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Post-COVID Scenario Modelling

Technical Report
Full Report

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Post-COVID Scenario Modelling

Non-technical summary

Context

This report presents the post-COVID scenario modelling work from the UK2070 Futures team.

Aim of the modelling study

The modelling work aims to understand new ways in spatial planning to connect two national policy imperatives: first, to accelerate post-Covid recovery; second, to get the UK back on track with sustainable and vigorous long-term growth.

At the time of writing, the raging debates in the two respective policy arenas have yet to make real and substantive connections. Naturally, there is a commonly shared aspiration for both rapid recovery and sustainable growth. The question is whether the two efforts can join and pull together.

On the recovery front, government is rolling out of a successful mass vaccination programme whilst continuing its support for those who are hardest hit by the pandemic, largely in a firefighting mode (as it has to be). The Covid mitigation measures are about easing pain and returning life to normality. There has been little time to consider how the pandemic mitigation measures – costing over £400 billion thus far – would bridge onto a new sustainable growth pathway. There is a risk that the success of Covid mitigation could take the country back to some kind of 'normality' that was deemed by many to be unsustainable even pre-pandemic.

On the other hand, the need for a new plan regarding longer term growth is looming large, particularly so as the public is expecting to be back to normality soon. But since public finance is now under unprecedented strain, the scope for tax rises is looking limited at least in the foreseeable future, and foreign direct investment are targeting only a relatively small number of growth hotspots in the country, it is fair to question how, and at what pace, government can provide the major investments that are known to be required to deliver its policy objectives such as levelling-up, net zero carbon emission target and green growth. The UK2070 Commission report estimated pre-pandemic that to deliver the main objectives of levelling up would require £15 billion/an, and since the neediest areas have been hardest hit by Covid, the investment needs are likely to have risen.

It is in this context that the scenario modelling work reported here sets out to understand the capabilities and potential of spatial planning, i.e. policy and investment packages that aim to steer the geographic distribution of economic activities, jobs, housing and transport access across the UK to achieve long-term prosperity and wellbeing. The work demonstrates that spatial planning fills a critical gap among the current policies and investments. Its important role is especially accentuated by the increasingly polarised patterns of regional growth and decline in the UK post-Pandemic.

Specific objectives

The new scenario analyses presented in this report update the team's previous research for the UK2070 Commission. The specific objectives are to:

- Examine the trajectories of recovery under far more challenging economic conditions – the scenarios tested include possibilities of protracted low growth over many years (i.e. the 'L-shaped' developments), of regional polarisation and divergence (i.e. the 'K-shaped', implying worsening polarisation and divergence overtime) and a dynamic recovery that continuously builds its own steam (i.e. the '√-shaped' for all UK countries and regions)

- Investigate the policy implications of a real 'levelling-up' across the UK in terms of geographic distribution of economic activities, jobs, housing, population, skills and infrastructure, starting from the actual economic geography of today
- Test the longer term effects of local improvements that are currently being made in post-Lockdown recovery, especially how they splice into new policy and investment options that target UK-wide levelling up
- Test the effects of the interventions upon all urban and rural communities, not just national capitals and big cities, and
- Take account of potentially changing business practices and life-style preferences in the wake of the forced mass experiments of remote working and at-distance social interaction during the COVID-19 Pandemic.

In summary, the scenario modelling work aims to account for two considerations that are currently underplayed in existing policy narratives: first, levelling up has just got much harder post pandemic, and will need an even larger sum of investment than estimated pre-pandemic; secondly, the bulk of this investment is unlikely to come from raising further debt in public finance, at least in the foreseeable future. The overarching objective of the study is therefore to find a new path to sustainable levelling up that is built on the right fundamentals of investment, development and business operations, so that the levelling up process itself can generate and attract the investment required.

Use of a predictive model in scenario-based analysis

At the heart of the study is a computer-based UK2070 Futures model which predicts economic activities, trade, jobs, housing development, transport access, business behaviour and consumer choice as symbiotic phenomena at the resolution of local authority areas in the UK. The model is based on the team's LUISA modelling software (version 2.3) at the Martin Centre of Architectural and Urban Studies, Department of Architecture, University of Cambridge.

- In the model, the demands for jobs, housing and transport access are all inter-dependent. At any given time, the available supply restricts the level of demand, but over a decade or more, job locations, house-building and transport service provision can adapt to one another and respond to demand
- Businesses' and consumers' decisions to stay or move are predicted through the trade-offs they are expected to make based on prices, time constraints and slow-changing preferences, which are in turn influenced by supply constraints, demographics and lifestyles (this is defined as 'recursive spatial equilibrium')
- The model does not predict the precise behaviours of a given business or individual; instead, it predicts the patterns of their choices for types of jobs and consumers at the level of local authority areas – the law of large numbers and the use of the discrete choice method make the choice patterns at this level highly predictable, including any irrational elements
- Whilst fundamental human choices are shown to be very stable, the circumstances in which the choices are made can be highly volatile, especially post-Pandemic. To contain the effects of arising from the uncertainties, the model makes scenario dependent predictions for a wide spectrum of overall demographic and economic changes, and of alternative patterns of distribution of supply-side conditions.

Past modelling work of a similar kind shows that this modelling approach serves to fill a gap between established transport planning models (which tend to focus on geographical details of traffic but ignoring the long term adaptations in the economy and land use) and regional economic models (which are excellent in representing the economic and trade flows but tend to address few supply-side constraints especially housing and transport).

For this study, a similar gap appears to exist between National Transport Model (DfT, online resource) and the national scale economic models. The UK2070 Futures model aims to serve as a bridging model to consider the interdependency of productivity, jobs, housing and transport.

Scenario design

The new policy scenarios consider (1) the global context of population stabilisation, (2) the need for a big policy change to shake up lagging productivity woes, and (3) the extent to which a growth scenario can bootstrap, i.e. building its own sources of investment and growth momentum over time.

Pending global population stabilisation. The scenario design starts from the increasingly apparent, though rarely discussed trend of global population stabilisation: as urbanisation sweeps through the globe, the rates of population growth have been steadily reducing. In most developed countries, population is barely growing now and quite a few major economies have already seen their national population shrinking, like Japan and Germany. More countries are expected to join this list. In another generation, this stabilisation is expected to occur in countries currently undergoing rapid urbanisation – this has already been occurring in Latin America and China, and is expected to spread to the South Asia subcontinent, the Middle East and sub-Sahara Africa as these regions urbanise further.

This implies that we are witnessing the start of a new, urbanised world where improvements in environmental sustainability, wealth and quality of life have to be increasingly driven by a continued rise in productivity of each working adult. It is still possible for current growth hotspots to fuel their prosperity through attracting migrants from poorer, more disadvantaged places, but this is increasingly unpalatable and, in any case, skilled young adults will be in shorter and shorter supply at a global scale.

The need for a 'big jolt' to reset the lagging productivity trends. In terms of per worker productivity, the current trends in the UK do not bode well. Even the most prosperous parts of the UK have not seen any rise in average per worker productivity since 2007. This suggests a need for a big change in policy design in order to relaunch the UK onto a more productive and more sustainable growth trajectory.

Any kind of such a 'big jolt' will necessarily need funding and investment. To make a compelling case, the scenario design will have to consider:

- are the new interventions capable of starting small and drive a dynamic recovery that builds its own momentum over time?
- will the interventions benefit all regions and communities, and level up job opportunities, income and quality of life across the countries and regions?
- will the interventions improve the UK's natural environment and accelerate the achievement of its environmental protection, decarbonisation and green growth goals?

Definition of policy scenarios. As appropriate for a spatial planning study, the main policy scenarios discussed in this study are structured as a combination between (a) the overall levels of economic growth, and (b) the alternative orientations of regional and local growth strategies. Two levels of growth are assumed for the overall UK economy and population:

- a persistent **Low Growth** of GDP at 0.6% per year; this is a slightly lower rate than what Japan had achieved over 1997-2017, which was 0.77% per year on average
- a **Gradual Recovery** that starts with GDP growth at 0.1% per year for 2021-2026, steadily rising to 3.5% per year for 2066-2071 through continuously improving per worker productivity; this gives an annualised average of 2.35% over 2021-2071, and is slightly higher than what the US achieved during 1997-2017, which was 2.27% per year on average
- The UK's **total population** is assumed to grow at an average of 0.1% per year under the **Low Growth**, and 0.55% under the **Gradual Recovery**. By comparison, the long term annual population growth rates from the UK's Office of National Statistics 2018-based scenarios are: Principal Projection 0.28% per year, High Population 0.52% and Low Migration 0.14%. The number of full-time-equivalent workers is assumed to grow at the same rate as the population, which implies a gradual rise in the ages of workers in the labour force.

Table A. Annualised growth rate assumptions for GDP per worker, population, number of workers and overall GDP growth

Annualised growth rates 2020-2071	GDP / worker	Population & workers	Implied GDP growth	Growth in earnings per worker
Low Growth (as previously defined and applied for Scenario A and B below)	**0.5%**	**0.10%**	**0.60%**	**0.25%**
High Growth (defined for previous tests and not used in Scenarios A-D below)	**1.8%** (annualised constant rate)	**0.55%**	**2.35%** (annualised constant rate)	**0.9%** (annualised constant rate)
Gradual Recovery	**0.55%-2.95%** (with an overall average of **1.8%**)	**0.55%**	**1.1% - 3.50%** (with an annualised average of **2.35%** per year over 2020-2071)	**0.28%-1.48%** (with an overall average of **0.9%** per year)

Two distinct approaches to regional distribution of the growth are assumed in terms the number and skill levels of jobs:

- one being **Business-as-Usual** where the diverging growth trends in jobs in each local council area persist as observed over the period 1991-2019, and so do the diverging local skills and occupation profiles
- the other being a **Convergent Economy** which sees the rates of jobs growth across the nations and regions gradually converge towards the UK average, and at the same time, the national and regional average profiles of skills and occupations converge towards those of London and the Wider South East (WSE).

A matrix of the above sets of assumptions gives rise to four main policy scenarios:

- Gradual Recovery with Business-as-Usual leads to **Persistent Regional Imbalance (Scenario A)**
- Low Growth with Business-as-Usual leads to **Continued Regional Recession (Scenario B)**
- Low Growth with Convergent Economy leads to **Slow Levelling-Up (Scenario C)**
- Gradual Recovery with Convergent Economy leads to **Dynamic Recovery (Scenario D)**.

Table B Summary of four main post-COVID scenarios

Geographic spread	Rates of overall economic growth in the UK	
	Low Growth	Gradual Recovery
Business as Usual	**Scenario B** Continued Regional Recession	**Scenario A** Persistent Regional Imbalance
Convergent Economy	**Scenario C** Slow Levelling-up	**Scenario D** Dynamic Recovery

Within the above framework of the four main scenarios, further assumptions are made regarding housing growth and transport interventions.

The **housing growth assumptions** are made in terms of

- the high and low rates of growth in the total number of dwellings, which are respectively in line with the population growth at 0.1% and 0.55% per year, and
- the geographic distribution of housing growth, which in England follows the patterns observed since 2004, as reported in the MHCLG data on total net additional dwellings (MHCLG, 2019) with adjustment made to account for short term growth spurts in some local authorities that are not expected to continue. Similar assumptions are made by the study team in Wales, Scotland and Northern Ireland based on the geographic patterns of population growth. In contrast to official house-building targets, this assumption reflects the lower actual delivery of housing per year in a number of local authorities in London and WSE, and the higher delivery in the English Midlands and beyond – in other words, the housing growth assumptions are made with a more realistic rates of housing delivery in the future in areas that have already shown signs of strain and backlog.

The **transport assumptions** distinguish the low growth and business-as-usual scenarios from a productivity-driven, dynamic recovery scenario:

- For Scenarios A (Persistent Regional Imbalance), B (Persistent Regional Imbalance) and C (Slow Levelling-Up), it is assumed that corresponding transport investments would be made, which keeps the door-to-door travel time for people and goods unchanged from today: under the Low Growth scenarios B and C the funds for transport investments would be very limited and the traffic flow volumes would also be little changed, and under the higher growth Scenario A, the increased road capacities would be taken up by increased traffic, and the catchment of stations on fast public transport services would expand in line with the increase of transit speeds
- For Scenario D (Dynamic Recovery), it is assumed that a significantly more ambitious additional transport improvement programme would be implemented when such funds become available as the economy grows.

Note that due to the long time span of the scenarios, it is impractical to make the transport assumptions in terms of specific projects of network or service improvements. Instead, the transport assumptions are made in terms of average travel times and generalised costs for those travelling within each local authority area or between each pair of the areas.

For Scenarios A, B and C, the travel times and generalised costs remain identical to those in the Base Year (i.e. 2018).

For Scenario D, the transport improvements are assumed to be in line with the overarching dynamic recovery assumptions, and consist of the following two categories:

- During 2021-2031 and before major infrastructure projects (such as HS2) come into full service, transport improvements will be implemented through a carefully designed package of transport, land use and urban design readjustments to improve local and regional travel, business access, air quality and decarbonisation. Such improvements would reduce door to door journey times and service quality such that during each year of the decade, the effective economic density (as defined by DfT's wider transport impact guidance in its webTAG documentation) of each region would increase by an annual average of 0.5%; and
- From 2031 onwards, it is assumed that a pipeline of major transport infrastructure projects will gradually reduce the travel times between the core of the regional cities through the most appropriate means of transport, such that by 2071, the fastest door-to-door business travel times among all such regional cities will be at or below 1 hour 45 minutes (which is the time currently taken between central London and all main centres of innovation in the Wider South East). These improvements build on the capabilities of a fully integrated multimodal transport system with rail, road and air modes all playing a part. Given the necessary lead time for this investment, Scenario D assumes that the interregional travel times will only start to reduce from the late 2020s i.e. when the HS2 services and low carbon road and air modes become available for commercial use. For an example of travel to Manchester, see Figures A and B below.

For each scenario the spatial equilibrium model predicts travel demand within and between the local authority areas which are used to work out the specific network and service improvements required for a given point in time in the future (see below under 'Findings'). This is a novel way of using the predictive model – the conventional way is to ask DfT and local transport planning authorities for their specifications, and that is infeasible given the timescale to 2070.

Findings from scenario tests

The main finding from the scenario tests is that new, feasible pathways to sustainable and vigorous long term growth do exist, but this would need to involve a geographic reconfiguration of the patterns of growth in jobs and housing plus coordinated transport investment. In other words, a radical new approach to spatial planning would hold the key to such growth pathways.

Out of a large number of alternative options considered, this report is focused on four distinct spatial planning scenarios that demonstrate that the differences in policy outcomes between them could imply making or breaking the UK. The central idea that emerges from the scenario work is that a regional reconfiguration of jobs, housing and transport, making use of the essential endowment and resources already present in the countries and regions, would not only increase average per person productivity, but also establish new engines of growth and prosperity outside London and the Wider South East.

The findings suggest that this big policy jolt purely on the basis of large scale capital investment in infrastructure alone will not be sufficient. Continued low interest rates may allow to investment in highly productive ventures but alone it would not result in the required growth in productivity. This report therefore examines how areas can raise productivity faster and spread this growth momentum across all countries and regions in the UK. This requires spatial planning drawing upon past experience of what has made areas prosperous.

Figure A Business travelling by fastest means: 2021

Figure B Business travelling by fastest means: by 2071

A comparison among the four main scenarios demonstrates that:

- Irrespective of the underlying rate of economic growth being low or high, a continuation of the current patterns of diverging economic fortunes would result in two distinct realms of regional change that are effectively separated by the Watford Gap: the growth dynamics of London, the wider South East and to some extent the South West would be so different from those for the rest of England and the devolved countries that the two realms may just well be considered as two different nations – this is particularly apparent under Scenario A)
- Under low rates of economic growth, the progress of levelling-up would prove slow and inconsequential (as shown under Scenarios B and C)
- The differences in policy outcomes between them would effectively imply making or breaking the UK's overall growth prospects: London and the South account for half of the UK's economic output, and if this is to be the only area that grows in the future, the hard work of delivering this growth would achieve half of the potential the UK has
- Only with progressively raised per person productivity under Scenario D (i.e. "Dynamic Recovery") could the UK consider an effective convergent regional growth agenda, and a gradual rebalancing between capabilities to deliver housing growth and jobs under this growth scenario could reap significant productivity, social and environmental benefits. This dynamic building of the growth momentum not only generates its own funding streams through raised per worker productivity, but also helps to inspire confidence through the accumulation of initial successes.

The differences in productivity growth that arise from the readjustments to the spatial layout of growth and transport connections, when assessed with HM Treasury and DfT agglomeration elasticities, show the potential to increase longer term average per person productivity by 1.7% per year for the UK as a whole, and more than 3% per year for knowledge-based sectors. This contribution through spatial planning, when coordinated with a forward-looking future jobs programme and wider policies, could thus raise UK's GDP growth from well below 1% today to more than 3% in the longer term.

The central message is that a regional reconfiguration of jobs, housing and transport, making use of the essential endowment and resources already present in the countries and regions, would not only increase average per person productivity, but also establish new engines of growth and prosperity outside London and the Wider South East. A scaling up of productivity in the currently low productivity areas (which covers three quarters of the population) directly contributes to the overall levels of productivity in the UK; the expanded economic mass will also provide opportunities to extend innovation through a richer and more diverse eco-system and more attraction to external direct investment. The significance of those programmes would ultimately determine the overall potential for the UK's environmental sustainability, wealth and quality of life, and whether the UK's constituent parts could prosper together or diverge in their separate ways.

