quality_model)	0.0073	0.0068	0.0020	0.0159^{*}
	(0.0052)	(0.0053)	(0.0055)	(0.0071)
noise_apartment_location	−0.0011	−0.0012	$-0.0012^{\cdot}$	$-0.0011^{\cdot}$
	(0.0007)	(0.0007)	(0.0007)	(0.0006)
green_public_noise_estimated		0.0010	0.0001	$0.0031^{\cdot}$
		(0.0017)	(0.0015)	(0.0018)
gr_transit_n		0.0018	0.0031	−0.0034
		(0.0120)	(0.0125)	(0.0116)
hhi		0.0337	0.0036	0.8556^{*}
		(0.0378)	(0.0371)	(0.3685)
log(gr_per_res_job + 1)			-0.0104^{*}	-0.0112^{*}
			(0.0046)	(0.0046)
log(gr_per_resident + 1)			0.0235^{***}	0.0239^{***}
			(0.0063)	(0.0062)
log(green_public + 1):log(quality_model)				−0.0062
				(0.0038)
log(green_public + 1):hhi				0.0578
				(0.0407)
log(quality_model):hhi				−0.0114
				(0.0127)
green_public_noise_estimated:hhi				-0.0162^{**}
				(0.0053)
Apartment controls	✓	✓	✓	✓
Local area controls	✓	✓	✓	✓
Demographic controls	✓	✓	✓	✓
Month and cadaster FE	✓	✓	✓	✓
R^2	0.7971	0.7972	0.7981	0.7987
Adj. R^2	0.7964	0.7965	0.7974	0.7979
Num. obs.	55512	55512	55512	55512

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Buyer controls include type of sale (developer-household, household-household), dummy if buyer's age is known (unknown is for firms buying property) buyer's age and age squared, whether buyers are married and whether married and in age group 25 to 45.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within a grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor areas within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.5.1: Baseline estimation

In the columns (2) and (3), additional variables capturing characteristics of the green spaces are added. In the column (2) noise in green spaces, accessibility by rail transit and spacial concentration of green spaces are added. In the column (3), area of public green open spaces per number of jobs and residents within 600 meters are added on top of the previous set of variables. Extensions in the column (2) and column (3) however do not yield statistically significant results in the case of variables of interest.

However, two coefficients added in the column (3) worth attention. The positive estimate of log of green areas per resident suggests there is a crowding effect - increasing provision of green spaces per resident, all else equal, has a positive and statistically significant effect. This could be further interpreted in a way that the size of public green open spaces matters only jointly with local residential density as size of green space by itself does not have any effect. Unlike for green areas per resident, green areas per job have an opposite sign suggesting there is no crowding in green open spaces caused by local jobs' density. Conversely, more jobs per given area of green spaces have positive effect. Explanation could arise from the fact that there are different times in a day and in a week when workers and residents use green open spaces and as a result these two groups are not rivals in consumption of this public good. Alternatively, higher jobs densities might provide other form of quality which is not captured by local controls.

Interactions between target variables are finally added in the column (4). First, this specification shows the distribution of open green spaces matters when interacted with other variables. More continuous green spaces are on average valued more compared to scattered green space of equal combined size. The negative effect of noise also depends on the spatial concentration of green spaces. The more concentrated green spaces are, the higher is the negative discount for noise. Equivalently could be stated that continuous green spaces are more valuable if they do have low levels of noise. This result is sensible as higher noise on average is likely to be perceived more negatively if only few green areas are available compared to situation when multiple green areas are accessible and only some of them are likely to be affected by an excessive noise. If all accessible public green open areas were concentrated into one, increasing noise in such a green space by 1 dB would decrease property values by 1.6%. However, green open spaces are not so concentrated in Prague so this result is rather an extrapolation. More realistically, increasing the noise by 1 dB in open green areas that are more concentrated by 0.2 of the HHI index (the same size of green open space is divided into two separate parks instead of into three parks) decreases local property values by 0.32% (that is one fifth of the estimated interaction coefficient). Surprisingly, coefficient for green public spaces is negative and significant, but that would hold only for cases when HHI approaches zero as interaction of size with HHI is also included. Coefficients of green space per residents and workers are almost unchanged between the columns (3) and (4) showing the value of green open areas size is indeed contingent on local residential and jobs densities.

As an extension, the table (4.A.1) in Appendix reports further results where additional interaction variables were included. Key results remain essentially unchanged and the effect of noise in green spaces interacted with spaces' concentration even increases by almost one fifth in magnitude and t-value drops. Additional interactions of noise in green open spaces with their size and quality do not show heterogeneity along these dimensions. The model further suggests the crowding effect caused by number of residents per given area of green spaces decreases with available size of green spaces which follows intuition. The result is however significant at the 10% level only.

Quasi-experimental setting

The second set of models exploits a quasi-experiment of noise reduction caused by opening the new urban road tunnel bypass followed by a change of traffic volumes across the city. It has been shown in the previous part that significant changes in traffic volumes occurred across the city, although the biggest changes were recorded in the North-Western part of the city where the bypass was opened.

The models are estimated according to the equation (4.3.5) with all terms present in the models (4a) and (4b) in the table (4.5.2) which mimic the model specification shown in the column (4) of the Table (4.5.1). Some terms of equation (4.3.5) are omitted in the columns (2a) and (2b) which follow specification shown in the column (2) of the Table (4.5.1). The columns (2a) and (4a) use data from the whole city of Prague while the models shown in the columns (2b) and (4b) are based on a subsample of data with observations only from cadastral areas mostly affected by the infrastructure improvement.

The columns (2a) and (4a) show results consistent with the baseline model, although higher in magnitude. In the baseline model, the effect of noise in green open spaces depended on green spaces' concentration and the effect was approximately -1.2% for 1 dB of fully concentrated green areas. The model exploiting time variation in noise shows baseline drop in value by -2% for additional 1 dB (significant at 10% level) without being dependent on HHI concentration index. For the subsample of observations in areas along the new tunnel Blanka reported in the columns (2b) and (4b) the effect is even larger at -7.3% for additional 1 dB of noise increase and again not dependent on the green areas concentration.

Higher magnitudes of effects of noise in green open spaces compared to the baseline results could be caused by data-smoothing over time when constructing noise maps as was mentioned in the earlier section. It might be possible that the true changes in noise are not fully captured in the noise maps as the change is attenuated. If this is the case, then the noise change based on noise maps would be biased downward and when regressing housing prices on these downward-biased variables, resulting coefficients would be upward-biased.

Analysing the on-site recorded changes of noise before and after of the tunnel Blanka opening has shown that these are some 2.5 times higher in magnitudes compared to the modelled noise maps. This is suggestive evidence that the noise maps indeed do not fully capture the true change in noise levels. If this relation holds for the whole city of Prague, the overall estimates from the column (2a) and (4a) would drop to some -0.8% per 1 additional dB which is aligned with the results from the cross-sectional study, although still higher on average. After the above mentioned adjustment, results for the local data subset reported in the columns (2b) and (4b) would decrease to still high -2.9% per 1 additional dB of noise. This could be caused either by the heterogeneity of the effect or unobserved improvements to the green open spaces that took place during the construction of the tunnel bypass. The second reason seems to be possible as majority of green spaces directly affected by the construction itself were refurbished at the end of the construction project.