Additionally, the scenario predictions reported here, particularly those regarding the demand for housing and transport, would help work out the precise specifications of local as well as national investments that collectively achieve the 'big jolt'. Such specifications at the individual site and project level are best worked in a rolling programme: the effects of the initial investments should be assessed against the long term benchmarks in the scenario predictions so that specifications and timescales can be adapted to what is feasible. This rolling programme would seem the most effective for managing the inherent uncertainties going forward.

Post-COVID Scenario Modelling

Main Report

1. Introduction

This report presents the post-COVID scenario modelling work from the UK2070 Futures team. This follows the report on the original UK2070 Futures work published earlier (Jin, Denman and Wan, 2019).

1.1 Aim of the modelling study

The modelling work aims to understand new ways in spatial planning to connect two national policy imperatives: first, to accelerate post-Covid recovery; second, to get the UK back on track with sustainable and vigorous long-term growth.

At the time of writing, the raging debates in the two respective policy arenas have yet to make real and substantive connections. Naturally, there is a commonly shared aspiration for both rapid recovery and sustainable growth. The question is whether the two efforts can join and pull together.

On the recovery front, government is rolling out of a successful mass vaccination programme whilst continuing its support for those who are hardest hit by the pandemic, largely in a firefighting mode (as it has to be). The Covid mitigation measures are about easing pain and returning life to normality. There has been little time to consider how the pandemic mitigation measures – costing over £400 billion thus far – would bridge onto a new sustainable growth pathway. There is a risk that the success of Covid mitigation could take the country back to some kind of ‘normality’ that was deemed by many to be unsustainable even pre-pandemic.

On the other hand, the need for a new plan regarding longer term growth is looming large, particularly so as the public is expecting to be back to normality soon. But since public finance is now under unprecedented strain, the scope for tax rises is looking limited at least in the foreseeable future, and foreign direct investment are targeting only a relatively small number of growth hotspots in the country, it is fair to question how, and at what pace, government can provide the major investments that are known to be required to deliver its policy objectives such as levelling-up, net zero carbon emission target and green growth. The UK2070 Commission report estimated pre-pandemic that to deliver the main objectives of levelling up would require £[250] billion, and since the neediest areas have been hardest hit by Covid, the investment needs are likely to have risen.

It is in this context that the scenario modelling work reported here sets out to understand the capabilities and potential of spatial planning, i.e. policy and investment packages that aim to steer the geographic distribution of economic activities, jobs, housing and transport access across the UK to achieve long-term prosperity and wellbeing. The work demonstrates that spatial planning fills a critical gap among the current policies and investments. Its important role is especially accentuated by the increasingly polarised patterns of regional growth and decline in the UK post-Pandemic.

1.2 Specific objectives

The new scenario analyses presented in this report update the team's previous research for the UK2070 Commission. The specific objectives are to:

- Examine the trajectories of recovery under far more challenging economic conditions – the scenarios tested include possibilities of protracted low growth over many years (i.e. the 'L-shaped' developments), of regional polarisation and divergence (i.e. the 'K-shaped', implying worsening polarisation and divergence overtime) and a dynamic recovery that continuously builds its own steam (i.e. the '√-shaped' for all UK countries and regions)
- Investigate the policy implications of a real 'levelling-up' across the UK in terms of geographic distribution of economic activities, jobs, housing, population, skills and infrastructure, starting from the actual economic geography of today
- Test the longer term effects of local improvements that are currently being made in post-Lockdown recovery, especially how they splice into new policy and investment options that target UK-wide levelling up
- Test the effects of the interventions upon all urban and rural communities, not just national capitals and big cities, and
- Take account of potentially changing business practices and life-style preferences in the wake of the forced mass experiments of remote working and at-distance social interaction during the COVID-19 Pandemic.

In summary, the scenario modelling work aims to account for two considerations that are currently underplayed in existing policy narratives: first, levelling up has just got much harder post pandemic, and will need an even larger sum of investment than estimated pre-pandemic; secondly, the bulk of this investment is unlikely to come from raising further debt in public finance, at least in the foreseeable future. The overarching objective of the study is therefore to find a new path to sustainable levelling up that is built on the right fundamentals of investment, development and business operations, so that the levelling up process itself can generate and attract the investment required.

1.3 Structure of this report

Chapter 2 below summarises the modelling methodology. This is followed by a presentation of the design of the post-Covid scenarios in Chapter 3, findings from the scenario tests in Chapter 4, and conclusions in Chapter 5. The algorithms and key equations are presented in a Model Appendix.

In spite of all the uncertainties, if one stands back and looks beyond the immediate event horizons, there are still many longer term, steady trends which are continuing to shape in a fundamental way the growth and development in the UK's constituent countries and regions. The scenarios in this study are designed in such a way to help us work out what national, regional and local scale interventions would be required and how to package coherent programmes of action. In essence, this is a proactive approach to exploring the future by design it (Batty, 2018)

The scenario design starts from the emerging trend of global population stabilisation: as urbanisation sweeps through the globe, the rates of population growth have reduced markedly. For instance, Vollset et al (2020) have identified these scenarios across 195 countries and territories after considering fertility, mortality and migration factors; similarly the UN Habitat would foresee a long term stabilisation of the global population as its median projection to 2100 (2019; see Figure 1). In a generation, this stabilisation is expected to occur in countries currently undergoing rapid urbanisation, just like what has already happened to a large number of urbanised nations including the UK. This means, increasingly, improvements in environmental sustainability, wealth and quality of life will have to be driven by a continued rise in per person productivity, or through attracting migrants from poorer, more disadvantaged countries and such regions within each country.

The current trends in productivity in the UK (and a large number of OECD countries) do not bode well. Even the most prosperous parts of the UK have not seen any rise in average per person productivity since 2007. This means that a big jolt in policy interventions may be needed to relaunch the UK onto a sustainable growth trajectory.

This follow-up report has therefore sought to update the earlier scenario design work in this context. In the first instance, the following four groups of issues have been recognised as having emerged since the previous UK2070 Futures scenario tests:

1) **The risk of far more challenging economic conditions post the pandemic than were assumed previously**. The UK faces real prospects of economic recession, a slow and protracted recovery process and potentially low rates of economic growth for many years. Under such situations, the productivity gap between rich and poor regions would widen, which creates an even more challenging context to stabilise and improve the regional economies, especially outside London and the Wider South East (WSE). The scenarios need to build from this harsher reality. They must also respect the logic of innovation and growth, building from the ground up (for discussions on how innovation and productivity growth actually occur, see Sainsbury, 2020)

2) **Need to investigate what the policy of 'levelling-up' means in terms of real physical and economic geography**. Since the original UK2070 Futures scenarios which were reported in the UK2070 Commission reports last year, the UK government has come out strongly in favour of a broad goal for 'levelling-up' the UK. The need remains to consider what the 'levelling up' means if it is to be translated into effective policy (e.g. for the geographic distribution of economic activities, jobs, housing, population, skills, and how all this distribution is to be supported by transport and telecommunications). Scenarios are a good way to spell out these in real geography for discussion and debate.

3) **The need to build and enhance resilience of at a local level**. The previous scenarios were at the time focused on the national capitals and main regional cities as the drivers of growth. Post pandemic, regional and local resilience has become a central concern in the process of recovery, not only for public health and social care, but also for building back local trade and services to enable the main cities to have the necessary local eco-systems supporting innovation and growth, to ensure the benefit of investments in recovery reaching out to all communities, and to dovetail efforts of recovery and levelling-up.

4) **Changing practices for work and leisure**. The unprecedented Lockdown has provided opportunities for businesses, local communities and government to experience en masse tele-working, distance learning, remote shopping and procurement, and online social interactions. The rapid advancement of online technology and business models would mean hybrid physical-virtual interaction would seep more deeply into many more realms of business and social life. This may pose a different set of conditions for achieving urban agglomeration which has proven vital in fostering innovation and growth since the Industrial Revolution.

Two long standing issues are also cogent to this discussion:

5) **A greater emphasis on per person productivity growth would be required**. In 1900, the UK had the second highest per capita GDP (behind Switzerland), and since WWII, the US, Germany, Canada, Japan and France have caught up with the UK, and the UK now has one of the lowest per capita GDP in G7 (see Figure 2). Given that the main drivers for growth in the longer term are likely to further shift to per person productivity rather than population growth, raising productivity is becoming a critical issue of the UK's future prosperity. This should also take into account of the specific structures and patterns of disparity in regional productivity in the UK (see Martin et al, 2019).

6) Connected to the above, **much of the UK also has a skills gap** (see UK2070 Commission, 2020). England, for example, has one of the largest proportions of low-skilled young workers among advanced economies (OECD, 2016). Furthermore, the skills profiles of young English workers are no better than older employees, which implies that the skills problem is to persist, if unaddressed.

1.4 Design of the post-COVID Scenarios

The overarching principle for the previous UK2070 Futures scenarios has been to adopt a wide though realistic range of possible growth rates and geographic patterns of distribution; this provides the users of the research with the scope to interpolate the reported scenario test results. It would seem that this principle remains valid, but the numerical range of the growth rates and geographic patterns of distribution would need to be reviewed.
This means that tor overall UK economic growth, we will continue to define a lower and an upper bound for economic growth scenarios, but a constant rate of high growth is no longer appropriate because of the need for the UK to recover gradually. Instead, the lower and upper bound should be defined thus:

- **Low Growth** should cover the lowest possible rates of population and productivity growth that could materialise.
- Instead of a constant high growth upper bound, it would seem that a trajectory of a **Gradual Recovery** would be more appropriate, gradual building up the rates of growth.

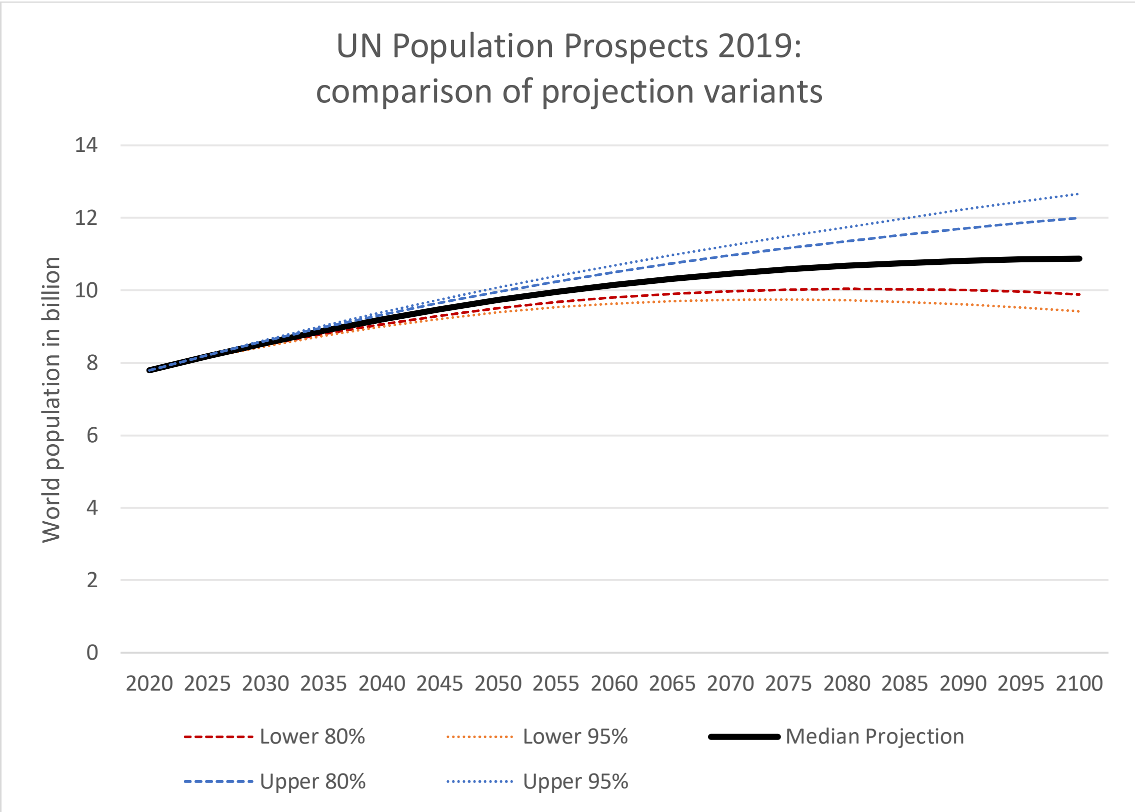

FIGURE 1 WORLD POPULATION PROSPECTS 2019: THE GLOBAL POPULATION SIZE IS EXPECTED TO STABILISE IN THE NEXT FEW DECADES

Source of data: UN Habitat (2019).

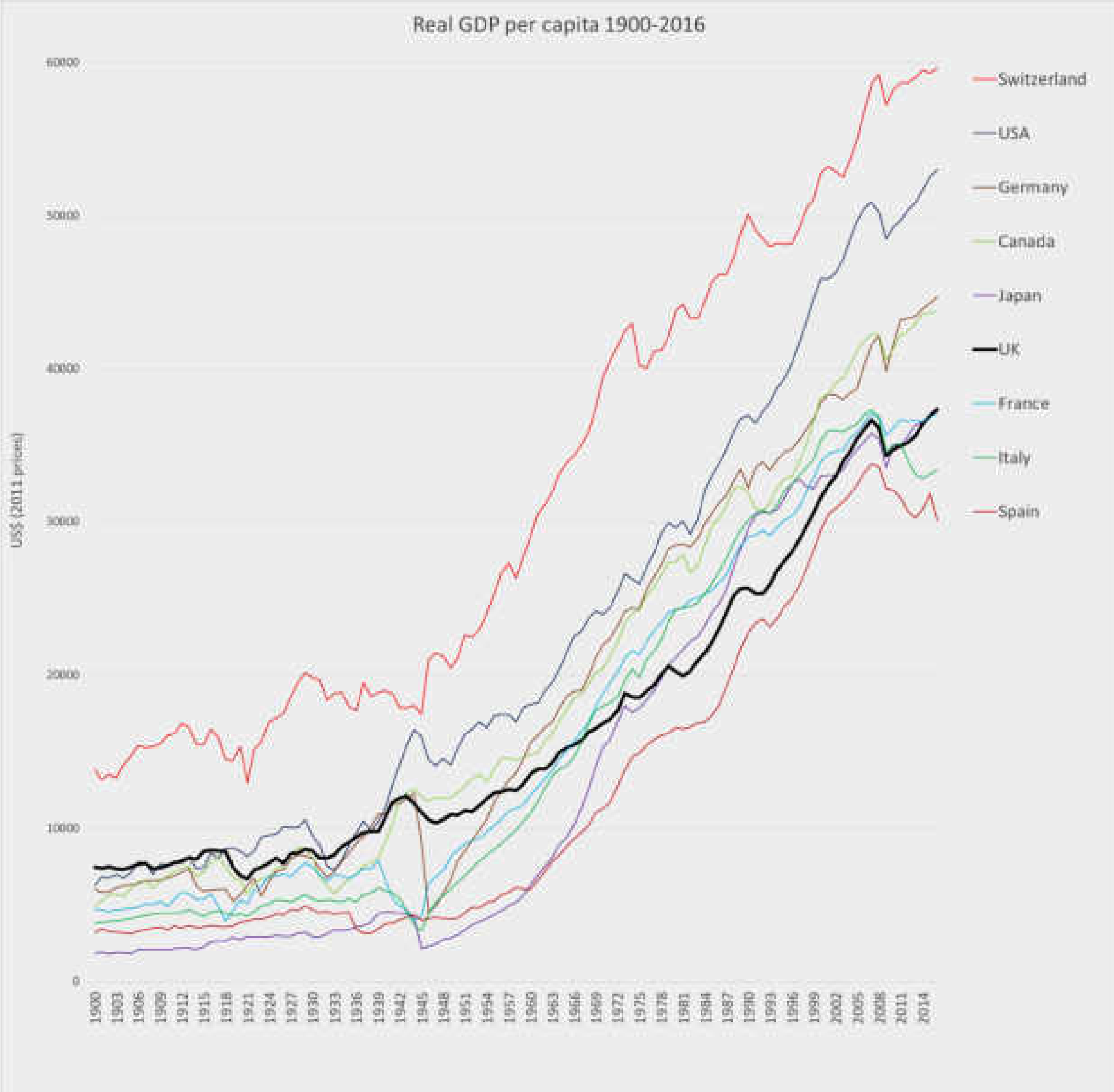

Figure 2 **An international comparison of the growth in GDP per capita: Is it a pure coincidence that Switzerland, the US, Germany, Canada and Japan all have multiple growth centres, whilst the UK, France, Italy and Spain have increasingly focused on one?**
Source of data: Maddison Project (2018).

For geographic spread of economic activities, a base case that represent minimal policy change would still be needed (as this could be a real possibility!), and the alternative reconfiguration of future growth would need to take account in more depth of the aspirations of levelling up goals, i.e.:

- **Business-as-Usual** where the growth trends in each local council area persist as observed over the period 1991-2019.
- **Convergent Economy** that sees the rates of jobs growth across the nations and regions gradually converge towards the UK average, and at the same time, the national and regional average profiles of productivity, skills and occupations converging towards those of London and the Wider South East (WSE) from now through 2071.

The combination of the above assumptions leads to four scenarios that are then tested in the UK2070 Futures Model for the UK – the four scenarios A to D are summarised in Table 1 below.

TABLE 1 SUMMARY OF FOUR POST-COVID SCENARIOS

Geographic spread	Rates of overall economic growth in the UK	
	Low Growth	Gradual Recovery
Business as Usual	**Scenario B** Continued Regional Recession	**Scenario A** Persistent Regional Imbalance
Convergent Economy	**Scenario C** Slow Levelling-up	**Scenario D** Dynamic Recovery

This report presents the post-COVID scenario modelling work from the UK2070 Futures team. Mainstream economics has failed to incorporate key global trends especially in demography. Financial markets and policymakers are unprepared for such developments.

At the end of the second world war, the country's innovators had an easier time of it, because the constraining hierarchies were broken. "Japan today isn't broken in that way, but everyone understands that it cannot just be left as it is," he says.

The national budget should be allocated more to education and research. "Only few percent can change the future." (page 321) According to his calculation, moving only few percent of the budget from social warfare to such investment can support many talented researchers and increase the county's growth potential.

As you know, Japan is super aging country, young people need to support the lives of too many elderly people by paying taxes and pension premiums in spite of the inconvenient truth they probably can't get the same benefit when they get old. Japanese people in the mid-20s and younger are called さとり世代(Satori Sedai), meaning generation who tend to lack ambition and desire.

How we can make innovation and update society using new technologies such as data, AI, or Robotics is the key to generate great values(page 57-58,380)

Shin Nihon AI x Japan's revitalization and human resource development in the data era
Kazuto Ataka, Newspicks 安宅和人　シン・ニホン AI×データ時代における日本の再生と人材育成
NewsPicks パブリッシング (February 20, 2020)
https://www.hitachi.com/rev/archive/2021/r2021_01/issues/index.html

Yes, the movie is where the inspiration came from. It is a space where people can enjoy lives that are vibrant and culturally active while also experiencing the area's natural beauty. When I spoke to people about the idea, I found more agreement than I had imagined and that led me to think about it more seriously.

When I started investigating how it could be put into practice, however, we learned that, in broad terms, the sort of places that are suffering advanced depopulation while also retaining their forests and other natural features faced two serious challenges. The first is the very high per capita cost of infrastructure, meaning the cost of maintaining the social infrastructure of roads, water, sewage, electricity, gas, healthcare, firefighting, waste disposal, and so on. The number of local authorities in Japan as of the end of 2019 was 1,741, of which several hundred run up annual costs of one million yen or more per resident, and in some cases significantly higher. As the majority of this funding is raised from urban residents, these spaces face a structural problem whereby their very existence is threatened should the burden prove too much for these urban areas to support.

The second problem is that rural areas lack the attractive power to counteract the convenience and enjoyment provided by cities. The consequence of this is a talent drain. It was evident to me that this was resulting in a two-fold vicious circle that was accelerating decline. These are deeply rooted problems and not something that can change quickly. Recognizing that a movement lasting 200 years or more would be needed to achieve genuine sustainability, we set to work with the aim of establishing an initial model.

2. Use of a predictive model

This chapter sets out the intellectual context through a review of the directly relevant literature on the predictive spatial modelling at a national scale. At the heart of the study is a computer-based UK2070 Futures model which predicts economic activities, trade, jobs, housing development, transport access, business behaviour and consumer choice as symbiotic phenomena at the resolution of local authority areas in the UK. The model is based on the team's LUISA modelling software (version 2.3) at the Martin Centre of Architectural and Urban Studies, Department of Architecture, University of Cambridge.

2.1 Theoretical premises of the model

The theoretical premise of this predictive model is that:

(1) the demands for jobs, housing and transport access are all inter-dependent. At any given time, the available supply restricts the level of demand, but over a decade or more, job locations, house-building and transport service provision can adapt to one another and respond to demand

(2) Businesses' and consumers' decisions to stay or move are predicted through the trade-offs they are expected to make based on prices, time constraints and slow-changing preferences, which are in turn influenced by supply constraints, demographics and lifestyles. The computational process that resolve the myriad of choices is defined as 'recursive spatial equilibrium' (see Section 2.2 below).

(3) The model does not predict the precise behaviours of a given business or individual; instead, it predicts the patterns of their choices for types of jobs and consumers at the level of local authority areas – the law of large numbers and the use of the discrete choice method (See review by McFadden, 2000) make the choice patterns at this level highly predictable, including any irrational elements (see Ariely, 2008; Kahneman, 2011).

(4) Whilst fundamental human choices are shown to be very stable, the circumstances in which the choices are made can be highly volatile, especially post-Pandemic. To contain the effects of arising from the uncertainties, the model makes scenario dependent predictions for a wide spectrum of overall demographic and economic changes, and of alternative patterns of distribution of supply-side conditions. The scenario input assumptions include constraints for the supply of jobs, housing and transport, as well as the long-term demographic evolution and lifestyle changes.

Since the theoretical model has been programmed as a computer software (LUISA version 2.3) by the study team, there is no physical limit as to how many scenarios are tested – in fact, this means that the scenarios can be tested systematically in lab conditions to measure the influences of the circumstances by scenario.

The mathematical structure of the model was first reported by Jin, Echenique and Hargreaves (2013). The model appendix of this report provides the equations of the model that were used for the scenario tests. The empirical model has been calibrated for the Census years 2001 and 2011 and then run to 2018 for validation, following a rigorous model validation methodology that is reported in Wan and Jin (2017).

The application of this UK-wide model was first carried out for a series of city region scale tests for Cambridgeshire and Peterborough, prior to the UK2070 Futures study. The results of that work was used in the Cambridgeshire and Peterborough Independent Economic Review to consider the implications of both:

(1) alternative distributions of employment growth on housing and transport, and

(2) alternative housing buildout rates, housing distribution and configuration of transport services on longer term employment and economic growth, environmental sustainability and quality of life

The model findings and there have been reported by CPIER (2018). The CPIER modelling work has shown that this modelling approach serves to fill a gap between established transport planning models (which tend to focus on geographical details of traffic but treating demand generation largely determined outside the model) and regional economic models (which are excellent in representing the economic and trade flows but tend to address few supply-side constraints especially housing and transport).

For this study, a similar gap appears to exist between National Transport Model (DfT, online resource) and the national scale economic models. The UK2070 Futures model aims to serve as a bridge model to consider the interdependency of productivity, jobs, housing and transport, and explore a diverse range of scenarios to identify pathways to achieve a sustainable job/housing balance.

2.2 Current theories and models for land use, built form and transport modelling

It is useful to contrast the user needs with what is already well understood in the modelling literature regarding the state of the art in land use, built form and transport modelling. This is particularly the case given that the fields of urban modelling have sprung from many disciplines and they are still evolving, exploiting the emerging data sources (Batty, 2009).
Given their traditional emphasis on land use and transport planning questions, the main urban models in policy use since Lowry (1964) are built on spatial interaction models (Wilson, 1967; Batty, 1976).

Effective and practical models have been created for assessing urban development and transport options at detailed geographic scales through a close integration of the spatial interaction model with random utility theory (McFadden, 1974), national/regional input-output tables (Leontief, 1986), land use planning and floorspace stock market models (Echenique, Crowther and Lindsay, 1969; Echenique, 2004), transport demand modelling (Domencich and McFadden, 1975; Ben-Akiva and Lerman, 1978; Daly and Zachary, 1978), road traffic assignment (Sheffi, 1985), GIS and web services (Batty, 2010). Their strengths lie with explicit incorporation of planning and infrastructure constraints and incorporation of policy inputs over explicit time horizons.

A second strand of models investigate general equilibrium of the spatial economy. The relationships between the economy, activity location and broadly defined transport costs have been under intense research since the pioneer work of the New Economic Geography (Fujita, 1989; Krugman, 1991; Venables, 1996; Fujita, Krugman and Venables, 1999) and of spatial general equilibrium models (Anas & Kim, 1996; Bröcker, 1996; Oosterhaven, Knaap, Ruijgrok and Tavasszy, 2001; Anas & Liu, 2007; Ivanova and Tavasszy, 2007).

These models are focused on the effects of spatial costs to producers and consumers whilst giving a fuller representation to product varieties and economies of scale, thus accounting for urban agglomeration and productivity effects which are the raison d'etre of the expansion and densification of cities. Significant progress has been made in empirical calibration of model parameters and elasticities (see e.g. Redding and Venables, 2004; Rice Venables and Patacchini, 2006; Graham and Kim, 2008; Redding, 2010). Growth, trade, transport and location are endogenously and mutually determined at spatial equilibrium. Although in theory they can incorporate an explicit time dimension, existing spatial equilibrium models, in their published form at least, tend to focus only on the end state rather than specific temporal trajectories.

A third strand of models are focused on urban dynamics, which are either represented in aggregate (Forrester, 1969; Allen, 1997; Wilson, 2000) or at a micro level through cellular automata, agent-based models and other forms of micro-simulation (Chapin and Weiss, 1968; Ingram, Kain and Ginn, 1972; Clarke, 1996; Batty, 2005). The micro-level dynamic models have been developed for land use activities (Waddell, 2002; UrbanSim, 2011) and traffic flows (Nagel, Beckman and Barrett, 1999). They offer insights into complex interactions between agents, particularly in property development and traffic management. They also introduce physical inertia in a much bigger way than the above two strands. However, so far they are predominantly used for investigating mechanisms and system-level emergence of microscopic interactions rather than policy analysis (Batty, 2009).

For a practical policy analyst, a city is clearly an amalgam reflecting all those revealed by the above paradigms: growth, trade, transport and location are mutually dependent; timing and growth trajectories are cogent to policy needs; urban dynamics is what every day of his/her job entails. It is clear that the needs of policy analysis will be better served if the above three traditions are brought closer together: both general equilibrium and Lowry-type spatial interaction models can and should absorb more insights from urban dynamics; A recursive use of static spatial equilibrium models over successive policy horizons may fall short of dynamic general equilibrium modelling, but it is a realistic way for producing policy analysis with transparency and short turnaround time.

For academic modellers, linking theoretically rigorous models of spatial interaction, general equilibrium and sectoral dynamic models may be an attractive way to break down hefty data and methodological challenges of dynamic urban system modelling. Several modelling research teams have sought to integrate the equilibrium and dynamic aspects of urban land use, built form and transport modelling, with Wegener (2001)'s IRPUD model focusing on differentiating the different activity dynamics in cities, Anas and Liu (2007)'s RELU-TRAN model on producing a rigorous general equilibrium among the activity distributions, Waddell (2002) and Waddell's UrbanSim (2011) work on microscopic simulation of household level dynamics of location and Jin, Echenique and Hargreaves (2013)'s LUISA model on connecting spatial equilibrium modelling with periodic, recursive dynamics.

Only very rarely have such models been applied to the investigation of air pollutant emissions in depth – notable examples are Echenique et al (2012)'s use of a precursor of the LASER3.0 model for four city regions in England, and Ustaoglu et al (2018) linking urban land use change with emission projections and air quality in a project under the Irish EPA which considered development in the Dublin area in modelling future NECD scenarios for Eire – The authors uses a land use and transport model MOLAND modelling to examine three land-use scenarios (dispersed, compact and public transit investment), and the resulting changes in air pollution emissions are included in a Cost-Benefit Analysis (CBA) to justify the investment of rail transport infrastructure provision and policy changes on land development processes.

DfT's National Trip End Model (NTEM; see DfT, 2018) presents base year (2011) employment, population and trip origins and destinations (or productions-attractions) data, and forecasts the growth in trip origin-destinations (or productions-attractions) up to 2051 for use in transport modelling at the national, regional and local levels. The forecasts take into account national projections of population, employment, housing, car ownership and the number of trip made ('trip rates') per person. Like all model results, the NTEM forecasts are subject to uncertainty, especially when disaggregated to local zones or travel modes. Nevertheless, in areas that are experiencing or expected to experience radical land use, built form or transport changes, the level of uncertainties of future changes could often be high.

The National Transport Model (NTM) is one systematic user of the NTEM data and forecasts. The NTM has been used to systematically compare alternative national-scale transport interventions, and/or widely-applied local transport policies across the national scale. These policy, investment and regulatory measures are examined against a range of scenarios taking into account major factors affecting future patterns of travel. Road traffic forecasts on the strategic road network have been made using the NTM.

To an extent the NTM has considered the interactions among some of the main drivers, such as between trip ends (which are derived from NTEM baseline projections), travel demand and traffic congestion effects at the national and sub-national scale. However, it is not the aim of the NTM to cover transport and traffic responses at a spatially detailed level for purposes such as assessing local air quality effects. The NTM Implementation Report (Atkins, 2018) states that at the core of the NTM there is a transport demand model which 'operates at an aggregate level of spatial detail with an innovative structure of distance bands to incorporate additional geography and reflect the various travel options available. A high level of segmentation is included within the model to reflect different travellers' propensity to use alternative modes and travel different distances for different journey purposes. The model 'produces trip length and mode choice profiles which match well with observed data' for national, strategic policy purposes. In other words, such national level modelling provides broad trend analyses which do not currently consider radically different development options of jobs or house-building. For long term, strategic scenarios, there is a need to connect transport demand and supply modelling with wider spatial economic and land use modelling.

2.3 Model calibration, verification, validation and corroboration

For concepts of model calibration, verification validation and corroboration, the classical definition of these terms is followed as defined by Batty (1976) in order to maintain the level of rigour required for land use, built form and transport modelling work. Whilst model calibration is the process of defining and estimating the model parameters and coefficients, model verification is to check the model is capable of reproducing the results that are implied by the model calibration process. Model validation, in a strict sense, requires the model to predict observations that have not been previously used for model calibration. For the LUISA series of models, we follow the more rigorous procedure of calibrating model for an initial year (in our case, 2011) and then require the model to predict a new year's observations (in our case, 2016 and 2018). Model corroboration is done through comparing predictions from models that follow separate and distinct methods to see if the predictions are comparable even the predictions are worked out in different ways.

The model tests use historic data (predominantly from the 2001 and 2011 Censuses, and non-Census data to 2018) to calibrate, verify and validate the model structures and parameters.

The LUISA model uses its own tradition for applying a more rigorous model calibration, verification and validation procedure, by first calibrating the model for an initial year (in this case 2011), and then validating the model for one or more base years (in this case 2018; for this procedure, see Wan and Jin, 2017).

3. Scenario design

The new policy scenarios consider (1) the global context of population stabilisation, (2) the need for a big policy change to shake up lagging productivity woes, and (3) the extent to which a growth scenario can bootstrap, i.e. building its own sources of investment and growth momentum over time.

3.1 Population, jobs, and total economic output in terms of GVA/GDP

To structure the main model assumptions, we first consider population, jobs and total economic output in terms of gross value added (GVA) for the countries and regions and gross domestic product (GDP) for the UK as a whole. Defining the population, jobs and total economic output together clarifies the underlying assumptions about per person and per job productivity.As discussed above, we assume two levels of growth – low and gradual – with the low scenario having less economic output, productivity, jobs and net in-migration, and the gradual scenario with the same list of variables but at a higher rate of population growth and a gradually increasing levels of growth in economic output.

To maintain comparability with the previous UK2070 Futures scenarios, the population assumptions are kept the same as previously, with the low growth scenario having an average rate of 0.1% of growth per year and the higher one of 0.55% per year. In our judgement these set a realistic lower and upper bound around the ONS's principal population projection which has an average rate of 0.24% per year. Note that we assume overall labour participation rate (i.e. employed people divided by total population) to remain constant, which implies that the growth rates for population and workers would be the same from 2019 onwards, and employed people would retire later as the population ages. For the actual assumptions at the UK level and by broad regions, see Table 2. The employment assumptions we have made cover a slightly wider range (from 30.7m at the low to 40.2m at the high growth for workplace employed population excluding full time students in 2071) than the OBR projections (which are from 33m at the lowest to 39.4m at the highest for those employed age 16+ in 2068).

To determine the numerical range of overall economic growth rates, we first compare recent OBR and IMF growth projections (published in May and June 2020 respectively) with those assumed in the previous UK2070 Futures scenarios. This shows that in spite of the recent hiatus of the GDP growth trajectory, the existing UK2070 Low-High growth range is still wide enough to cover all the eventualities currently under consideration and debate, including the symmetry V, asymmetry V, W, U shaped recovery and the assorted combinations thereof. In particular, the UK2070 Futures Low Growth assumption (with an annualised GDP growth rate of 0.6% per year till 2071 and could thus be called a 'pear shaped' one) would see the UK getting back to the 2011 output levels in real terms only in 2045 and is more pessimistic than any of the current projections; on the other hand, the High Growth assumption (with an annualised rate of GDP growth of 2.35%) would see the UK economy getting back to the 2011 levels by 2026, and thus slightly surpassing the most optimistic V-shaped recovery e.g. the economy would get back to its 2019 level by the end of 2021. In other words, this Low-High range is still wide enough to cover the GDP growth projections under discussion.

To maintain comparability with the previous scenario tests, we therefore adopt the same range of growth assumptions as demarcated by the Low and High Growth. However, some adaptations are necessary to account for the changing context and the need to define a Gradual Recovery pathway, as follows:

- For Low Growth, we now incorporate the drop in the overall output that has been estimated by OBR in May 2020 (i.e. a reduction in UK GDP by 12.8% relative to 2019);
- For Gradual recovery, the GDP growth rates are assumed to start low during 2021-2026 at 1.1% and they would gradually rise to 3.5% for 2066-2071. This leads to the same overall size of the UK economy in 2071, thus maintaining the same overall annualised average of 2.35% per year.

The growth assumptions are summarised in Table 2 and Figure 3 below.