	(2a)	(4a)	(2b)	(4b)
after_intervention	0.37526^{***}	0.38630^{***}	0.40981^{***}	0.41711^{***}
	(0.03523)	(0.03236)	(0.03597)	(0.03260)
log(green_public + 1)	−0.00756	-0.03323^{*}	0.00406	−0.03793
	(0.01080)	(0.01491)	(0.02264)	(0.04308)
log(green_private + 1)	0.02160	0.01418	0.10929^{**}	0.09567^{***}
	(0.01325)	(0.01547)	(0.03356)	(0.02794)
noise_apartment_X_after_intervention	0.00279	0.00462	0.00294	−0.00012
	(0.00417)	(0.00432)	(0.01341)	(0.01095)
noise_apartment	0.00285	0.00255	−0.00167	0.00167
	(0.00277)	(0.00268)	(0.01317)	(0.01235)
green_public_noise_change_X_intervention	$-0.02240^{\cdot}$	$-0.01918^{\cdot}$	$-0.07328^{\cdot}$	−0.08356
	(0.01193)	(0.01128)	(0.03868)	(0.05176)
green_public_noise_change	0.02111^{**}	0.02156^{**}	0.07285^{*}	0.06545^{*}
	(0.00770)	(0.00773)	(0.02945)	(0.03029)
gr_transit_n	−0.01503	−0.01591	0.01217	0.02132
	(0.01470)	(0.01475)	(0.01665)	(0.01299)
hhi	0.03914	0.01407	0.09618	0.26405
	(0.04803)	(0.15250)	(0.10620)	(0.42660)
gr_quality_n		0.02231		$-0.37314^{\cdot}$
		(0.05112)		(0.21773)
log(gr_per_res_job + 1)		$-0.00880^{\cdot}$		−0.00041
		(0.00464)		(0.00331)
log(gr_per_resident + 1)		0.02416^{***}		0.05014^{***}
		(0.00722)		(0.01267)
log(green_public + 1):gr_quality_n		−0.01131		0.15460^{*}
		(0.02334)		(0.07765)
log(residents + 1):hhi		-0.03275^{**}		−0.00160
		(0.01128)		(0.05119)
log(green_public + 1):hhi		0.04950		−0.12591
		(0.05599)		(0.09824)
green_public_noise_change_X_intervention:hhi		−0.03032		0.08457
		(0.02778)		(0.11416)
Apartment controls	✓	✓	✓	✓
Local area controls	✓	✓	✓	✓
Demographic controls	✓	✓	✓	✓
Month and cadaster FE	✓	✓	✓	✓
R^2	0.56425	0.56509	0.45892	0.46112
Adj. R^2	0.56254	0.56332	0.45006	0.45177
Num. obs.	47215	47215	6394	6394
RMSE	0.40541	0.40504	0.59000	0.58908

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within a grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor areas within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.5.2: Models exploiting quasi-experimental change of noise

Despite some variation in magnitudes of estimated coefficients of interest, the models follow the same pattern and it might be concluded the quasi-experimental data variation is aligned with the results obtained from the cross-sectional analysis.

Alternative proximity-discounting models

In the third set of specifications, proximity to green spaces is modelled differently. Unlike assuming there is a threshold distance up to which green spaces are considered while green spaces beyond the threshold are ignored. In the next specification it is assumed the perceived value is exponentially decreasing with increasing distance from a place of residence to green open spaces.

To construct proximity-discounted size of open green spaces and other proximity-discounted variables, it is necessary first to estimate the distance-decay parameter ϕ from the equation (4.3.2). The estimates are shown below in the table (4.5.3). The model log-lin 1 uses 15 concentric rings of public spaces, each ring 100 meter wide ($\bar{N} = 15$), with green spaces entering in levels. The model log-lin 2 is similar, but uses only first six rings ($\bar{N} = 6$). The last model log-log uses 6 most proximate rings similarly to the model log-lin 2, but green areas size enters in natural logs. The results reported in the table show the distance-decay parameter ϕ has a value around -0.8 no matter which specification being used. The preferred value used later is -0.79 as log specifications are used throughout the analysis. With this distance decay parameter, the perceived value of green open size drops approximately to one half with each additional 100 meters of distance from a green open space.

	(log-lin 1)	(log-lin 2)	(log-log)
green_space_size	0.000003***	0.000003***	0.05283***
	(0.000001)	(0.000001)	(0.01745)
distance_decay	-0.85858^{***}	-0.80811^{***}	-0.78808^{***}
	(0.12791)	(0.13130)	(0.14577)
Num. obs.	62193	62193	62193

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Explained variable in all models is log of apartments' price. Standard errors are reported in parentheses. Controls include apartment size, distance from CBD and noise within a grid cell of apartment.

Table 4.5.3: Green space size distance decay factor

The last set of two models reported in the columns (1) and (2) of the table (4.5.4) is estimated according to the equations (4.3.3) and (4.3.4) and shows results using proximity-discounted variables which are labelled with *decay* in the table. First of all, based on the explanatory power of these alternative models, it might be concluded the model with proximity discounted variables of green spaces size and non-green spaces noise reported in the column (1) outperforms very slightly otherwise comparable baseline model reported in the column (4) of the table (4.5.1).

The results of both models in the columns (1) and (2) are similar and do not differ substantially from the baseline models. Regarding the variable of main interest, the effect of 1 additional dB of noise increase in green open spaces has again an effect of -1.2% when evaluated at HHI equal to 1 in the column (1) and the magnitude decreases to roughly one half when noise in

	(1)		(2)
log_green_public_decay	−0.01378	log_green_public_decay	0.07069
	(0.04445)		(0.05554)
gr_quality_n	0.01637	gr_quality_decay	0.01588
	(0.01794)		(0.01690)
non_green_noise_decay	−0.00309***	non_green_noise_decay	−0.00338**
	(0.00092)		(0.00114)
green_public_noise_estimated	0.00424*	green_public_noise_decay	0.00258$^{\cdot}$
	(0.00198)		(0.00136)
gr_transit_n	−0.00378	gr_transit_n	−0.00391
	(0.01144)		(0.01197)
hhi	1.05752**	hhi	0.59435*
	(0.33464)		(0.24465)
log(residents + 1)	0.00907*	log(residents + 1)	0.00945*
	(0.00354)		(0.00368)
log(gr_per_res_job + 1)	−0.01189**	log(gr_per_res_job + 1)	−0.01170**
	(0.00426)		(0.00380)
log(gr_per_resident + 1)	0.02391***	log(gr_per_resident + 1)	0.02314***
	(0.00599)		(0.00580)
log_green_public_decay:gr_quality_n	0.19908$^{\cdot}$	log_green_public_decay:gr_quality_decay	−0.15393$^{\cdot}$
	(0.11563)		(0.08422)
hhi:log(residents + 1)	−0.02079*	hhi:log(residents + 1)	−0.02479*
	(0.01056)		(0.01226)
log_green_public_decay:hhi	0.03641	log_green_public_decay:hhi	0.00133
	(0.09180)		(0.08886)
green_public_noise_estimated:hhi	−0.01600**	green_public_noise_decay:hhi	−0.00801*
	(0.00518)		(0.00388)
Apartment controls	✓	Apartment controls	✓
Local area controls	✓	Local area controls	✓
Demographic controls	✓	Demographic controls	✓
Month and cadaster FE	✓	Month and cadaster FE	✓
R^2	0.83715	R^2	0.83698
Adj. R^2	0.83654	Adj. R^2	0.83637
Num. obs.	55475	Num. obs.	55475
RMSE	0.19483	RMSE	0.19494

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$ $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor areas within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.5.4: Models with spatially-discounted variables

more distant green open spaces is discounted (column 2).

The results of proximity-discounted models follow a similar pattern to results shown in the baseline specification. It is however difficult to judge whether proximity-discounted models should be preferred to models with maximum threshold accessibility. In this paper the models using distance threshold are preferred for their simpler estimation not requiring to estimate the distance decay parameter in the first step.

4.6 Discussion and Conclusions

The results from both cross-sectional and quasi-experimental analyses confirm the negative effect of noise on the perceived value of open green spaces when accessible open green spaces are concentrated into a few units. A conservative interpretation of the results suggests a decrease in apartment value between 0.5% and 1.0% for each additional 1 dB of noise in open green areas accessible from the apartment, given the accessible open green space is highly spatially concentrated. Depending on the specification, the effect decreases when open green spaces are not concentrated into one large unit, and they are instead distributed into many separate green spaces. For instance, dividing one green space into two separate ones decreases the effect to one half. Splitting a green space into four would approximately decrease the magnitude of the effect by one fourth.

The effect is, however, quite sizeable, especially when compared to the ordinary noise depreciation caused by the noise present at the location of an apartment, which was estimated in the baseline models at approximately 0.1% per dB, that is at the lower bound of effects found in the literature. The results show that properties are not only affected directly by excessive noise in their immediate vicinity, but also indirectly by noise further away in recreation areas used by the residents of those properties.

The interaction term can be also interpreted conversely - all else being equal, a greater number of compact open green spaces are valued more when they have low levels of noise.

When interpreting the other results, it is worth mentioning that the size of open green spaces is particularly sensitive to the model specification. The size of green spaces by itself does not seem to be valuable, but it turns out that the relative provision of green spaces per resident has a relatively large positive effect.

As the majority of urban noise is caused by road traffic, the results have implications for transport planning and management. Considering the direct and indirect effects of noise on property values when planning major arterial roads within an urbanised area where open green areas are present, three general options arise: locate arterial roads along or inside open green spaces, navigate them through the built-up environment, or build them underground. If the indirect effect of noise via open green spaces is omitted, locating arterial roads along open green spaces would be preferred because a smaller number of buildings is affected by the increased noise. However, if the indirect effect is accounted for, locating arterial roads along open green spaces might not be optimal anymore. Although there would be larger overall disbenefits via the direct channel if a road is lined by buildings on both sides as both sides would be affected by higher levels of noise, on the other hand, unaffected open green spaces still provide amenity value for all properties in reasonable proximity. The overall effect is largely dependent on the size of affected open green spaces, marginal increase of noise in these open green spaces and the concentration of these spaces in affected areas.

The second policy implication concerns the currently frequently discussed policy of decreasing the speed limit in urban areas from 50 km/h to 30 km/h. Based on an analysis from Switzerland, Rossi et al. (2020) assumes that such a speed limit reduction would decrease noise levels by 3 dB. This potential noise reduction is also confirmed in other literature. For instance, in their literature review Desarnaulds et al. (2004) mention noise reduction ranging from 2 to 4 dB resulting from the speed limit adjustment. Depending on the evaluation of my model, the reduction in noise caused by a reduction of the speed limit could increase property values by some 0.5%. This could further foster existing arguments supporting such policies.

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4.A Appendix

Auxiliary models

	(1)	(2)
log(green_public + 1)	-0.0609	-0.0112
	(0.0809)	(0.0799)
log(green_private + 1)	0.0177	0.0182
	(0.0187)	(0.0188)
log(quality_model)	-0.0038	-0.0193
	(0.0565)	(0.0563)
noise_apartment_location	$-0.0012^{\cdot}$	$-0.0012^{\cdot}$
	(0.0006)	(0.0006)
green_public_noise_estimated	0.0026	0.0040
	(0.0034)	(0.0033)
gr_transit_n	-0.0029	-0.0011
	(0.0112)	(0.0112)
hhi	0.9568^{*}	1.0102^{*}
	(0.3965)	(0.4080)
log(gr_per_res_job + 1)	-0.0110^{*}	-0.0096^{*}
	(0.0046)	(0.0048)
log(gr_per_resident + 1)	0.0239^{***}	0.0414^{***}
	(0.0061)	(0.0106)
log(green_public + 1):log(quality_model)	-0.0055	-0.0032
	(0.0045)	(0.0053)
log(quality_model):hhi	-0.0115	-0.0148
	(0.0138)	(0.0153)
log(green_public + 1):hhi	0.0550	0.0669
	(0.0419)	(0.0420)
green_public_noise_estimated:hhi	-0.0177^{**}	-0.0190^{***}
	(0.0054)	(0.0055)
log(quality_model):green_public_noise_estimated	0.0003	0.0004
	(0.0008)	(0.0008)
log(green_public + 1):green_public_noise_estimated	0.0006	0.0000
	(0.0013)	(0.0013)
log(green_public + 1):log(gr_per_resident + 1)		$-0.0079^{\cdot}$
		(0.0041)
log(quality_model):log(gr_per_resident + 1)		0.0003
		(0.0021)
Apartment controls	✓	✓
Local area controls	✓	✓
Demographic controls	✓	✓
Month and cadaster FE	✓	✓
R^2	0.7987	0.7989
Adj. R^2	0.7979	0.7981
Num. obs.	55512	55512

$^{***}p < 0.001$; $^{**}p < 0.01$; $^{*}p < 0.05$; $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Buyer controls include type of sale (developer-household, household-household), dummy if buyer's age is known (unknown is for firms buying property) buyer's age and age squared, whether buyers are married and whether married and in age group 25 to 45.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within a grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor areas within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.A.1: Extended model within 600 meters

Initially, the effects of individual categories of green spaces as they are defined in the land use data were tested to define final set of green open spaces that are assumed to have positive amenity value.

For the later parts of the analysis, only the following seven types of open green spaces as defined in the land use map were included: parks, cemeteries, natural recreation, park-woods, woods, meadows and vineyards and orchards. Additionally, only publicly accessible fractions of these land uses were aggregated into 'green public' variable.

As it seen from the results below, increased provision of these land uses is typically associated with higher property prices, but most of the results are not statistically significantly different from zero. Sport sites and golf courses were not included as they are expected to provide different kind of amenity value.

	Log-log		Log-lin
log(1 + parks_public)	0.00749	parks_public	0.00224
	(0.00722)		(0.00180)
log(1 + park_like_sites_public)	−0.00746	park_like_sites_public	−0.00153*
	(0.00981)		(0.00069)
log(1 + cemeteries_public)	0.01354	cemeteries_public	0.00241
	(0.00844)		(0.00204)
log(1 + recreation_natural_public)	0.06868*	recreation_natural_public	0.04839*
	(0.02862)		(0.01924)
log(1 + park_woods_public)	−0.00099	park_woods_public	0.00090
	(0.00734)		(0.00173)
log(1 + woods_public)	0.00557	woods_public	0.00112
	(0.00733)		(0.00170)
log(1 + non_woods_public)	−0.00616	non_woods_public	−0.00213
	(0.00756)		(0.00139)
log(1 + surrounding_greenery_public)	−0.00276	surrounding_greenery_public	−0.00013
	(0.01225)		(0.00445)
log(1 + meadows_public)	0.02503*	meadows_public	0.00882*
	(0.01004)		(0.00349)
log(1 + gardens_houses_public)	−0.07432*	gardens_houses_public	−0.05818*
	(0.03344)		(0.02322)
log(1 + gardens_insistutions_public)	−0.00583	gardens_insistutions_public	−0.00096
	(0.00989)		(0.00153)
log(1 + wineyards_orchards_public)	0.00446	wineyards_orchards_public	0.00193
	(0.00939)		(0.00248)
log(1 + fields_public)	−0.00233	fields_public	0.00051
	(0.00782)		(0.00102)
log(1 + zoos_public)	−0.07672	zoos_public	−0.10986
	(0.11978)		(0.12577)
log(1 + sport_sites_public)	0.06609·	sport_sites_public	0.03324
	(0.03434)		(0.02167)
log(1 + golf_courses_public)	0.02264	golf_courses_public	0.00321
	(0.01626)		(0.00351)
log(1 + victory_gardens_public)	0.03344	victory_gardens_public	0.02572
	(0.08959)		(0.06265)
log(1 + wetlands_public)	−0.02920	wetlands_public	−0.00392
	(0.05197)		(0.01605)
log(1 + water_bodies_public)	−0.18331	water_bodies_public	−0.11863
	(0.27744)		(0.22409)
Apartment controls	✓	Apartment controls	✓
Buyer controls	✓	Buyer controls	✓
Local area controls	✓	Local area controls	✓
Demographic controls	✓	Demographic controls	✓
Month and cadaster FE	✓	Month and cadaster FE	✓
R^2	0.83616	R^2	0.83605
Adj. R^2	0.83552	Adj. R^2	0.83541
Num. obs.	55579	Num. obs.	55579
RMSE	0.19559	RMSE	0.19566

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$ $^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Explanatory variables in Log-log model are in logs of open green spaces in hectares plus 1, in the Log-lin model the explanatory variables are hectares of open spaces by types.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Buyer controls include type of sale (developer-household, household-household), dummy if buyer's age is known (unknown is for firms buying property) buyer's age and age squared, whether buyers are married and whether married and in age group 25 to 45.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within a grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor areas within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.A.2: Specification with separate open green space types

To decide about preferred functional form, log-log model and log-linear model with second-order polynomial terms were considered to test for non-constant marginal values of green open spaces. The log-liner model shows statistically significant squared term for public spaces with expected negative sign showing decreasing marginal value of additional hectare of public green spaces. It could be mentioned the maximum of the polynomial function is reached almost at the maximum values of public green spaces present in the data: When evaluated, the maximum is reached at 23 hectares while the maximum in the data is 60, but the third quartile is 15.5. For the purpose of the models' simplification and also imposing condition of non-negative marginal value of open space the Log-log specification is preferred and used in later models. The the table also shows the Log-log model very slightly outperforms Log-linear model in terms of the predictive power when same set of controls are used.