Table 2 Annualised growth rate assumptions for GDP per worker, population, number of workers and overall GDP growth

Annualised growth rates 2020-2071	GDP / worker	Population & workers	Implied GDP growth	Growth in earnings per worker
Low Growth (as previously defined and applied for Scenario A and B below)	0.5%	0.10%	0.60%	0.25%
High Growth (defined for previous tests and not used in Scenarios A-D below)	**1.8%** (annualised constant rate)	**0.55%**	**2.35%** (annualised constant rate)	**0.9%** (annualised constant rate)
Gradual Recovery (New assumptions; used for Scenario C and D below)	**0.55%-2.95%** (with an overall average of **1.8%**)	**0.55%**	**1.1% - 3.50%** (with an annualised average of **2.35%** per year over 2020-2071)	**0.28%-1.48%** (with an overall average of **0.9%** per year)

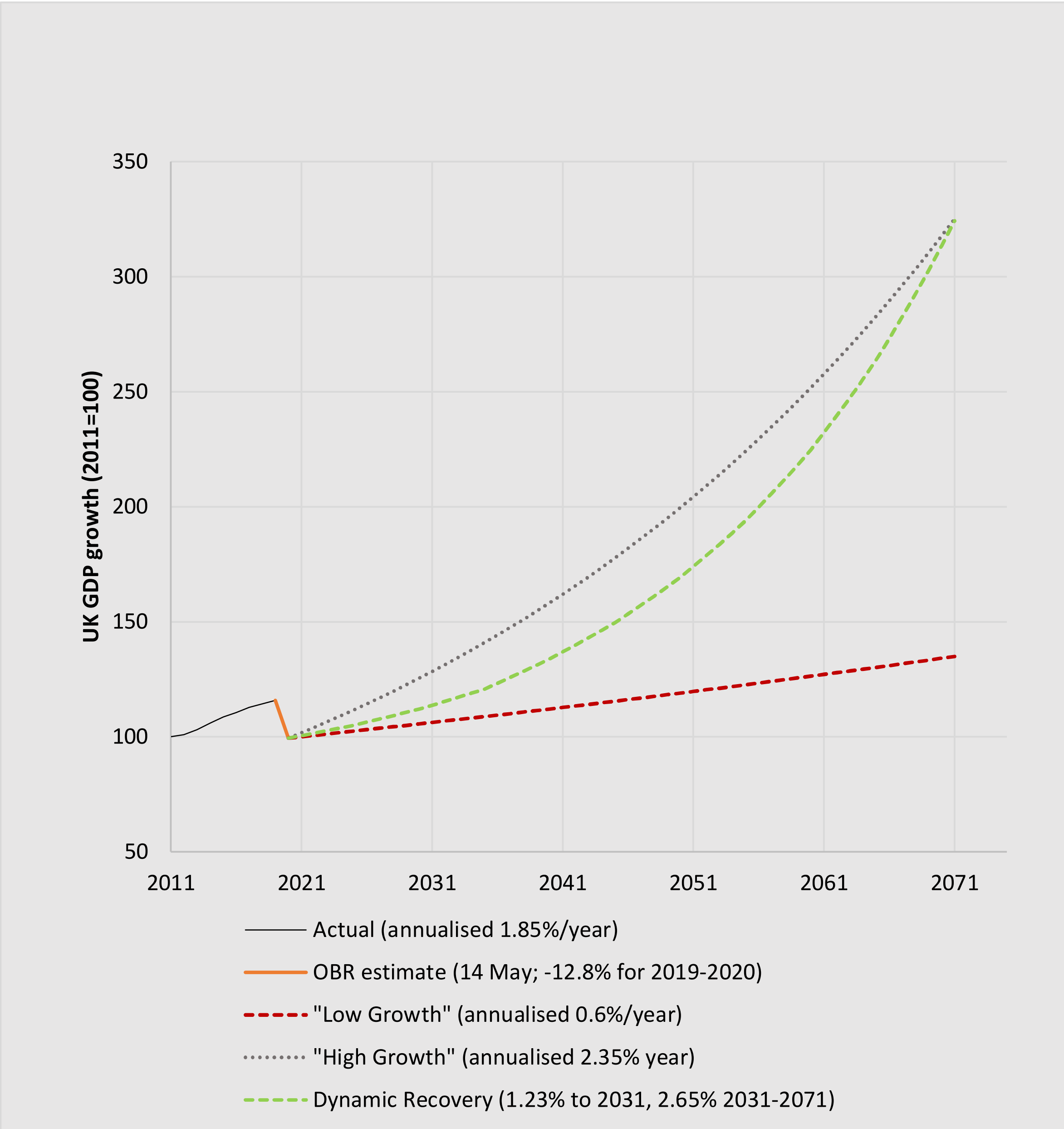

Figure 3 Alternative GDP growth trajectory assumptions to 2071: Low Growth, High Growth and Dynamic Recovery

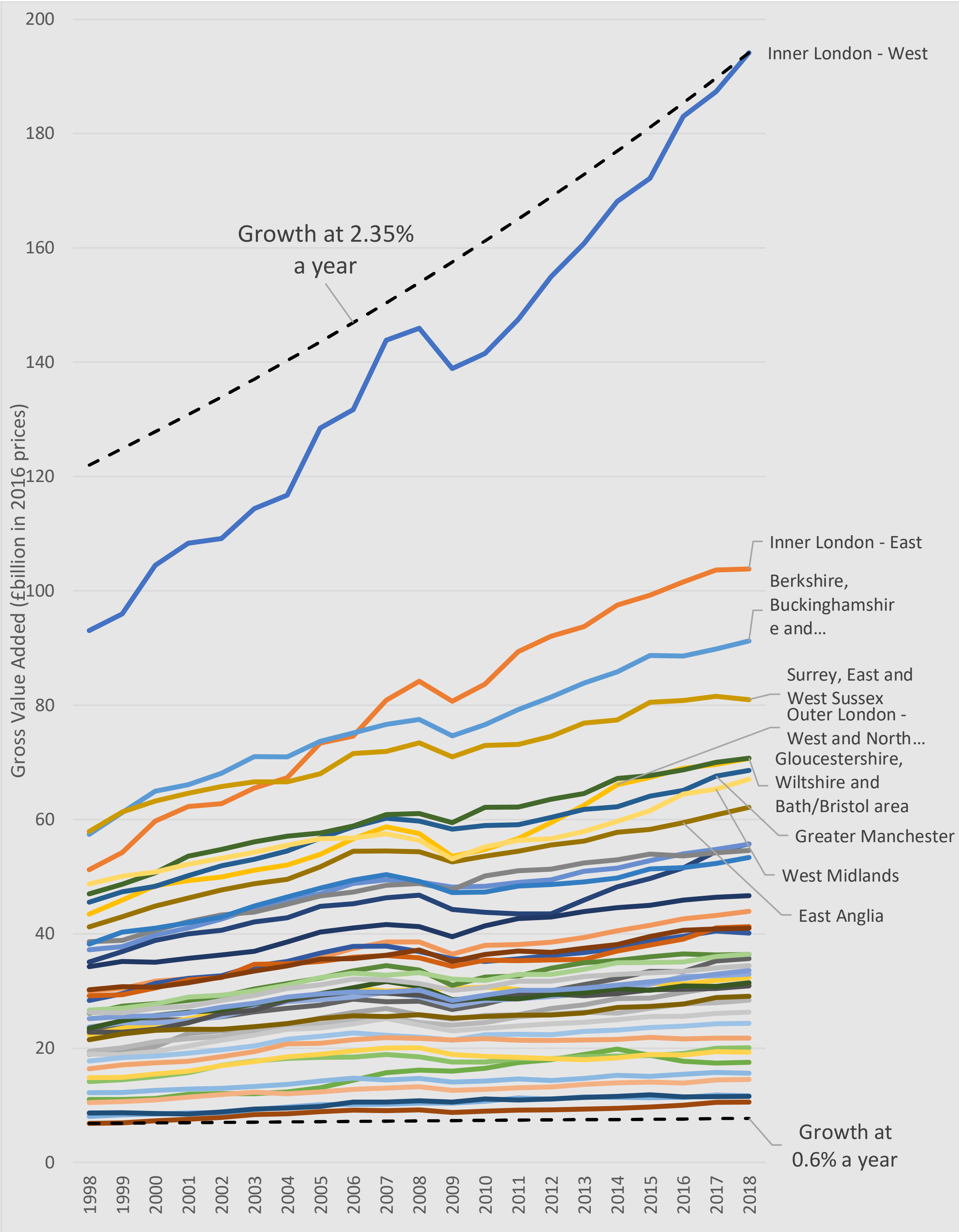

Figure 4 **Evolution of GVA: All NUTS1 regions in the UK have grown more than 1.1% a year on average; the highest being Inner London West which grew by 3.7% a year on average. Of the top ten highest growth areas, seven are in London and the Wider South East**

3.2 Regional spread of jobs and economic activity

For the regional spread of economic and jobs growth, we assume two contrasting patterns of geographic distribution:

- The first, **Business-as-Usual**, follows the regional and local jobs growth trends since 1991. The share of future jobs growth or decline in each local authority or local council districts (including local authority districts, unitary authorities, local council areas, etc) are computed accordingly. Because the expected overall rates of jobs growth (assumed to be 0.1% under Low Growth and 0.55% under Gradual Recovery) would be only a fraction of the historic growth (e.g. annualised growth of employment was 1.1% for 1991-2011 according to the Census, and 1.5% for 2011-2019 according to the ONS Business Register and Employment Survey), those areas that had weak growth as well as those had suffered decline historically would suffer net reductions in total jobs under this assumption. This is particularly so under Scenario B (which is a combination of Low Growth and Business-as-Usual distribution of new jobs);

- By contrast, **Convergent Economy** assumes that the growth in jobs picks up gradually, including areas outside London and WSE as a result of proactive investment and business innovation among the countries and regions, to the extent that by 2031, the rate of jobs growth in all countries and regions would converge to the UK average rates (i.e. 0.1% per year under Scenario C (with Low Growth) and 0.55% per year under Scenario D (with Gradual Recovery), and by 2051 the broad skill profile of the new jobs start to converge to upskilled profile in terms of the socio-economic classification as defined by the population census (i.e. the ONS's NS-SeC grouping of skill and occupation profiles).

Since the **Convergent Economy** assumption are a new introduction to scenario tests, it is useful to explain the grounds upon which it could be considered a realistic proposition. Without doubt, the **Convergent Economy** assumption is a radical departure from the historic and recent trends for the UK. In the last five decades, the best job opportunities and talents were increasingly doing precisely the opposite and gravitating towards London and WSE, so much so that many if not most people have already taken this as a fact of life. This needs to be considered also within the context of the suggestions of moving of jobs out of London in significant numbers, e.g. the government's plans to move out some of its own officials to the countries and regions.

Historically, there has indeed been a contra-flow of jobs out of London to an area covered by a circle of about 100km in radius. This includes not only the WSE but also the nearer fringes of South West and Midlands. In the past five decades areas around the M4/Great Western corridor, Oxford, Milton Keynes, Cambridge, Chelmsford, Colchester, Canterbury, Gatwick-Crawley, Guildford and Southern Hampshire saw their share of high productivity jobs surge, where their ever-closer connections with London helped to turn these areas into distinct centres of innovation in their own right, with the quality of life in those areas converging to, and in some cases surpassing, the best in London. This experience, albeit with a more limited geographic scope, does indicate that it is not inevitable that the 'best' jobs have to follow a one-way flow to central London.

This regional scale convergence which has been taking place in both the rate of jobs growth and the quality of jobs in the WSE, has been facilitated by a range of factors including:

- A general consensus, since the Garden City Movement, that it is feasible to have **a radically different alternative model of urban development** that avoids both overcrowding in London and multiple deprivation in under-developed areas, whilst creating a new lifestyle that combines the benefits of the town and the country;
- **The existence of historic cities, towns and villages with attractive and well-protected natural and cultural environment** – practically, every new centres of innovation mentioned above have sprung up from or close to such a historic city, town or village;

- **Fast improving travel from those cities, towns and villages to core business activities in London and to one another** – it is no coincidence that the M4/Great Western corridor which benefited from the earliest Intercity125 trains became the first to attract good quality jobs in large numbers, and all the main regional cities are now within two hour of door-to-door travel time to central business and administrative areas of London;
- **Fast improving travel connections within each journey to work catchment area** that provides the skills and services necessary for the growing businesses – in the past fifty years, this was mainly through the spread of a strategic road network, which – cogent to the discussion here – has reached a critical threshold of traffic congestion in the WSE and now requires significant investment and demand management to accommodate any further growth;
- **The willingness of the local communities to supply affordable housing and the availability of suitable land space to build the housing in order to support employment growth** – since 1971, the WSE has added many times more new housing relative to that within London, although practically all local/unitary authority areas in the Home Counties – covering practically all the areas of strong jobs growth, can no longer keep building housing at the national average, let alone the rate deemed necessary for catching up with the housing supply backlog;
- Often, though not exclusively, **close connections to local universities and wider innovation** have played a role in seeding and catalyzing this spread of good quality jobs
- As the quality of the jobs improved in the WSE, schools, hospitals, social care, local government and businesses benefited from the spill-over of skills, which in turn led to **improvements in the overall quality of life, nature conservation and a virtuous cycle that continues to add good quality jobs** increasingly through attracting unique global investments that London alone would not have been able to secure alone.

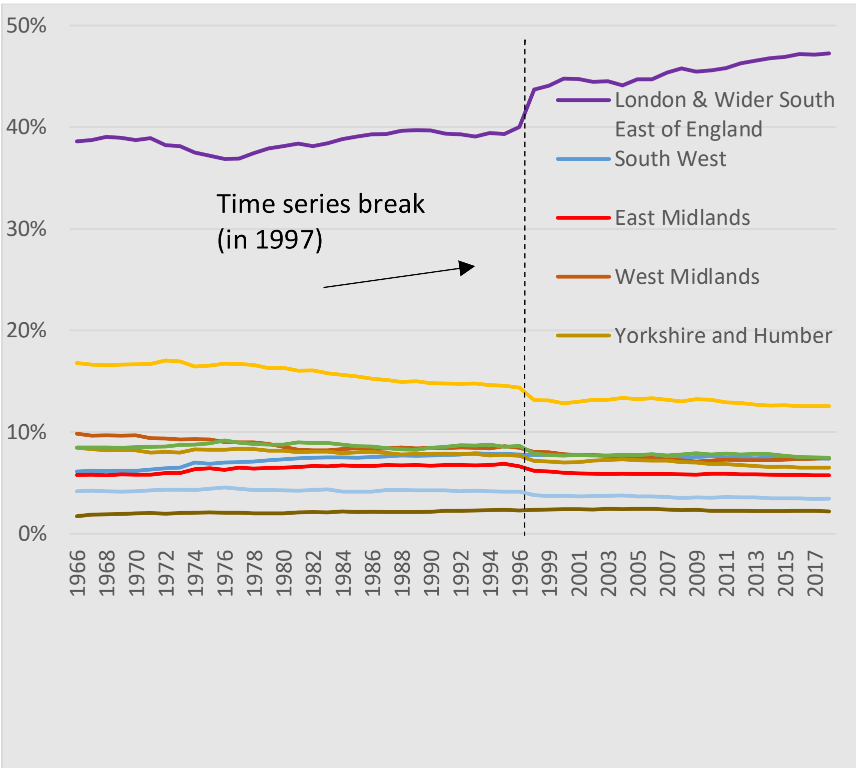

Figure 5 Evolution of the GVA %share: 1966-2018 (All UK = 100)

Data sources: ONS historic GDP/GVA data 1966-1996 (https://www.ons.gov.uk/economy/regionalaccounts/grossdisposablehouseholdincome/adhocs/006226historiceconomicdataforregionsoftheuk1966to1996) and ONS GVA (balanced method) 1998-2018 (https://www.ons.gov.uk/economy/grossvalueaddedgva/datasets/nominalandrealregionalgrossvalueaddedbalancedbyindustry).

This historic experience of London and the WSE, a region of 25 million, needs to be set in the context of the need for levelling up the UK as a whole, as the sixth largest global economy. The UK has 68 million people, and by 2071, its population size could reach close to 90 million[1] if there is sustained population growth at our High Growth rate. This could well materialise if there has been excellent recovery and growth. Could a successful city-region level experience be repeated at the level of a whole nation of around 90 million people?

From a global perspective, integral city regions (which have historically been called ‘megacity-regions’) now routinely involve more than 100 million residents as daily commuters and supply-chain provisions today. A prominent example for spatial planning at this scale is Japan, where air and high-speed rail have been successfully used to support the coordination and balance of regional growth since the 1960s. This effort is still continuing today – a new high speed rail project, the Chuo Shinkansen bullet train is currently under construction to bring Japan’s two biggest cities, Tokyo and Osaka, which are 500 km apart to be within one hour of train travel time within this decade.

Compared with Japan, the UK would have two notable advantages: first, the UK is spatially more compact: the physical distances between the main cities are all below 650km (e.g. London to Derry or London to Aberdeen) whereas in Japan the crow-fly distance from Sapporo to Fukuoka is over 1,400km; secondly, the UK still has a window of opportunity to grow: it expects to grow substantially whereas Japan’s total population has been reducing and the economy had a growth rate much less than the Low Growth scenario since the late 1980s.

In the age of prolific online communications, why would one still be concerned by physical geography and travel time? Research on this topic so far suggests that transport and telecommunications tend to complement each other – i.e. where people go, online connections are better established and vice versa. Specifically in the UK, the work of Chen and Hall (2011) is an insightful retrospect of the long-term benefits of Intercity125 trains on economic growth: their findings show that the effects of Intercity125 falls off sharply beyond a 2-hour radius from central London.

Since the Lockdown, even with dramatically better online communications, the needs for face-to-face business and social meetings do not seem to diminish for strategic and complex discussions, although there is an ample scope to substitute routine meetings with online calls. This means that online communications may extend the reach of innovation activities whilst cutting down the demand for travel per unit of economic activity – this would represent excellent news for spreading jobs and economic activity from London and WSE.

In designing the Convergent Economy assumption, it would therefore be appropriate to consider whether the UK would be able to replicate the successful experience within London and WSE, and spread jobs, economic activity and in particular high-quality jobs and living standards to the rest of the UK within the next half century. Strategically, this would mean re-coupling of the countries and regions as one closely integrated economic area, reversing the past decoupling described and explained in McCann (2019) for the UK2070 Commission.

Here a simple logic is applied with the specification of the Convergent Economy assumption. We postulate that as a first approximation, if the conditions that enabled the economic convergence to take place in London and the WSE in the last 50 years are met in the wider UK, then a similar convergence could take place in the next 50 years in this wider area. Of course the scale of this UK-wide convergence is much more ambitious, but there is also now better transport and telecommunications technology to overcome the greater extent of distance and area.

[1] For instance, the ONS high population projection expects the UK population to reach 88.1 million by 2071.

The process of specifying the conditions for a UK-wide Convergent Economy is necessarily an iterative one, as the first approximations would need to be tempered and refined to take account of the real circumstances of each and every country and region in the UK. However, we cannot straightaway think of a show-stopper, a barrier that would prevent the realization of a Convergent Economy if all the conditions are met.

The practical purpose of discussing the conditions is precisely to identify if such barriers would exist, as well as fleshing out further details of the conditions. This process would then help policy makers and citizens alike to gauge by when and by dint of what the supporting conditions could be met, if they would have the ambitions to achieve the level of re-coupling underlying the Convergent Economy assumptions.

To start this process off here we confirm the first approximation of the conditions to achieve the level of reconfiguration of jobs and economic activities:

- A general consensus that it is necessary and feasible to engender **a radically different alternative model of spatial development** that makes appropriate use of the resources and endowment already present in each local area, raises productivity and benefits the whole of the UK;
- **There are existing historic cities, towns and villages with attractive and well-protected natural and cultural environment** where new business innovation could take hold and spread to the wider region;
- **Fast improving travel from the new centres to existing centres of business and innovation**, and through persistent improvements over half a century all the main regional cities are within one hour and 45 minutes door-to-door travel time to one another, so that all critical face-to-face meetings can take place with the same convenience as currently within London and WSE;
- **Fast improving travel connections within each journey to work catchment area** that provides the skills and services necessary for the growing businesses in all countries and regions;
- **The willingness of the local communities to supply affordable housing and the availability of suitable land space to build the housing in order to support employment growth** in areas that are outside London and the WSE, including gradually catching up with the housing supply backlog where this has not been addressed through the spatial reconfiguration of jobs and economic activity;
- **Establish and enhance local universities and wider innovation** to train and supply the skills base needed, as well as seeding and catalyzing the spread of good quality jobs
- As the quality of the jobs improved, engender the spill-over of skills, invest in schools, hospitals, social care and other local services to **improve the overall quality of life, nature conservation and to create a virtuous cycle that continues to add good quality jobs** increasingly through attracting unique global investments that London and the WSE alone would not have been able to secure.

3.3 Definition of main policy scenarios

Two distinct approaches to regional distribution of the growth are assumed in terms the number and skill levels of jobs:

- one being **Business-as-Usual** where the diverging growth trends in jobs in each local council area persist as observed over the period 1991-2019, and so do the diverging local skills and occupation profiles
- the other being a **Convergent Economy** which sees the rates of jobs growth across the nations and regions gradually converge towards the UK average, and at the same time, the national and regional average profiles of skills and occupations converge towards those of London and the Wider South East (WSE).

A matrix of the above sets of assumptions gives rise to four main policy scenarios:

- Gradual Recovery with Business-as-Usual leads to **Persistent Regional Imbalance (Scenario A)**
- Low Growth with Business-as-Usual leads to **Continued Regional Recession (Scenario B)**
- Low Growth with Convergent Economy leads to **Slow Levelling-Up (Scenario C)**
- Gradual Recovery with Convergent Economy leads to **Dynamic Recovery (Scenario D).**

Table 3 Summary of four main post-COVID scenarios

Geographic spread	Rates of overall economic growth in the UK	
	Low Growth	Gradual Recovery
Business as Usual	**Scenario B** Continued Regional Recession	**Scenario A** Persistent Regional Imbalance
Convergent Economy	**Scenario C** Slow Levelling-up	**Scenario D** Dynamic Recovery

The resulting Convergent Economy assumptions in terms of jobs are shown below in Table 4.
, and the convergent skills profile in terms of the shares of higher skilled jobs (equivalent to the ONS Higher level professional and managerial jobs today) are shown in Table 5.

Table 4 Convergent Economy: Assumptions for total jobs

Area	**2011**	**2031**	**2051**	**2071**
London and WSE	10.8	13.3	14.2	15.0
Midlands	4.4	5.3	6.1	7.0
South West	2.4	2.9	3.3	3.8
N England	6.5	7.6	8.8	10.1
Wales	1.3	1.5	1.7	2.0
Scotland	2.4	2.7	3.1	3.6
N Ireland	0.8	0.8	1.0	1.2
All UK	**28.5**	**34.2**	**38.2**	**42.7**

Table 5 **Convergent Economy: Assumptions for shares of high skilled jobs**

Area	% share 2011	% share 2031	% share 2051	% share 2071
London and WSE	16.5%	24.1%	36.0%	54.0%
Midlands	11.8%	19.3%	32.6%	50.6%
South West	12.5%	20.0%	32.6%	50.6%
N England	11.7%	19.3%	34.2%	50.4%
Wales	10.4%	18.0%	31.1%	48.5%
Scotland	11.8%	19.4%	33.4%	50.0%
N Ireland	10.1%	17.5%	33.5%	49.9%
All UK	**13.5%**	**21.2%**	**34.2%**	**51.6%**

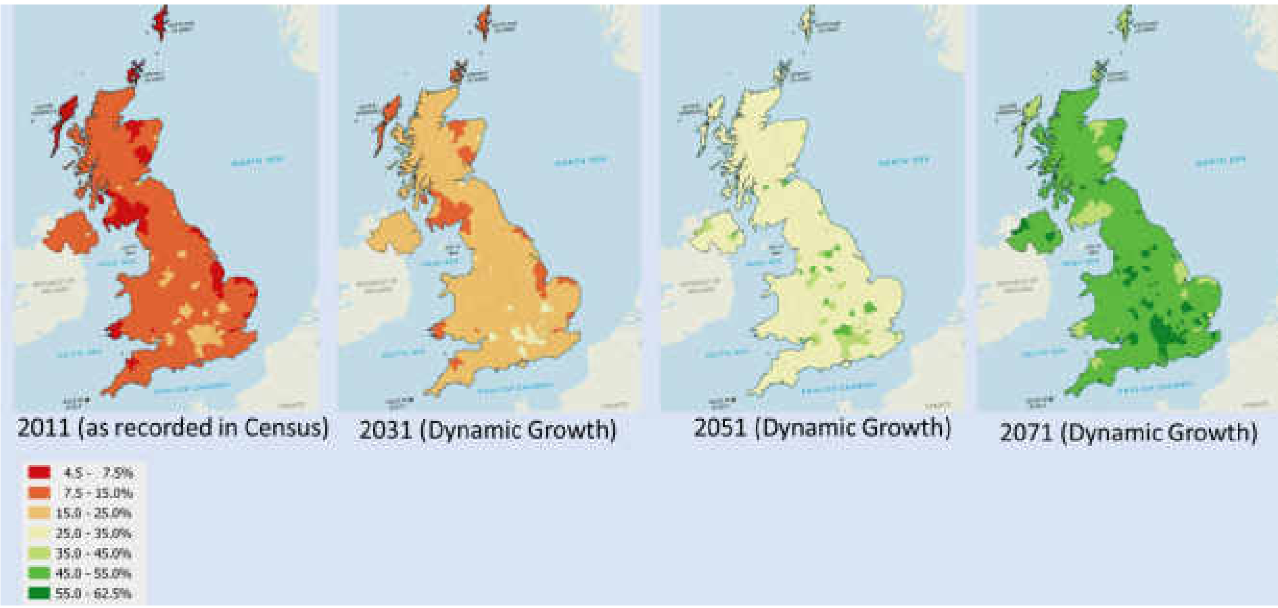

Figure 6 Changes in the shares of higher skilled workers: 2011-2071

Among the conditions above there is no doubt that, prima facie, the biggest policy ‘jolt’ would seem to be the transport improvements required. At a closer look, the other conditions are no easier, either. The three sections below deal respectively with each category of assumptions.

3.4 Assumptions regarding housing development

Within the above framework of the four main scenarios, further assumptions are made regarding housing growth (this section) and transport interventions (Section 3.5 below).

The housing growth assumptions are made in terms of

(1) the high and low rates of growth in the total number of dwellings, which are respectively in line with the population growth at 0.1% and 0.55% per year, and
(2) the geographic distribution of housing growth

In terms of the geographic distribution of housing development, assumptions have benefited from the insights of the MHCLG data on total net additional dwellings data since 2004 (Figure 7). The scenario assumptions in England follows the patterns observed since 2004, as reported in the MHCLG data on total net additional dwellings (MHCLG, 2019) with adjustment made to account for short term growth spurts in some local authorities that are not expected to continue. Similar assumptions are made by the study team in Wales, Scotland and Northern Ireland based on the geographic patterns of population growth. In contrast to official house-building targets, this assumption reflects the lower actual delivery of housing per year in a number of local authorities in London and WSE, and the higher delivery in the English Midlands and beyond – in other words, the housing growth assumptions are made with a more realistic rates of housing delivery in the future in areas that have already shown signs of strain and backlog.

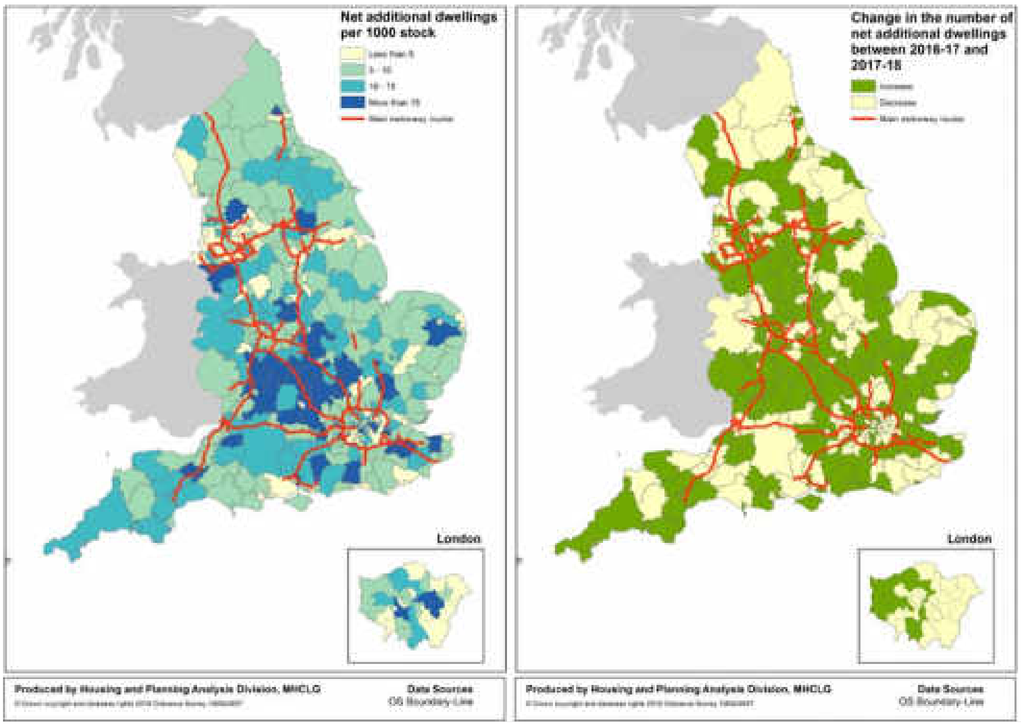

Figure 7 MHCLG Net Additional Dwellings for England

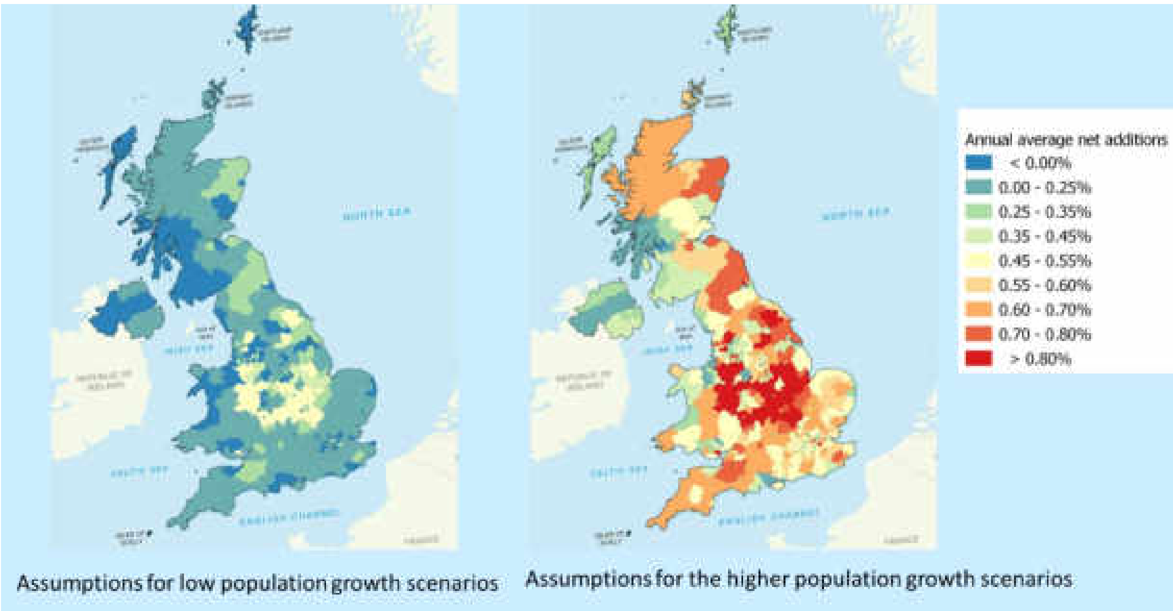

Figure 8 Housing development assumptions for low and higher population growth scenarios

Table 6 Housing growth assumptions for the low population growth scenarios

Dwellings (million)	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	9.6	10.3	10.4	10.6	10.7
Midlands	4.3	4.7	4.8	4.9	5.1
South West	2.4	2.6	2.6	2.7	2.8
N England	6.6	7.0	7.1	7.3	7.5
Wales	1.4	1.4	1.4	1.4	1.4
Scotland	2.5	2.5	2.5	2.5	2.5
All Britain	26.8	28.5	28.8	29.4	30.0
% change/year		2011-20	2020-31	2031-51	2051-71
London & WSE		0.86%	0.07%	0.08%	0.07%
Midlands		0.78%	0.20%	0.18%	0.17%
South West		0.92%	0.14%	0.16%	0.17%
N England		0.64%	0.11%	0.11%	0.12%
Wales		0.12%	0.04%	0.04%	0.05%
Scotland		0.10%	-0.04%	-0.02%	0.00%
All Britain		0.69%	0.10%	0.10%	0.10%

Table 7 Housing growth assumptions for the higher population growth scenarios

Dwellings (million)	2011	2020	2031	2051	2071
London & WSE	9.6	10.3	11.0	12.2	13.5
Midlands	4.3	4.7	5.0	5.7	6.4
South West	2.4	2.6	2.8	3.1	3.5
N England	6.6	7.0	7.5	8.4	9.4
Wales	1.4	1.4	1.5	1.6	1.8
Scotland	2.5	2.5	2.6	2.8	3.1
All Britain	26.8	28.5	30.3	33.8	37.7
% change/year		2011-20	2020-31	2031-51	2051-71
London & WSE		0.86%	0.52%	0.53%	0.52%
Midlands		0.78%	0.66%	0.63%	0.62%
South West		0.92%	0.59%	0.61%	0.62%
N England		0.64%	0.56%	0.56%	0.57%
Wales		0.12%	0.49%	0.49%	0.50%
Scotland		0.10%	0.41%	0.43%	0.45%
All Britain		0.69%	0.55%	0.55%	0.55%

The scenario assumptions presented here have not explicitly considered issues like historic supply backlogs. The net growths in housing are assumed in terms of overall population growth (i.e. under low population growth, the total amount of housing needed would be low) and the observed, historic patterns of housing delivery. We acknowledge that current provision of housing has been slower than the outturn demand, despite the stated objective by all parties to provide c. 300,000 dwelling units per year. The on-going higher growth in population in London and many parts of the WSE has led to the estimation that new housebuilding in London and the Wider South East needs to increase by c.90,000/year if the regional disparity status quo continues. Unless there is a change in the trajectory, housing costs in London and the Wider South East would continue to rise more sharply relative to the rest of the UK. This could be further reinforced by maintaining existing policies which indirectly subsidise the overheating of housing markets and disparities in wealth. For example, 80% of Homes England funding is currently targeted at 'highest affordability pressure' areas, which are mostly in London and the WSE.