	Log-log
log(green_public + 1)	0.01822*
	(0.00784)
log(green_private + 1)	0.02266
	(0.01772)
Apartment controls	✓
Buyer controls	✓
Local area controls	✓
Demographic controls	✓
Month and cadaster FE	✓
R^2	0.83520
Adj. R^2	0.83461
Num. obs.	55579
RMSE	0.19613

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

	Log-lin
green_public	0.00261*
	(0.00115)
green_public_sqrd	−0.00005*
	(0.00002)
green_private	0.01319
	(0.01215)
green_private_sqrd	−0.00042
	(0.00085)
Apartment controls	✓
Buyer controls	✓
Local area controls	✓
Demographic controls	✓
Month and cadaster FE	✓
R^2	0.83517
Adj. R^2	0.83458
Num. obs.	55579
RMSE	0.19616

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$, $^{\cdot}p < 0.1$

Explained variable in both models is log of apartments' price. Heteroscedasticity-robust standard errors clustered at the cadastral area level are reported in parentheses.
Explanatory variables in Log-log model are in logs of open green spaces in hectares plus 1, in the Log-lin model the explanatory variables are hectares of open spaces.
Apartment controls include log of apartment size, property type (new, old), construction type (brick, prefabricated panels), building age, connection to gas and log of proximity to the CBD.
Buyer controls include type of sale (developer-household, household-household), dummy if buyer's age is known (unknown is for firms buying property) buyer's age and age squared, whether buyers are married and whether married and in age group 25 to 45.
Local area controls contain elevation, terrain slope, dummy for south slopes, log of residents plus 1 within a grid cell, log of jobs plus 1 within a grid cell, proximity to a metro or train station, proximity to a tram or bus stop, gross floor area within 250 meters radius and number of retail stores within 250 meters radius.
Demographic controls from 2011 Census on Elementary statistical unit level contain share of children below the age of 15, share of residents above the age of 65, share of college educated and share of unemployed.

Table 4.A.3: Specification with merged public and private green areas

Green open spaces details

In this section uneven provision of green open spaces types with respect to the distance to the CBD is shown. Variation of in local green open spaces provision will be discussed later. The distribution of green open spaces by type with respect to the proximity to the CBD[103] is shown on the following plot. The share of green open spaces is rising from almost zero in the city centre to approximately 60% 5 kilometres away from the CBD. Around this distance also peaks the share of non-agricultural open green spaces with an exception of large share of woods on the city outskirts. From the 5 kilometres

[103] Various locations in the central Prague have been selected as the CBD in literature, for instance Melichar and Kaprová (2013) use Old Town Hall tower, the statue of Saint Wenceslas on Wenceslas square in Melichar et al. (2009), Sklenářová (2015) approximates CBD as a minimum distance to either Saint Wenceslas statue, the Old Town Hall tower or Powder tower. Lastly Láznička (2016) assumes CBD to be located at the north-western edge of the Wenceslas square that I consider a reasonable approximation as it is very close to my previous empirical findings about Prague's CBD location based on monocentric city model assumption and exploiting land value gradient (Makovsky, 2018). Therefore I use north-western edge of the Wenceslas square as a CBD location in this chapter.

up to the city boundaries the share of agricultural land is increasing up to some 50%.

On the bottom side of the plot with vertical hatch are shown mostly privately accessible green open spaces with highest land-shares attributable to gardens of detached houses and gardens belonging to public institutions. Minor land-use shares of privately accessible open green amenities are attributed to zoos, victory gardens and sport sites.

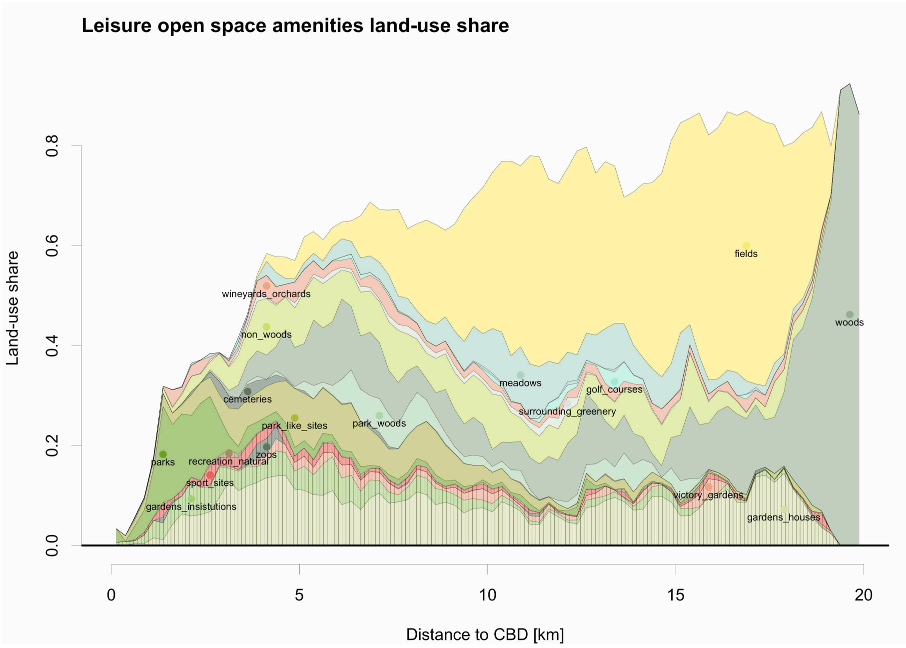

Figure 4.A.1: Open green spaces by type and proximity to the CBD

Due to the variation in types of green open spaces across the city, recreation potential proxied by quality of open spaces is used throughout the chapter. While some green open spaces could be very large, their recreation potential might be actually very low due to factors other than size.

As the distance to the CBD increases, typology of open green spaces changes. While the predominant type of publicly accessible green spaces up to 3 kilometres are urban parks, in the range from 3 to 10 kilometres significant share have park-like-sites that are commonly urban recreation sites with less intensive maintenance or green spaces between building in stand-alone urban form typology. Also from some 3 kilometres away from the CBD up to the city boundaries woods and wood-parks cover significant share of land.

The accessibility of open spaces is defined for all individual geometries and could be divided into three categories: public, semi-public and private. Publicly accessible areas are free to enter and typically there are no limitations in their usage. Semi-public areas often have some constrains in their usage, such as opening hours, but otherwise are freely opened to general public. Throughout the analysis these two types are in general called public green open spaces. Private areas are the remaining ones not generally accessible for public. While portions of each type of green open spaces can fall within any one of these three accessibility categories, most of the types tend to be either public or private as it is shown on the figure 4.A.2.

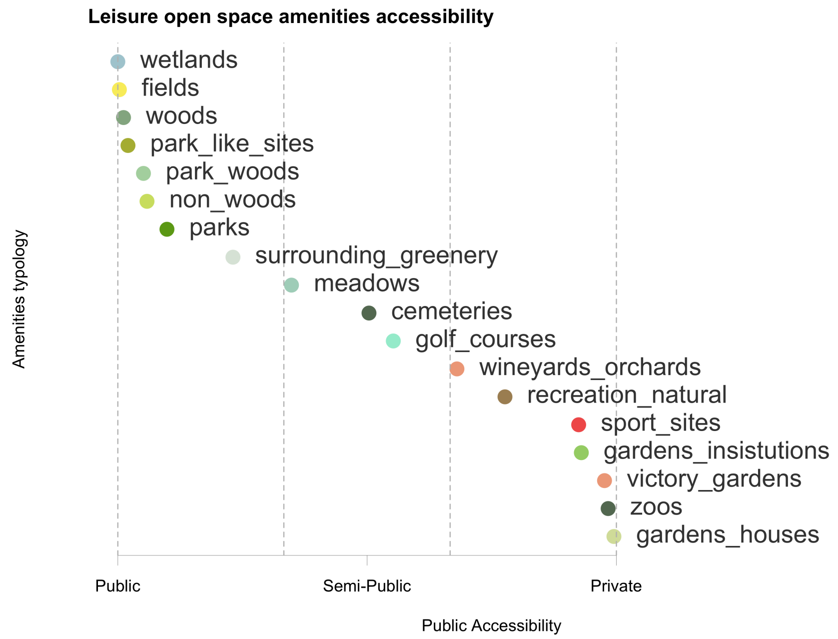

Figure 4.A.2: Open green space by accessibility

Large green open spaces are defined as areas formed by at least 2 rook-contiguous grid cells (sharing common edge) with more than 50% coverage of publicly accessible green areas each. These large green spaces are outlined with thick black line on the figure 4.A.3 below.