The advantage of scenario modelling for the housing supply debate is that it can introduce new variables to be considered. In this case if the growth in jobs would become more convergent across the UK in the longer term, there could be a gradual easing of the housing pressures in London and WSE, as well as the potential of healthier housing demand across the rest of the UK.

3.5 Assumptions regarding transport

The transport assumptions distinguish the low growth and business-as-usual scenarios from a productivity-driven, dynamic recovery scenario:

- For Scenarios A (Persistent Regional Imbalance), B (Persistent Regional Imbalance) and C (Slow Levelling-Up), it is assumed that corresponding transport investments would be made, which keeps the door-to-door travel time for people and goods unchanged from today: under the Low Growth scenarios B and C the funds for transport investments would be very limited and the traffic flow volumes would also be little changed, and under the higher growth Scenario A, the increased road capacities would be taken up by increased traffic, and the catchment of stations on fast public transport services would expand in line with the increase of transit speeds
- For Scenario D (Dynamic Recovery), it is assumed that a significantly more ambitious additional transport improvement programme would be implemented when such funds become available as the economy grows.

Note that due to the long time span of the scenarios, it is impractical to make the transport assumptions in terms of specific projects of network or service improvements. Instead, the transport assumptions are made in terms of average travel times and generalised costs for those travelling within each local authority area or between each pair of the areas.

For Scenarios A, B and C, the travel times and generalised costs remain identical to those in the Base Year (i.e. 2018).

For Scenario D, the transport improvements are assumed to be in line with the overarching dynamic recovery assumptions, and consist of the following two categories:

- During 2021-2031 and before major infrastructure projects (such as HS2) come into full service, transport improvements will be implemented through a carefully designed package of transport, land use and urban design readjustments to improve local and regional travel, business access, air quality and decarbonisation. Such improvements would reduce door to door journey times and service quality such that during each year of the decade, the effective economic density (as defined by DfT's wider transport impact guidance in its webTAG documentation) of each region would increase by an annual average of 0.5%, and
- From 2031 onwards, it is assumed that a pipeline of major transport infrastructure projects will gradually reduce the travel times between the core of the regional cities through the most appropriate means of transport, such that by 2071, the fastest door-to-door business travel times among all such regional cities will be at or below 1 hour 45 minutes (which is the time currently taken between central London and all main centres of innovation in the Wider South East. These improvements build on the capabilities of a fully integrated multimodal transport system with rail, road and air modes all playing a part. Given the necessary lead time for this investment, Scenario D assumes that the interregional travel times will only start to reduce from the late 2020s i.e. when the HS2 services and low carbon road and air modes become available for commercial use.

For each scenario the spatial equilibrium model predicts travel demand within and between the local authority areas which are used to work out the specific network and service improvements required for a given point in time in the future (see below under 'Findings'). This is a novel way of using the predictive model – the conventional way is to ask DfT and local transport planning authorities for their specifications, and that is infeasible given the timescale to 2070.

Because of the existing emphasis on a London centric interregional network, the specification would introduce a more balanced pattern of improvements. This would particularly benefit the regional capitals (see e.g. the example of Manchester below).

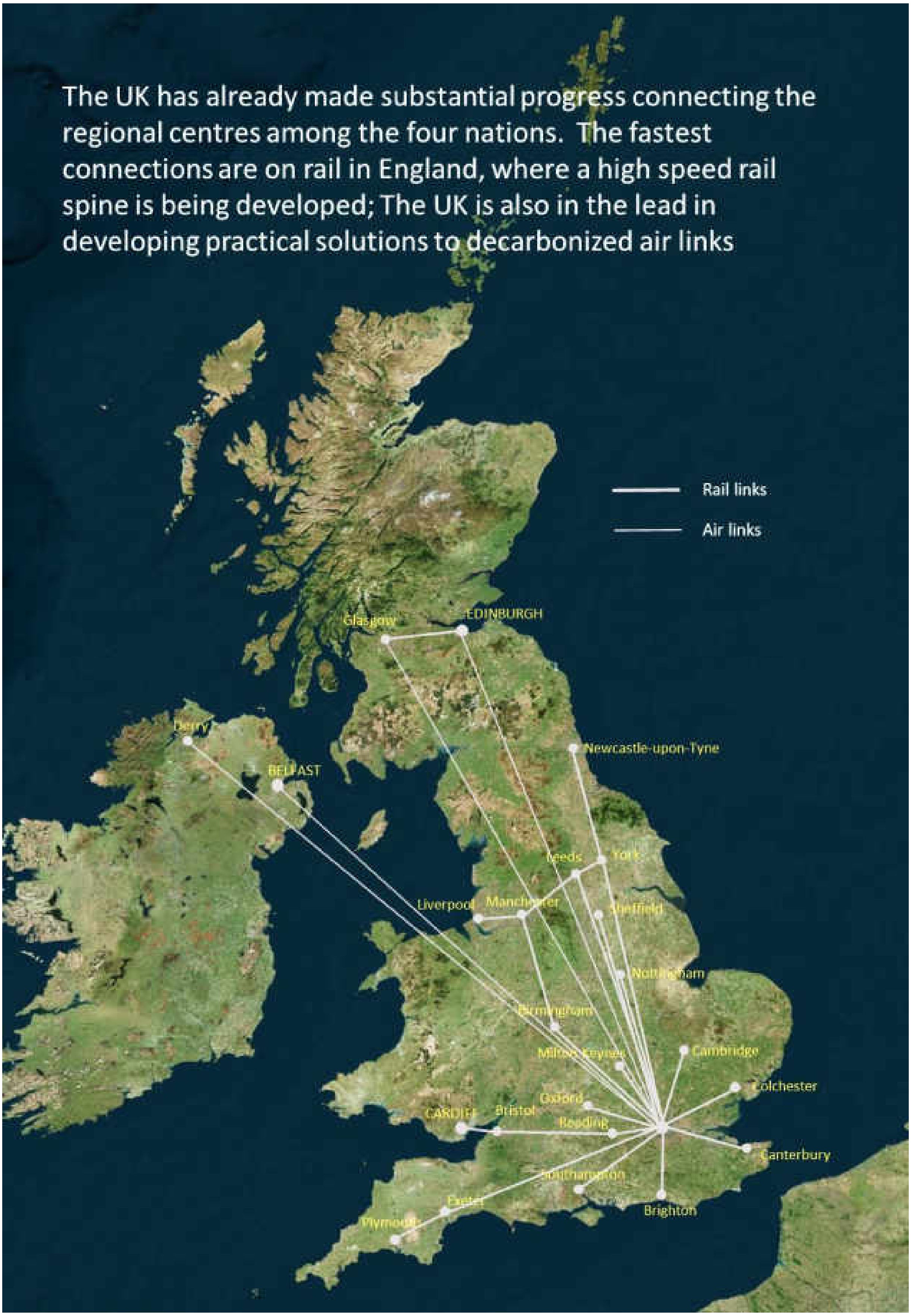

Figure 9 The UK's interregional transport network is currently highly focused on London

Figure 10 A comparison of the door-to-door travel times to/from London: 2021

Figure 11 Regional capitals like Manchester tend to have less direct connections

Figure 12 A comparison of the door-to-door travel times to/from Manchester: 2021

Figure 13 A vision for radically reduced door-to-door travel times to/from Manchester through environment- and climate-friendly means of transport

3.6 Summary

In comparison with the pre-Covid scenarios, the main differences of the scenarios here in this report are

(1) an assumption of a gradual rise in economic growth, which bridges the low growth rates in the next few years to the longer-term rising rates of growth
(2) an emphasis on the role of productivity, postulating rising rates of per worker productivity in the longer term as a result of the spread of automation and artificial intelligence in society rather than the conventional assumptions of constant or falling productivity
(3) a new emphasis on radical improvements in business travel to support innovation and external direct investment in the regional cities outside London and the Wider South East (LWSE) under the Dynamic Recovery (D) scenario.

These scenario inputs are used in the LUISA (v2.3) tests and the findings of the scenario test results are presented in Chapter 4 below.

4. Findings from Scenario Tests

The scenarios tests seek to answer:

- What would the effects be if the UK would face a prolonged period of low growth, if the trend distribution of business activities and sustained imbalance were to persist?
- To what extent would a geographically more convergent growth strategy help or hinder growth, productivity and quality of life?
- To what extent could the environmental capacities of the existing UK growth hotspots cope with the different distributions of jobs and housing?
- What roles could a geographically more convergent growth strategy play in fostering or hindering a green economic recovery stimulate local economies and embed upskilling at a regional level?
- Could a long term strategy inform the design of short term, ‘shovel ready’ investments?

The model test results show that the geographic configuration does matter in a critical way, and the difference between Continued Regional Recession and Convergent Discovery is as stark as it can be, with the former diminishing the UK’s long-term growth potential and the latter enabling the UK to grow sustainably within the environmental capacity of each of the local areas.

The scenario profiles and findings are presented below for each of the scenarios A, B, C and D.

4.1 Scenario A: Sustained Imbalance

Even though an overall higher growth would be expected to help all regions, there would be expected to be significant differences in the rates of growth between the regions and nations, as well as a continued erosion of job quality outside the areas of high growth (linked to low wage economies).

The traffic congestion and housing cost pressures become wide spread in London and WSE, with real housing costs increasing at a rate that is 140% above that of the national average earnings, compared with, for example, 17% above in the North of England to 2031. The longer term trend suggest even worse disparities. This shows that a geographically more convergent growth strategy is badly needed to ease the growth pressures in the high growth areas, as well as to improve job opportunities in the rest of the UK.

Table 8 Scenario A: Sustained Regional Imbalance - Distribution of jobs by mega-region

Jobs (million)	**1981***	**1991***	**2001**	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	7.6	8.7	9.9	11.2	12.8	14.0	16.6	19.6
Midlands	3.4	3.9	4.1	4.6	4.9	5.2	5.6	6.1
South West	1.6	2.0	2.3	2.5	2.7	2.8	3.2	3.5
N England	5.4	5.7	6.1	6.8	7.1	7.3	7.6	7.9
Wales	0.9	1.1	1.2	1.3	1.4	1.4	1.5	1.6
Scotland	2.1	2.1	2.3	2.5	2.5	2.6	2.7	2.8
All Britain	19.2	23.4	27.3	28.9	31.4	33.4	37.2	41.6

% change/year	**1981-91**	**1991-01**	**2001-11**	**2011-20**	**2020-31**	**2031-51**	**2051-71**
London & WSE	1.36%	1.31%	1.27%	1.44%	0.85%	0.85%	0.85%
Midlands	1.26%	0.64%	0.98%	0.85%	0.39%	0.41%	0.43%
South West	2.45%	1.27%	1.16%	0.62%	0.55%	0.53%	0.49%
N England	0.52%	0.60%	1.07%	0.57%	0.25%	0.21%	0.16%
Wales	1.36%	0.76%	1.41%	0.47%	0.38%	0.34%	0.28%
Scotland	-0.24%	1.04%	0.94%	0.17%	0.25%	0.22%	0.18%
All Britain	2.02%	1.53%	0.59%	0.93%	0.55%	0.55%	0.55%

Table 9 Scenario A: Sustained Regional Imbalance - Distribution of dwelling stock by mega-region

Dwellings (million)	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	9.6	10.3	11.0	12.2	13.5
Midlands	4.3	4.7	5.0	5.7	6.4
South West	2.4	2.6	2.8	3.1	3.5
N England	6.6	7.0	7.5	8.4	9.4
Wales	1.4	1.4	1.5	1.6	1.8
Scotland	2.5	2.5	2.6	2.8	3.1
All Britain	26.8	28.5	30.3	33.8	37.7

% change/year	2011-20	2020-31	2031-51	2051-71
London & WSE	0.86%	0.52%	0.53%	0.52%
Midlands	0.78%	0.66%	0.63%	0.62%
South West	0.92%	0.59%	0.61%	0.62%
N England	0.64%	0.56%	0.56%	0.57%
Wales	0.12%	0.49%	0.49%	0.50%
Scotland	0.10%	0.41%	0.43%	0.45%
All Britain	0.69%	0.55%	0.55%	0.55%

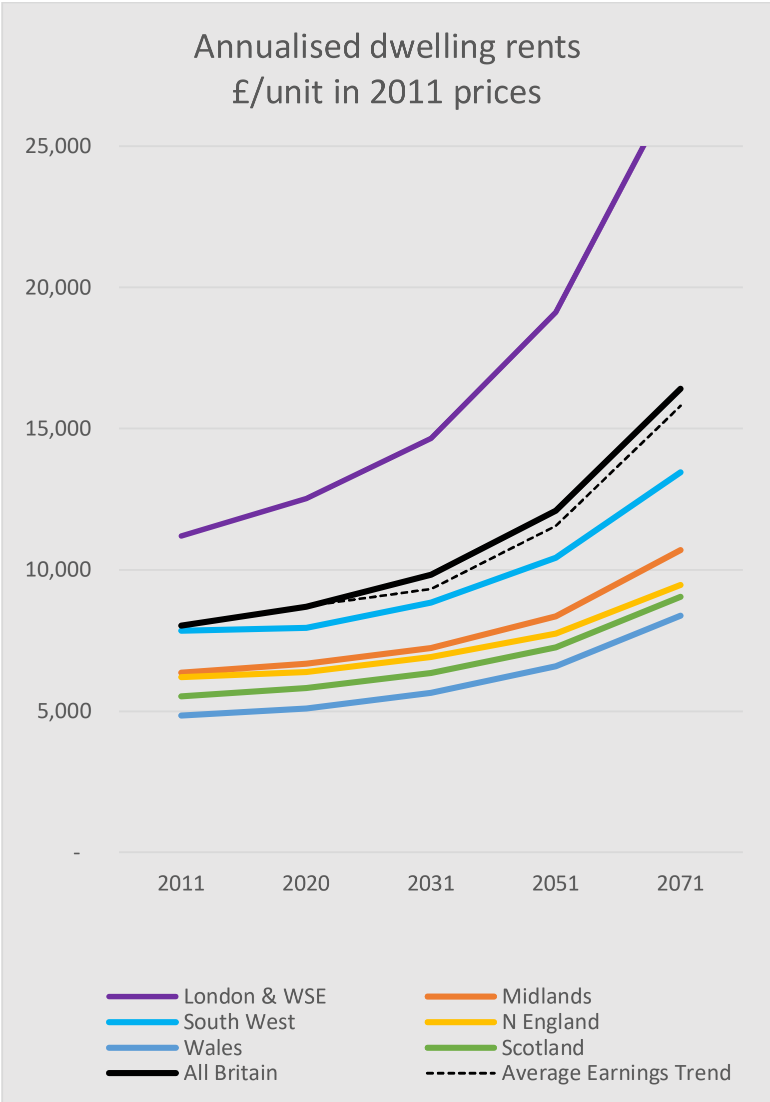

Figure 14 Scenario A: Sustained Imbalance: Rising tide lifts all boats but London and WSE face unsustainable growth pressures

Table 10 Scenario A: Sustained Regional Imbalance - Changes in average dwelling rents

Dwelling rents (annualised £/unit in 2011 prices)					
	2011	2020	2031	2051	2071
London & WSE	11,200	12,519	14,653	19,115	27,491
Midlands	6,359	6,670	7,239	8,353	10,702
South West	7,841	7,951	8,840	10,431	13,456
N England	6,201	6,385	6,906	7,745	9,465
Wales	4,839	5,100	5,644	6,588	8,377
Scotland	5,519	5,813	6,351	7,259	9,047
All Britain	8,027	8,687	9,831	12,093	16,410
Average Earnings Trend Line	8,027	8,720	9,327	11,550	15,806
		% change/year			
		2011-20	2020-31	2031-51	2051-71
London & WSE		1.2%	1.4%	1.3%	1.8%
Midlands		0.5%	0.7%	0.7%	1.2%
South West		0.2%	1.0%	0.8%	1.3%
N England		0.3%	0.7%	0.6%	1.0%
Wales		0.6%	0.9%	0.8%	1.2%
Scotland		0.6%	0.8%	0.7%	1.1%
All Britain		0.9%	1.1%	1.0%	1.5%

4.2 Scenario B: Continued Regional Recession

Combining low growth, without change in current policies, would result in continued regional recession beyond the immediate effect of the COVID-19 economic shock. If recent trends in the regional concentration of jobs were to continue under a prolonged period of low growth, London and Wider South East could be the only region to grow. The South West might hold steady, but all other areas of the UK could see decline in the overall number of jobs, with likely erosion in good quality and better paid jobs. Across the whole of the UK there could be net growth of only 400,000 jobs, whilst London and Wider South East could see 500,000 additional jobs. Housing costs would be expected to rise in London and Wider South East and the South West, well above national average, but with the risk of house price deflation elsewhere.