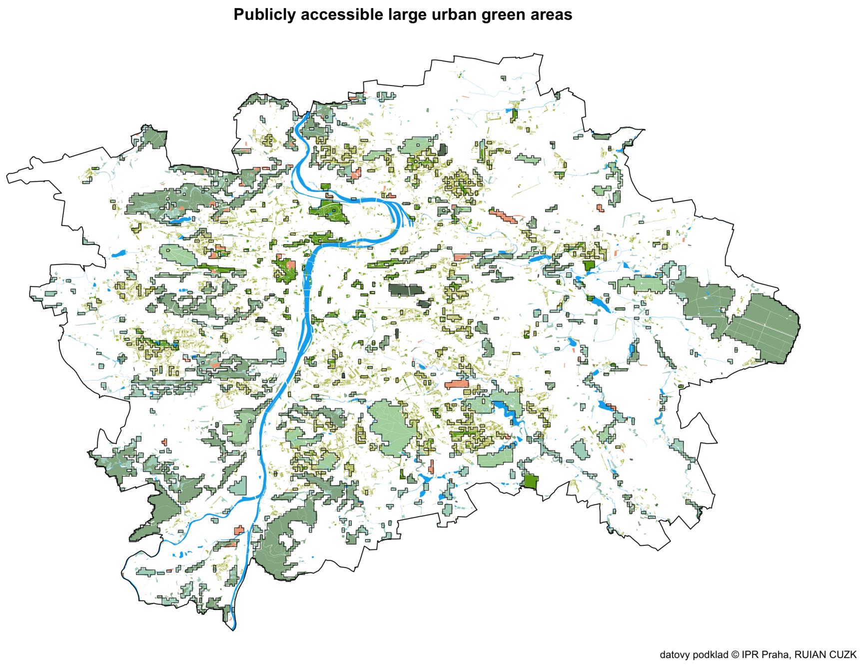

Figure 4.A.3: Large accessible urban green spaces without agricultural land

Other spatial data

Additional spatial data used are buildings' footprints and floor counts, dataset published at Prague's Geoportal. This dataset was used to calculate gross floor area (GFA) defined as number of floors above ground multiplied by area of building footprint. This variable is used as a control for structural density and as it is derived from building-level information, it provides sufficiently detailed local variation between grid cells. Buildings' footprint layer was also intersected with the land-use data to obtain buildings' functional use. Buildings' functional use was used to model detailed population and jobs distribution.

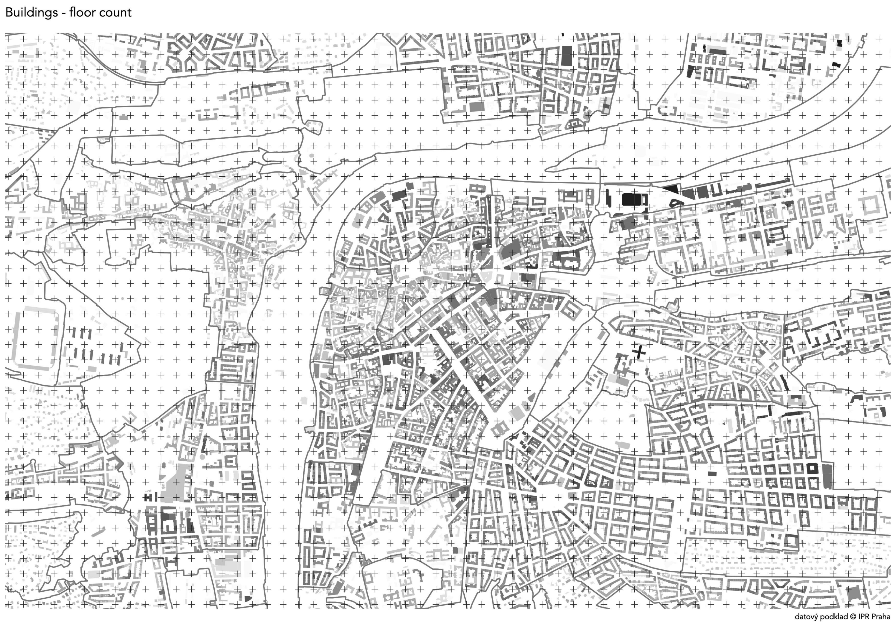

Figure 4.A.4: Floor count data, detail

The distribution of jobs is using parameters defined by the Prague Institute of Planning and development for the evaluation of the currently prepared spatial plan (IPR Praha, 2018). These parameters define average square meters of land area, buildings' gross floor area by functional use per one job and additionally number of jobs per unit of retail store located on ground floor. Therefore exploiting gross floor areas and functional use estimated previously with these parameters provide number of jobs per building that is later aggregated on a level of grid cells.

Number of residents is based on the 2011 population census aggregated at th level of 916 elementary statistical units. Inside each elementary statistical unit population is distributed proportionally into residential and residential-mixed buildings by their gross floor areas. From the individual-building population distribution is then aggregated population by grid cells. Distribution of jobs is based on method used by the Prague Institute of Planning and Development for planning purposes. Based on their analysis, they list mean gross floor areas or mean land areas per job for all land uses. Jobs' distribution by

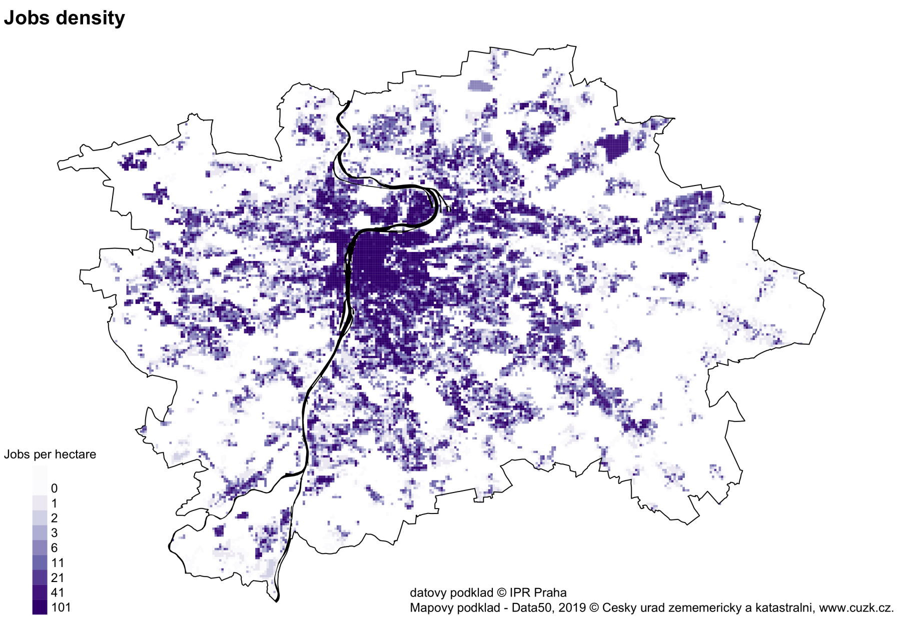

Figure 4.A.5: Jobs' density

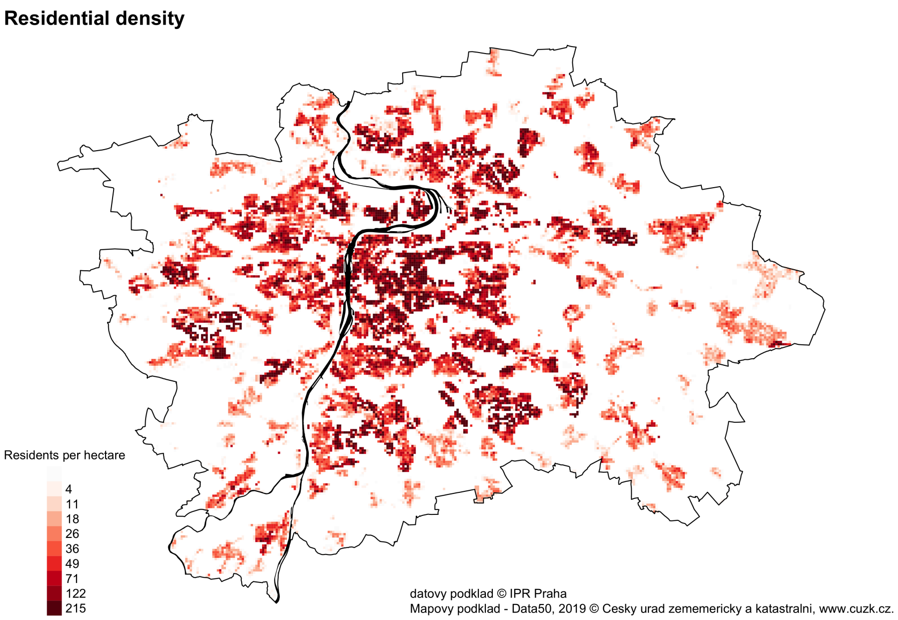

Figure 4.A.6: Residential density

buildings and plots of land is then again aggregated to the grid cells level.

Local transit accessibility is measured by euclidean distance to a nearest public transit stop and a station. These variables are derived from the spatial point data containing train stations, metro stations, tram stations and bus stops. These data are as of December 2019 and are used to create two variables: proximity to high capacity rail public transit (metro and train) and proximity to local public transit (tram and bus). In both cases minimum of the two variables is considered. The accessibility measure is then adjusted such that it is zero for distances beyond conventional walking distance 1000 meters for high capacity public transit and 600 meters for local transit, and within the accessibility threshold maximum walking distances are subtracted from the actual transit node proximity. Resulting accessibility variables are therefore ranging between -1000 (-600) and zero and are increasing with distance from the transit stop.

To control for potential effects of terrain slopes and orientation, dataset of 2-meters height contour lines is used to calculate slope orientation and slope steepness. Figure 4.A.7 shows in darker colours steeper slope. North, East, South and West are plotted in blue, green, red and magenta respectively

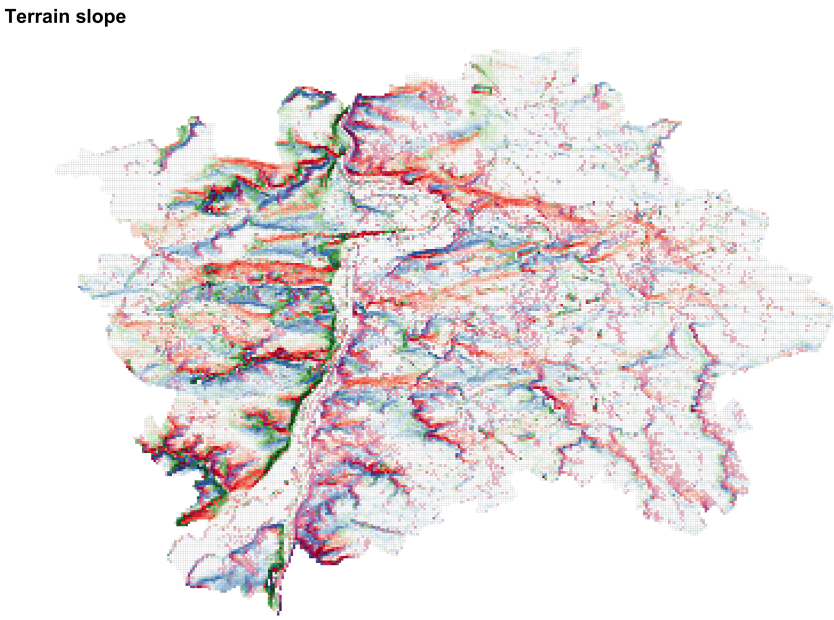

Figure 4.A.7: Terrain slope and orientation

Figure 4.A.8 shows some types of permeable land uses are not evenly distributed with respect to terrain slopes. This is most notable for fields, which are mostly located on flat land, and opposite to that woods are more likely to occupy the steepest slopes.

To measure local services provision, 2014 data of street-front retail stores are used. Number of retail stores is aggregated to grid cells.

Spatial data are supplemented with 2019 land values dataset issued as a Prague municipal ordinance for information purposes of average build-able land values. This dataset is a vector polygon layer that aggregates plots of similar expected values according to recorded transactions adjusted for site specifics.

Throughout the analysis it is assumed Prague fits well the concept of monocentric city. To support this assumption, several gradients with respect to the proximity to the CBD are showed below: jobs' density, residential density, structural density and apartment prices.