Table 11 Scenario B: Continued Regional Recession - Distribution of jobs by mega-region

Jobs (million)	**1991***	**2001**	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	8.7	9.9	11.2	12.8	13.3	14.4	15.6
Midlands	3.9	4.1	4.6	4.9	4.9	4.9	4.8
South West	2.0	2.3	2.5	2.7	2.7	2.7	2.8
N England	5.7	6.1	6.8	7.1	7.0	6.6	6.3
Wales	1.1	1.2	1.3	1.4	1.4	1.3	1.3
Scotland	2.1	2.3	2.5	2.5	2.5	2.4	2.3
All Britain	23.4	27.3	28.9	31.4	31.8	32.4	33.1

% change/year	**1991-01**	**2001-11**	**2011-20**	**2020-31**	**2031-51**	**2051-71**	
London & WSE	1.36%	1.31%	1.27%	1.44%	0.40%	0.40%	0.39%
Midlands	1.26%	0.64%	0.98%	0.85%	-0.06%	0.04%	-0.02%
South West	2.45%	1.27%	1.16%	0.62%	0.10%	0.08%	0.04%
N England	0.52%	0.60%	1.07%	0.57%	-0.20%	0.24%	-0.29%
Wales	1.36%	0.76%	1.41%	0.47%	-0.07%	0.11%	-0.17%
Scotland	-0.24%	1.04%	0.94%	0.17%	-0.20%	0.23%	-0.26%
All Britain	2.02%	1.53%	0.59%	0.93%	0.10%	0.10%	0.10%

Table 12 Scenario B: Continued Regional Recession - Distribution of dwelling stock by mega-region

Dwellings (million)	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	9.6	10.3	10.4	10.6	10.7
Midlands	4.3	4.7	4.8	4.9	5.1
South West	2.4	2.6	2.6	2.7	2.8
N England	6.6	7.0	7.1	7.3	7.5
Wales	1.4	1.4	1.4	1.4	1.4
Scotland	2.5	2.5	2.5	2.5	2.5
All Britain	26.8	28.5	28.8	29.4	30.0

% change/year	2011-20	2020-31	2031-51	2051-71
London & WSE	0.86%	0.07%	0.08%	0.07%
Midlands	0.78%	0.20%	0.18%	0.17%
South West	0.92%	0.14%	0.16%	0.17%
N England	0.64%	0.11%	0.11%	0.12%
Wales	0.12%	0.04%	0.04%	0.05%
Scotland	0.10%	-0.04%	-0.02%	0.00%
All Britain	0.69%	0.10%	0.10%	0.10%

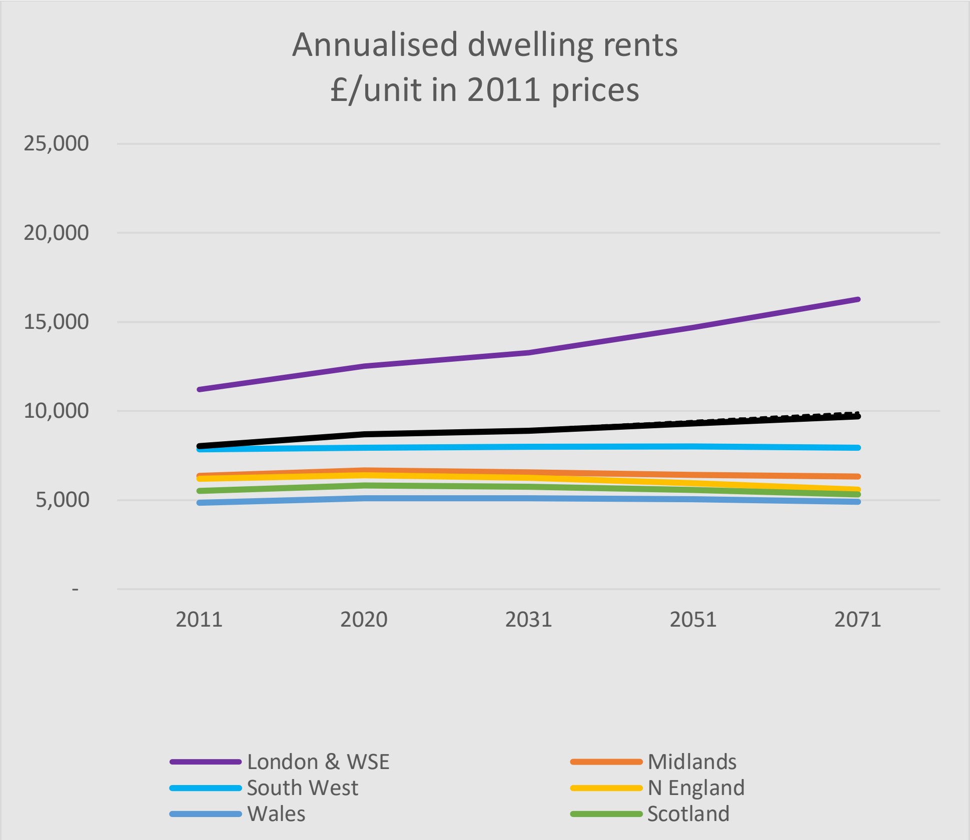

Figure 15 Scenario B: Polarisation of housing markets in the UK under low growth

Table 13 Scenario B: Continued Regional Recession - Changes in average dwelling rents

Dwelling rents (annualised £/unit in 2011 prices)					
	2011	2020	2031	2051	2071
London & WSE	11,200	12,519	13,266	14,707	16,276
Midlands	6,359	6,670	6,551	6,411	6,312
South West	7,841	7,951	8,000	8,017	7,951
N England	6,201	6,385	6,250	5,950	5,588
Wales	4,839	5,100	5,099	5,042	4,909
Scotland	5,519	5,813	5,742	5,574	5,319
All Britain	8,027	8,687	8,898	9,296	9,701
Average Earnings Trend	8,027	8,720	8,962	9,421	9,904
% change/year		2011-20	2020-31	2031-51	2051-71
London & WSE		1.25%	0.53%	0.52%	0.51%
Midlands		0.53%	-0.16%	-0.11%	-0.08%
South West		0.16%	0.06%	0.01%	-0.04%
N England		0.33%	-0.19%	-0.25%	-0.31%
Wales		0.59%	0.00%	-0.06%	-0.13%
Scotland		0.58%	-0.11%	-0.15%	-0.23%
All Britain		0.88%	0.22%	0.22%	0.21%

4.3 Scenario C: Slow Levelling-up

In Scenario C (Slow Levelling-up) there would be some redistribution of growth away from London and the south to address the growth pressures but at such a slow rate that the effects are negligible.

The lower growth would also require resources to be found to invest in transport and IT infrastructure under sustained very subdued market conditions. As a result, a scatter of the new jobs would be expected to fail to achieve the level of business agglomeration that would be required for innovation.

In a period of sustained low growth, even with regional development policies to stimulate convergence there would be limited impact on the overall balance of the economy. As a result, there would be a slow levelling-up of the UK with some re-distribution of growth away from London and Wider South East to address the growth pressures but at a low rate.

Table 14 Scenario C: Slow Levelling-Up - Distribution of jobs by mega-region

Jobs (million)	**1981***	**1991***	**2001**	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	7.6	8.7	9.9	11.2	12.8	12.7	12.3	11.9
Midlands	3.4	3.9	4.1	4.6	4.9	5.0	5.3	5.6
South West	1.6	2.0	2.3	2.5	2.7	2.7	2.9	3.0
N England	5.4	5.7	6.1	6.8	7.1	7.3	7.7	8.1
Wales	0.9	1.1	1.2	1.3	1.4	1.4	1.5	1.6
Scotland	2.1	2.1	2.3	2.5	2.5	2.6	2.7	2.9
All Britain	19.2	23.4	27.3	28.9	31.4	31.8	32.4	33.1

% change/year	**1981-91**	**1991-01**	**2001-11**	**2011-20**	**2020-31**	**2031-51**	**2051-71**
London & WSE	1.36%	1.31%	1.27%	1.44%	-0.04%	-0.15%	-0.16%
Midlands	1.26%	0.64%	0.98%	0.85%	0.20%	0.26%	0.26%
South West	2.45%	1.27%	1.16%	0.62%	0.19%	0.26%	0.26%
N England	0.52%	0.60%	1.07%	0.57%	0.19%	0.26%	0.26%
Wales	1.36%	0.76%	1.41%	0.47%	0.19%	0.26%	0.26%
Scotland	-0.24%	1.04%	0.94%	0.17%	0.18%	0.26%	0.26%
All Britain	2.02%	1.53%	0.59%	0.93%	0.10%	0.10%	0.10%

Table 15 Scenario C: Slow Levelling-Up - Distribution of dwelling stock by mega-region

Dwellings (million)	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	9.6	10.3	10.4	10.6	10.7
Midlands	4.3	4.7	4.8	4.9	5.1
South West	2.4	2.6	2.6	2.7	2.8
N England	6.6	7.0	7.1	7.3	7.5
Wales	1.4	1.4	1.4	1.4	1.4
Scotland	2.5	2.5	2.5	2.5	2.5
All Britain	26.8	28.5	28.8	29.4	30.0

% change/year	2011-20	2020-31	2031-51	2051-71
London & WSE	0.86%	0.07%	0.08%	0.07%
Midlands	0.78%	0.20%	0.18%	0.17%
South West	0.92%	0.14%	0.16%	0.17%
N England	0.64%	0.11%	0.11%	0.12%
Wales	0.12%	0.04%	0.04%	0.05%
Scotland	0.10%	-0.04%	-0.02%	0.00%
All Britain	0.69%	0.10%	0.10%	0.10%

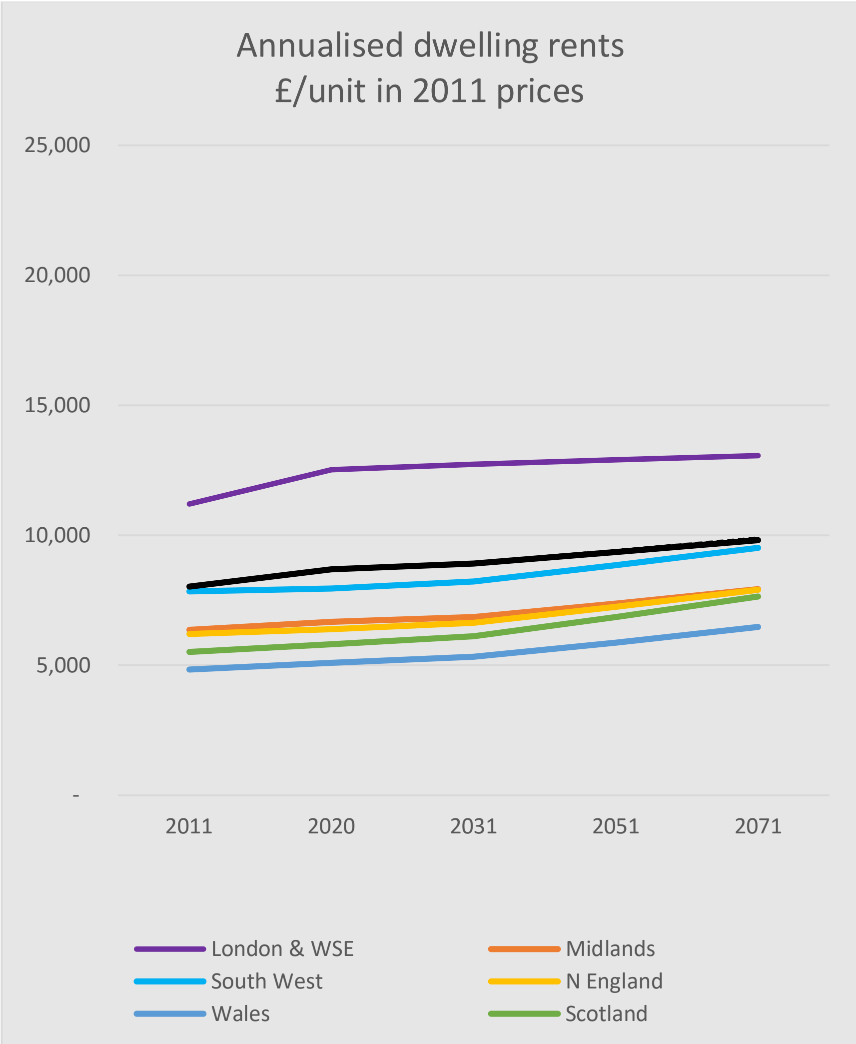

Figure 16 **Slow Levelling-up: A gradually convergent growth pattern does affect the balance of growth, but the lower rates of overall growth constrains the resources available for major interventions**

Table 16 Scenario C: Slow Levelling-Up - Changes in average dwelling rents by mega region

Dwelling rents (annualised £/unit in 2011 prices)					
	2011	2020	2031	2051	2071
London & WSE	11,200	12,519	12,730	12,899	13,060
Midlands	6,359	6,670	6,848	7,363	7,924
South West	7,841	7,951	8,223	8,855	9,517
N England	6,201	6,385	6,638	7,250	7,907
Wales	4,839	5,100	5,330	5,878	6,470
Scotland	5,519	5,813	6,119	6,849	7,641
All Britain	8,027	8,687	8,913	9,352	9,813
Average Earnings Trend	8,027	8,720	8,962	9,421	9,904
% change/year		2011-20	2020-31	2031-51	2051-71
London & WSE		1.25%	0.15%	0.07%	0.06%
Midlands		0.53%	0.24%	0.36%	0.37%
South West		0.16%	0.31%	0.37%	0.36%
N England		0.33%	0.35%	0.44%	0.44%
Wales		0.59%	0.40%	0.49%	0.48%
Scotland		0.58%	0.47%	0.57%	0.55%
All Britain		0.88%	0.23%	0.24%	0.24%

4.4 Scenario D: Dynamic Recovery

In Scenario D (Dynamic Recovery) an increasingly more convergent spread of growth would ease growth pressures in London and the South, and increase economic performance in the rest of the UK, reducing patterns of inequality and skills gaps. New jobs, linked to higher incomes and productivity, would be created outside the London and the South first in growth hubs, and then spread from there to the wider region.

Higher levels of growth would be expected to result in dynamic recovery of the UK despite the COVID-19 shock. This would be reflected in a more spread of growth easing excessive growth pressures in London and Wider South East and increasing local economic performance in the rest of the UK and reducing the patterns of inequality and skills gap across the nations and regions of the UK.

Dynamic Recovery also implies a demand for new jobs, linked to higher incomes associated productivity levels, through the creation and expansion of new growth hubs outside the London and the Wider South East (the centres of excellence for example referred to in the UK2070 Final Report). To use an analogy, the economy moves from flying with one big, highly strained engine to an economy which is driven by multiple and distributed engines, increasing the overall capacity, performance and resilience to risk.

Table 17 Scenario D: Dynamic Recovery - Distribution of jobs by mega-region

Jobs (million)	**1981***	**1991***	**2001**	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	7.6	8.7	9.9	11.2	12.8	13.3	14.2	15.0
Midlands	3.4	3.9	4.1	4.6	4.9	5.3	6.1	7.0
South West	1.6	2.0	2.3	2.5	2.7	2.9	3.3	3.8
N England	5.4	5.7	6.1	6.8	7.1	7.6	8.8	10.1
Wales	0.9	1.1	1.2	1.3	1.4	1.5	1.7	2.0
Scotland	2.1	2.1	2.3	2.5	2.5	2.7	3.1	3.6
All Britain	19.2	23.4	27.3	28.9	31.4	33.4	37.2	41.6
% change/year		**1981-91**	**1991-01**	**2001-11**	**2011-20**	**2020-31**	**2031-51**	**2051-71**
London & WSE		1.36%	1.31%	1.27%	1.44%	0.41%	0.30%	0.29%
Midlands		1.26%	0.64%	0.98%	0.85%	0.65%	0.71%	0.71%
South West		2.45%	1.27%	1.16%	0.62%	0.64%	0.71%	0.71%
N England		0.52%	0.60%	1.07%	0.57%	0.64%	0.71%	0.71%
Wales		1.36%	0.76%	1.41%	0.47%	0.64%	0.71%	0.71%
Scotland		-0.24%	1.04%	0.94%	0.17%	0.63%	0.71%	0.71%
All Britain		2.02%	1.53%	0.59%	0.93%	0.55%	0.55%	0.55%

Table 18 Scenario D: Dynamic Recovery - Distribution of dwelling stock by mega-region

Dwellings (million)	**2011**	**2020**	**2031**	**2051**	**2071**
London & WSE	9.6	10.3	11.0	12.2	13.5
Midlands	4.3	4.7	5.0	5.7	6.4
South West	2.4	2.6	2.8	3.1	3.5
N England	6.6	7.0	7.5	8.4	9.4
Wales	1.4	1.4	1.5	1.6	1.8
Scotland	2.5	2.5	2.6	2.8	3.1
All Britain	26.8	28.5	30.3	33.8	37.7

% change/year	2011-20	2020-31	2031-51	2051-71
London & WSE	0.86%	0.52%	0.53%	0.52%
Midlands	0.78%	0.66%	0.63%	0.62%
South West	0.92%	0.59%	0.61%	0.62%
N England	0.64%	0.56%	0.56%	0.57%
Wales	0.12%	0.49%	0.49%	0.50%
Scotland	0.10%	0.41%	0.43%	0.45%
All Britain	0.69%	0.55%	0.55%	0.55%