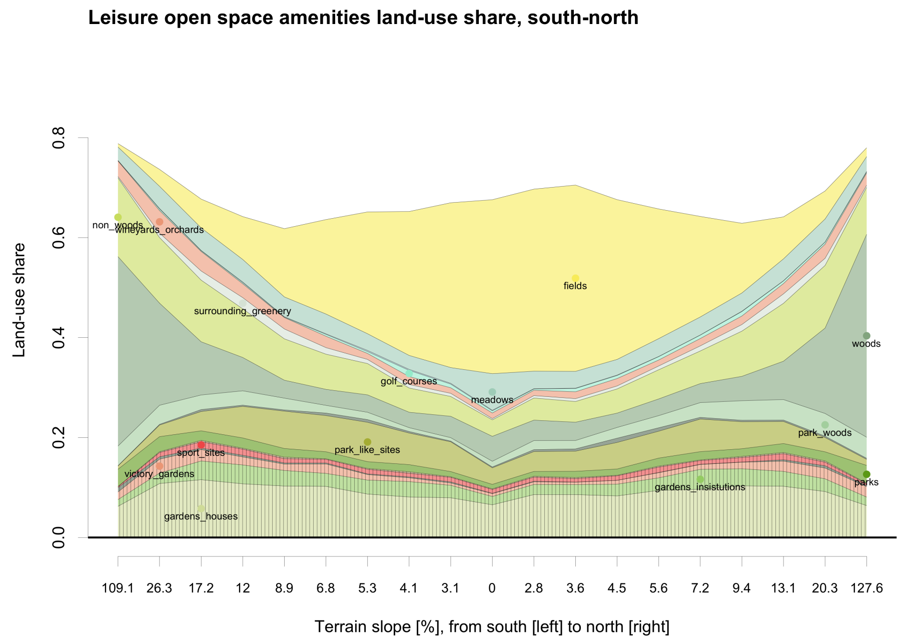

Figure 4.A.8: Land-use with respect to terrain slope and orientation

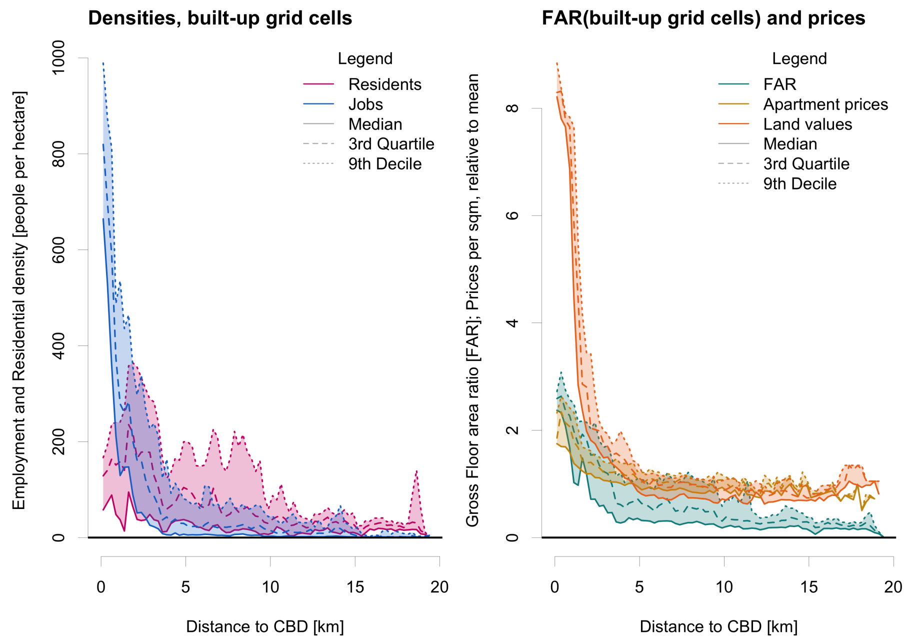

Figure 4.A.9: Gradients with respect to proximity to the CBD

Median, third quartile and ninth decile gradients with respect to the proximity to the CBD are plotted in full, dashed and dotted lines respectively. The observation of these gradients confirms the monocentric city concept is a good approximation for the city of Prague as jobs' density sharply decline with distance to the CBD. Residential density is on average low, but heterogeneous as up to 10 kilometres the ninth percentile spikes to 200 residents per hectare while median values are around one tenth of this value.

The right side of the plot shows much steeper land value gradient exceeding city-wide mean land value 8 times in the city centre. Median apartment price gradient is only two times higher in the city centre when compared to city-wide mean figure.

Data processing and analysis

Data manipulations and statistical analysis were done in R[104] (R Core Team, 2019). Data stored in MS Excel format were uploaded with the readxls package (Wickham and Bryan, 2019). For data cleaning, manipulation and aggregation dplyr and tidy packages were used (Wickham et al., 2019, Wickham and Henry, 2019). For processing string data package stringr was used (Wickham (2019)). Spatial data were uploaded, processed and plotted with rgdal, sp and sf packages (Bivand et al., 2019, Pebesma and Bivand, 2005, Pebesma, 2018). Robust standard errors were estimated with lmtest package (Zeileis and Hothorn, 2002) and fixed-effect models with clustered standard errors were estimated with plm package (Millo, 2017).

[104]Polygon grid, its intersection with noise, land-use and buildings dataset were prepared in QGIS3 software as well as some of map outputs

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5 Conclusions

In this thesis I have focused on two themes. First, to investigate areas in urban economics that have not been studied before or for which literature is still scarce. And second, to show how quantitative spatial models could be employed in a context with limited data and in particular for purposes of spatial and urban planning.

Contribution to the urban economics literature

Agglomeration economies are relatively well documented phenomenon. However, most of the evidence comes from developed countries with only a handful of estimates from developing countries. To my knowledge no research has been conducted in any formerly planned Eastern European country. Additionally, it is documented agglomeration economies, and knowledge spillovers in particular, dissipate rather quickly across space. There is however not enough evidence how rapidly agglomeration economies decline across space as spatially very disaggregated wage or productivity data are typically not available.

Due to the limitations of unobserved wage data on a fine geographical level, I use quantitative spatial model based on Ahlfeldt et al. (2015) to infer wages from detailed commuting patterns derived from individual-level 2011 Census data. These data allow me not only to infer wages at a fine geographical level comparable with census tracts, but also to infer wages for three groups of workers defined by their level of education.

Using wages inferred from the quantitative spatial model, I estimate urbanisation wage elasticity, which is elasticity of wages with respect to overall size of local labour market. To tackle the endogenous quantity of labour (Combes et al., 2010), a case when larger labour market could be a result of higher productivity and not vice versa, I instrument current labour size with gross floor areas of buildings built before 1919. This instrument is similar to a conventional lagged population, but unlike lagged population individual buildings are exactly geocoded that allows me to aggregate them into small geographical units for which lagged population would not be available.

First, I estimate urbanisation wage elasticity at the level of labour markets, which are defined as commuting areas using methodology based on OECD (2012). This allows me to compare my results with exiting literature in which metro-level estimates are more common. Preferred specification yields elasticity of 6.7%, slightly higher than 6% for the US by Ciccone and Hall (1996), 4.5% for European countries (Ciccone, 2002) and 4.6% for Spain (de la Roca and Puga, 2017). Results for workers with primary, secondary and tertiary education are 3.8% (not significant on conventional levels), 6.8% and 7.5% respectively. This pattern is qualitatively similar to results found by Ahlfeldt et al. (2021).

Second, exploiting geographical detail of inferred wages, I estimate time-distance decay of urbanisation economies. Estimated decay parameters are all close to -0.3 for a representative worker and for all groups of workers by their education. The estimate is also not far away from one reported by Ahlfeldt et al. (2015) who found -0.36 for Berlin. To my knowledge, urbanisation wage elasticity decay by education groups hasn't been studied before and it is a curious fact it does not change much for the three types of workers. While one might think the decay should be steeper for high educated as in their case knowledge spillovers play more important role, it might be also true this is compensated by the effect of thicker labour markets operating on a larger geographical scale. Possibly, agglomeration wage elasticity for high educated might show steeper decay with respect to workplaces of other high educated workers and not all workers. However, this remains for further research.

Spatial planning regulation is a widespread practice across developed countries. There are 89 types of local plans in the 32 OECD countries and almost nine out of ten of them are legally binding (OECD, 2017). Despite spatial planning is so common, there is relatively little evidence what are the effects of planning on real estate markets and social welfare. For the case of the US, Hsieh and Moretti (2019) estimated that stringent planning reduced economic growth by roughly one third over the past half century.

I conceptualise planning regulation with three separate channels: zoning of developable and undevelopable land, setting maximum allowed development density and stringency of building permit authorities which affects length and predictability of the construction permit process. As housing is durable and its supply could be expressed by the kinked supply curve (Glaeser and Gyourko, 2005), regulation should have different implications in places experiencing long-term steady growth and in places where demand for housing has declined from past maximum. While in case of the former planning constraints should be binding, they should not bind in the case of the later.

First, I show reduced-form evidence of negative effects of more constraining regulation on new construction. Employing boundary discontinuity design, I analyse effects of varying stringency of building permit authorities along their jurisdiction boundaries. Increasing stringency by 10% reduces supply of new detached houses by 0.6% and reduces size of apartment houses by some 3%. These results apply for all locations, not only for ones predicted by the kinked supply curve.

For the amount of developable land which is measured as planned gross floor areas relative to the existing stock, decreasing available developable capacities by 10% reduces construction of both detached and apartment buildings by 1%, but only in places where property prices are sufficiently high relative to construction costs that is consistent with the kinked supply curve concept. Lower construction as a result of more stringent regulation is consistent with existing literature (Quigley and Raphael, 2005; Saks, 2008) and similarly as Glaeser and Ward (2009) I haven't found price effect of regulation as neighbouring municipalities are good substitutes and regulation itself does not seem to create any amenity effect.

Second, to study effects of planning beyond housing markets, I built a quantitative spatial model based on Ahlfeldt et al. (2015); Heblich et al. (2020); Monte et al. (2018) with a novel realistic housing supply function which features the concept of kinked supply curve and the three channels of planning regulation. Then I calibrated the model using data from 1991 and 2011. In the next step I run counterfactual scenarios studying general equilibrium effects of relaxing some of the planning constraints.

From the calibrated model I calculated long-term housing supply price elasticities for each of more than 6,250 municipalities in the Czech Republic. Interquartile range of estimates ranges from 0.39 to 0.77 that is somewhat higher than estimates for Central Europe by Caldera and Johansson (2013) with 0.44 and 0.43 for Poland and Germany respectively, and 0.23 for Austria. I also do show that in many places low supply price elasticities are not driven by regulation, but rather by current position in the inelastic part of the kinked supply curve caused by past decline in demand.

In counterfactual scenarios I assume building permit authorities' stringency would be relaxed to the 20th percentile of the national distribution combined with either increasing amount of developable land uniformly by 50%, or with increasing permitted densities uniformly by 50%. Both of these two scenarios would increase households' welfare by almost 4%. Depending on a scenario, 1% to 1.7% of workers would migrate from rural areas to large cities and property prices would decline on average by roughly 8%. Households' welfare gain is quite similar to estimated 3.9% by Cheshire and Sheppard (2002) who however included small positive amenity effect of protecting open space and then assumed the regulation would be lifted altogether.

Open green spaces are important part of urban fabric. They provide ecosystem services and recreation amenities. Increasing size of green spaces in residential districts has become one of important goals of the modernist movement which crucially affected city planning in the second half of the 20th century. While planning was mostly concerned with sheer size of green spaces, their quality was neglected.

I focus on one dimension of green open spaces' quality - lack of noise. This could be also understood as a complementarity of two public goods - lack of noise and open green spaces provision. The main analysis exploits cross-sectional data and further evidence is based on a quasi-experiment of opening new tunnel system which diverted traffic from ground to underground leading to reduction of noise levels along the streets which experienced traffic decline.

Major problem of Prague open green spaces when it comes to estimating their value is their varying quality such as level of maintenance or equipment. This quality is not captured in any available dataset. For that reason I have utilised a framework of quantitative spatial model developed in Ahlfeldt et al. (2015). Unlike their model, instead of inferring wages from commuting, I infer quality of green open spaces from number of their visitors using results from a participatory GIS project by Pánek et al. (2021). While the data seem to be spatially skewed toward several locations of particular attention, resulting quality index seems promising despite its noisiness. When it is included in a hedonic pricing model it yields effects of similar magnitudes as effects of green space sizes. In more elaborate model, I find that increasing green space quality by 10% in places with smallest areas of green spaces increases property values by 0.16%.

The key results are effects of noise on open green amenities. The cross-sectional evidence shows negative effect for places where open green spaces are spatially concentrated. If all accessible green spaces were formed by two equally sized parks, then increase in noise by 1 dB would lower property values by 0.8%. In practice open green spaces are however more scattered, so the resulting effects are smaller in magnitudes. To compare, effects of road noise on property values have been estimated to be between 0.08% and 1.05% per dB (Nelson, 1982) and in my models they are reaching 0.11%.

Supportive evidence exploiting noise change resulting from the opening of the new tunnel system yielded an effect of 2% per 1 dB measured for the whole city and even 7% per 1 dB on a subsample of neighbourhoods most directly affected by the transport improvement, without being affected by spatial distribution of green spaces. The results are however likely upward-biased as noise maps which were used as a primary data source do not fully reflect real changes in noise. Comparison of on-site-measured noise levels and respective noise levels in noise maps have revealed the change in real noise is almost three times as large as in the noise maps. If the estimates are adjusted by this factor of 3, their magnitudes are comparable with the cross-sectional estimates.

Applications of quantitative spatial models in planning

Quantitative spatial models used in the three chapters show how this relatively new tool could be valuable for spatial and urban planning. First, in some cases these models could overcome a problem of missing data. Vorel (2015) lists availability of sufficiently detailed data as one of the main reasons why simulation modelling in spatial planning hasn't been so far adopted in the Czech Republic. Missing wage data is an example of notorious problem limiting economic analyses. However, this particular problem could be sufficiently tackled with the new class of quantitative spatial models as it is shown in the first chapter of this thesis. Although estimated wages are far from ideal, they still provide significant improvement over alternative approaches. Additionally, the ability to construct them for the whole country is also appealing.

Second, quantitative spatial models provide useful framework within which possible policies could be tested and effects could be analysed with full equilibrium adjustments including residents' migration, jobs' relocation, changes in productivity, changes in commuting patterns, adjustment of wages and rents or changes in local amenities. There are already many papers extending the basic framework with many amendments as it is reviewed for instance in Redding (2023). In the second chapter, I have focused on effects of spatial planning regulation and building permitting processes on spatial distribution of economic activity and simulated adjustment of the economy if these constraint were relaxed.

There are however many other potential policies that could be of interest to policy makers: for instance general equilibrium effects of transport improvements and subsequent relocation of jobs, residents and adjustments to demand for new construction. The models could be also used to test effects of transport policies such as congestion charging or city centre tolls on urban structure, in particular shift of demand between suburban and central locations. The list is not exhaustive and actually wide variety of potential policies could be tested using the framework.

The framework of quantitative spatial models could be also used in a less standard way, for instance as it is shown in the third chapter. In that case the model essentially uses the method of travel costs and infers unobserved quality of green open spaces from number of visitors and their expected residences.

Implications of the results for planning do range from large-scale country-level to very localised. To start with the broadest level, the first chapter shows evidence of sizeable agglomeration economies that are comparable to other developed countries. This fact should be taken into account whenever strategies and policies regarding regional development are considered. Supporting less developed and peripheral regions might have its benefits, but it must be acknowledged it has also its costs. Whoever would leave these regions for larger cities would be on average more productive in larger cities, contributing to the overall productivity gains of the whole country. These productivity losses should be therefore taken into account when assessing alternative policy options. The issue might become even more important in the future when workforce becomes on average more educated. As the first chapter has shown, agglomeration economies are more pronounced among high educated and therefore productivity difference between sparsely populated areas and large cities is considerably larger for them.

Current spatial planning system does not seem to be able successfully achieve some of its stated objectives. One such an instance is suburbanisation. OECD (2018) shows Czech Republic had the most suburbanising metro areas out of all OECD countries when measured by the change of population in core cities and suburban locations. Calculated housing supply price elasticities in the second chapter show common pattern across the country. Suburbs are more supply elastic compared to core cities. This shouldn't be surprising due to more available land. However, if actual policies want to promote more compact development, they need to create more favourable conditions for development in core cities compared to suburbs. That however does not seem to be the case. Descriptive data show there are on average higher appeal rates against decisions of building permit authorities (which are used as a proxy for local permitting stringency) in larger cities than in more remote areas. As it has been shown in the second chapter, uniform relaxation of planning regulation would trigger growth of large cities, however their suburban areas would grow larger as well. To control suburban growth, if desirable, further policies aiming at easing construction in core cities or somehow discouraging development in suburbs would be needed.

Modernist planning called for strict division of cities into zones dedicated for particular functions - residential, production or recreational. The post-modern or New urbanism planning conversely emphasize importance of urban mix-use and a concept of cities of short distances where all functions are easily accessible. While strict exclusion of all non-residential uses like retail, leisure or local services from residential zones in the modernist spirit seems unreasonable and its integration to residential neighbourhoods is welcome, other policies promoted by the new urbanism, for instance like general decentralisation of jobs, are questionable. For example the Prague Strategic Plan (Prague Institute of Planning and Development, 2016) vaguely promotes jobs decentralisation and strengthening of the polycentric city structure and it supports stronger emphasis on residential use in the city centre. However, as it has been shown in the first chapter, agglomeration economies are very strong locally and they dissipate sharply with distance. Therefore it is a result of these economic forces that jobs do cluster in city centres or in other accessible locations because they gain productivity advantage there. For instance trying to disperse traded services, such as consulting, finance, insurance or software engineering, by force could lead to loss of their competitiveness.

Major Czech cities and their metro areas have been experiencing growth and it is expected they will continue to grow in recent future. These cities are typically trying on one hand to balance sustainable growth combined with preventing suburbanisation, and on the other hand to protect urban green spaces and other undeveloped areas while maintaining developed densities at current levels. This does not provide much room for new construction. Undeveloped urban land is commonly assumed to be positive amenity. However, as the third chapter shows, this is not the whole story. Although sheer size of green open spaces in simple models seem to be valued, more elaborate models show it is contingent on other factors, such as perceived quality, provision of green spaces per resident, noise or spatial distribution of accessible green spaces. In some cases, even reduction of open green spaces and their development combined with improvement of the remaining ones could in overall bring higher perceived value. Although it seems noise negatively affects value of green open spaces only when they are concentrated, decrease in noise would likely increase value of green open spaces on average. This could be supportive argument for instance for currently ongoing protests for imposing Prague city-wide speed limit of 30km/h which would effectively decrease traffic noise levels and likely increase recreational value of open green spaces.

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