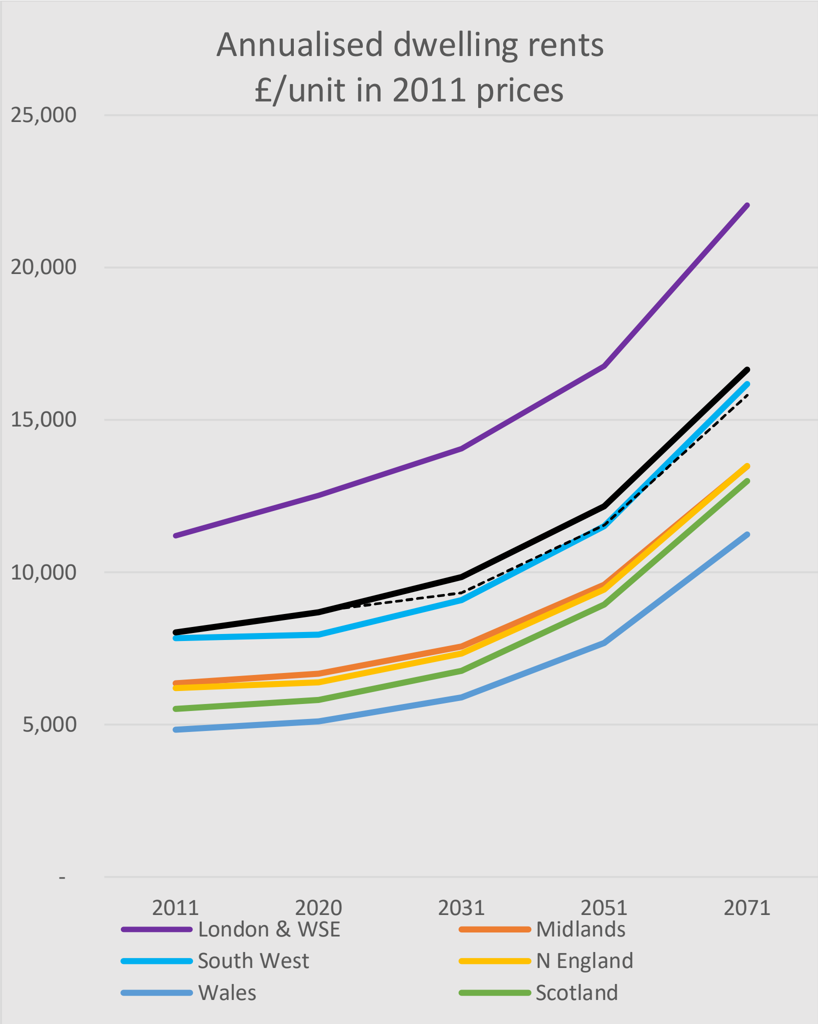

Figure 17 Scenario D: **Dynamic Recovery: A rapid convergent growth pattern creating more balanced growth**

Table 19 Scenario D: Dynamic Recovery - Changes in average dwelling rents by mega region

Dwelling rents (annualised £/unit in 2011 prices)					
	2011	2020	2031	2051	2071
London & WSE	11,200	12,519	14,060	16,762	22,045
Midlands	6,359	6,670	7,570	9,593	13,479
South West	7,841	7,951	9,087	11,522	16,179
N England	6,201	6,385	7,337	9,438	13,491
Wales	4,839	5,100	5,899	7,679	11,236
Scotland	5,519	5,813	6,768	8,935	12,999
All Britain	8,027	8,687	9,849	12,167	16,653
Average Earnings Trend	8,027	8,720	9,327	11,550	15,806
% change/year		2011-20	2020-31	2031-51	2051-71
London & WSE		0.56%	0.58%	0.88%	1.38%
Midlands		0.24%	0.64%	1.19%	1.72%
South West		0.07%	0.67%	1.19%	1.71%
N England		0.15%	0.70%	1.27%	1.80%
Wales		0.26%	0.73%	1.33%	1.92%
Scotland		0.26%	0.76%	1.40%	1.89%
All Britain		0.40%	0.63%	1.06%	1.58%

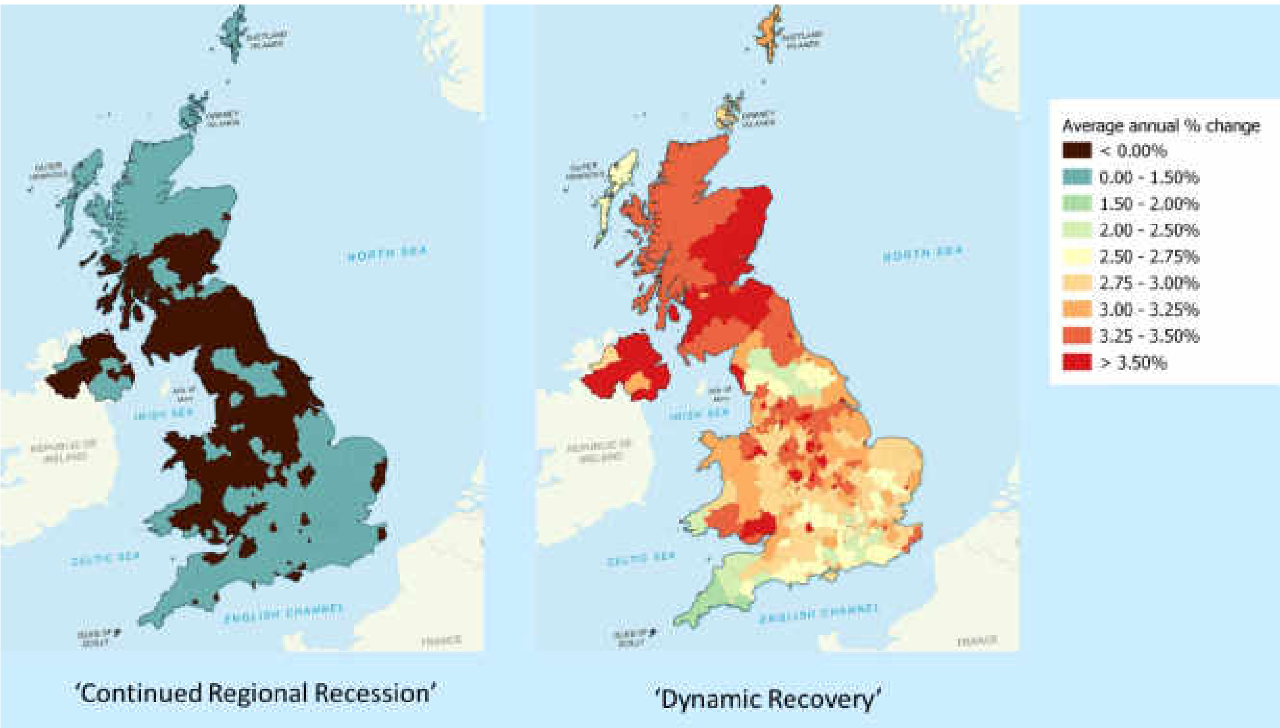

Figure 18 The most stark comparison of dwelling rent patterns is between Scenario B and D

4.5 Wider impacts: effects on productivity

A long term, gradual reconfiguration of the jobs, along with a rise in the higher skilled jobs, would create many more highly dense areas at a density of central London, Birmingham, Manchester, Edinburgh and Glasgow. This raises the effective economic density (which can be understood as the level of the overall mass of economic activity), and according to HM Treasury and DfT transport project assessment guidance, this increase in effective economic density and mass raises per job productivity through urban agglomeration effects.

The increase in per job productivity under modest population growth is important, because it generates the wealth and taxes to pay for major infrastructure investment. The reconfiguration of jobs and housing growth also makes better use of the environmental capacity of the UK regions and countries, which would ensure more sustainable longer term development.

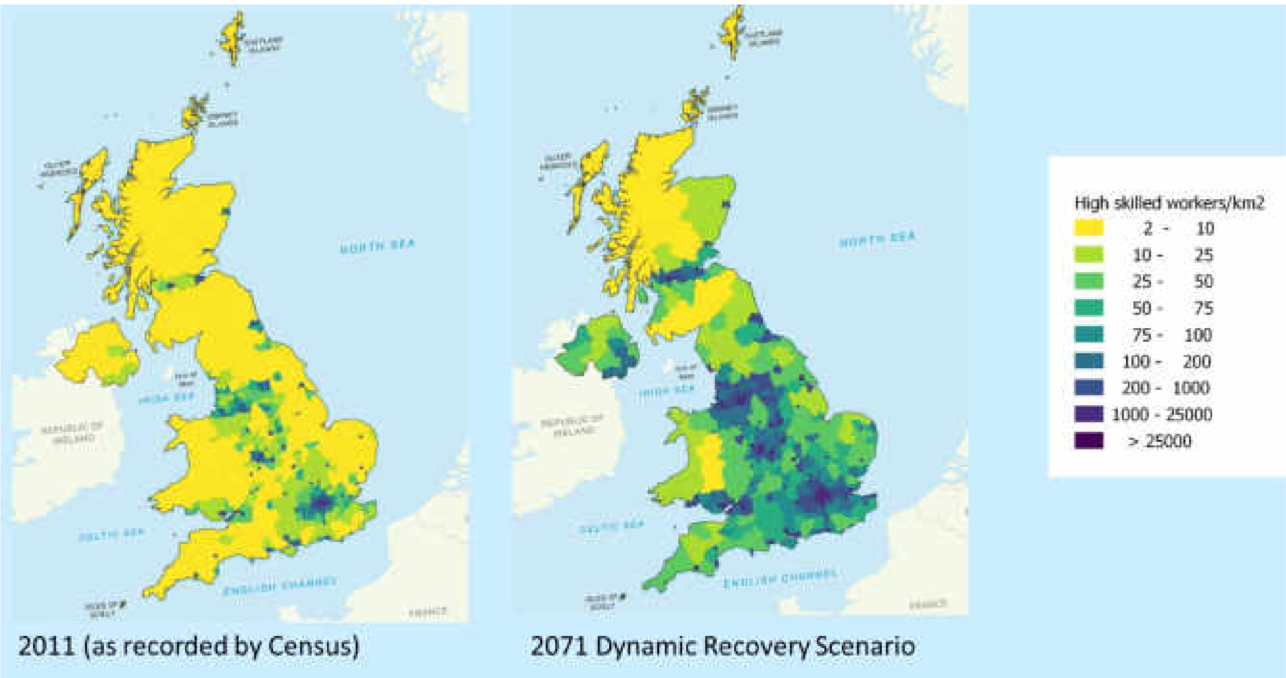

Figure 19 Distribution of the density of higher skilled workers: 2071 vs 2011

Figure 20 tells the story of productivity effects through:-

(1) the historic trends of 1960-2007 when per job productivity grew by 2.2% a year;
(2) the trends of 2010-2019 which saw average growth of 0.6% a year (but the 2007-2020 (Q1) average was 0.04% a year);
(3) the black line, which divides areas A and B, indicates the trajectory of the Dynamic Recovery Scenario: according to the assumptions for this scenario, the target for per job productivity is for it to rise gradually from 0.5% per year in 2021 to 2.95% in 2070; If there is more progress made in the 2030s, the UK could make up more loss from the current crisis, and the path to 2070 would become less steep;
(4) In other words, the Dynamic Recovery scenario represents a lower growth trajectory than the pre-COVID the High Growth upper bound, which was expecting a 1.8% a year continuous growth; Area A is a theoretical loss from COVID-19;
(5) How does the Dynamic Recovery scenario target compare with the growth that we are likely to generate from the reconfigured economic activities and transport improvements? Area D in Figure 20 shows that the effective economic density effects from the reconfigured economic activities and transport improvements would generate up to 1.7% of productivity growth per year by 2071.

Table 20 traces through this contribution over the years, and shows that this part of the contribution account for 100% in 2021 (because local transport improvements could bring an immediate productivity effect) and its share gradually declines to 39% by 2071 even though the magnitude of the effect grows – the decline in the share of contribution is simply because effects from skills and other policies pick up;
(6) The increase in the share of higher skilled jobs would generate an additional productivity uplift which starts from a 6% share in the total productivity contribution in 2031 to 27% in 2071;
(7) The combined effects of spatial planning and skills would not by themselves reach the productivity targets for this scenario – additional productivity gains need to be generated in wider policy areas, e.g. through the promotion of AI technology, business management, market competition, etc. This would account for between 42% in 2031 to 34% in 2071 of the total contribution.

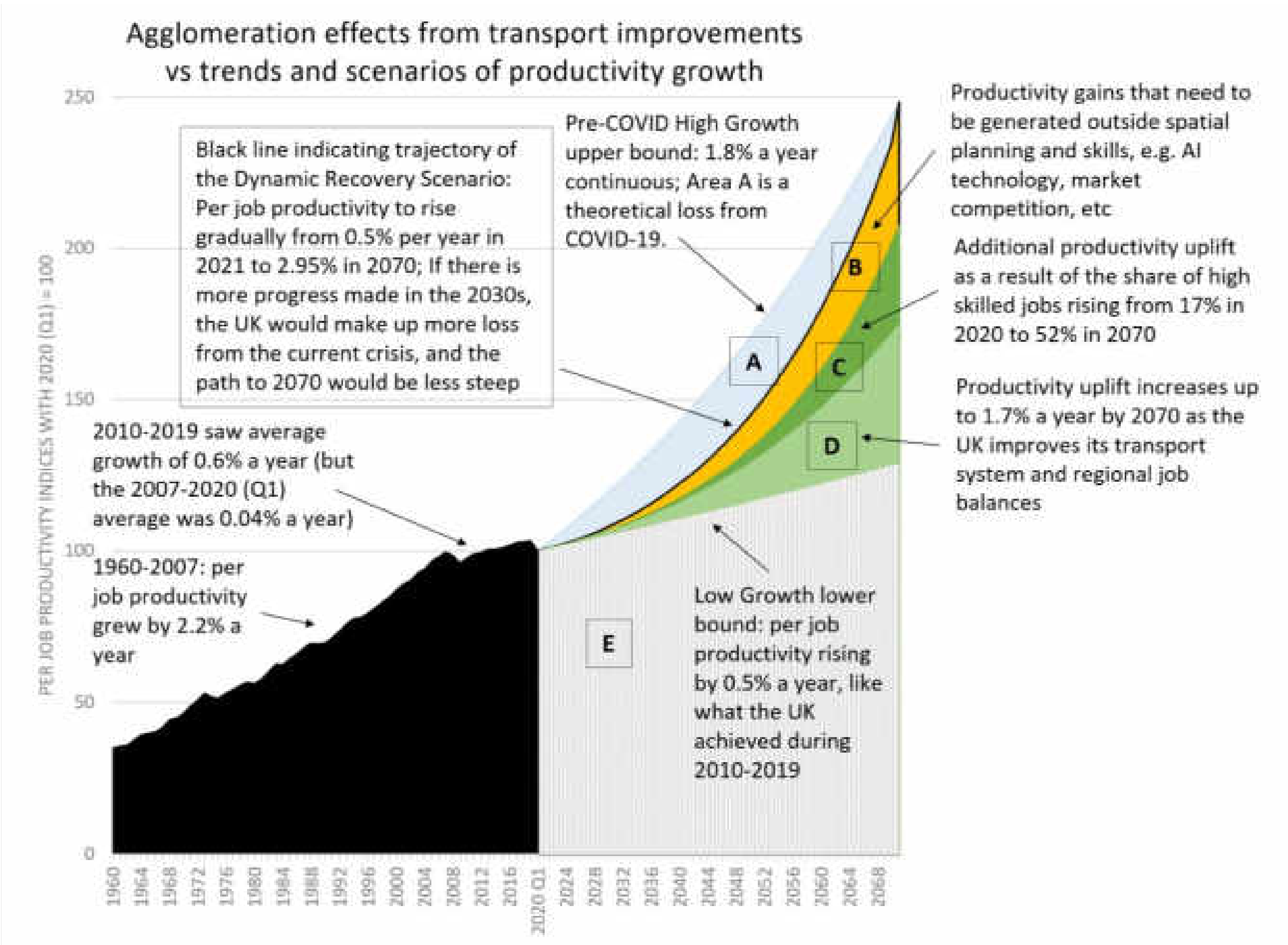

Figure 20 Agglomeration effects from spatial reconfiguration of jobs and transport improvements: a comparison with the historic trends and scenarios of productivity growth
Sources: 1960-2020 (Q1): ONS output per filled job of the whole UK economy;2020 (Q1) – 2070: UK2070 Futures scenario tests

Table 20

	2020 Q1	2021	2031	2041	2051	2061	2071
Productivity levels in percentage indicies (2020 Q1 = 100)							
Low Growth Scenario	100.0	100.5	105.6	111.0	116.7	122.7	129.0
Pre-COVID High Growth Scenario	100.0	101.8	121.7	145.4	173.9	207.8	248.4
Dynamic Recovery Scenario	**100.0**	**100.6**	**109.0**	**124.0**	**147.8**	**184.7**	**248.4**
Differences among scenarios							
Theoretical loss: compared with Pre-COVID High Growth	**0.00**	**1.25**	**12.6**	**21.4**	**26.0**	**23.1**	**0.0**
Growth over and above the Low Growth Scenario	**0.00**	**0.05**	**3.4**	**13.0**	**31.1**	**62.1**	**119.5**
Contribution from spatial planning	0.00	0.05	1.7	6.2	14.2	27.0	46.2
Contribution from up-skilling	0.00	0.00	0.2	1.4	4.9	13.5	32.5
Contriubtion that needs to come from other policy areas	0.00	0.00	1.4	5.4	12.0	21.5	40.7
Contribution from all policy areas	**0.00**	**0.05**	**3.4**	**13.0**	**31.1**	**62.1**	**119.5**
Percentage share of contributions (%)							
Contribution from spatial planning		100%	51%	48%	46%	44%	39%
Contribution from up-skilling		0%	6%	11%	16%	22%	27%
Contribution that needs to come from other policy areas		0%	42%	42%	39%	35%	34%
Contribution from all policy areas		100%	100%	100%	100%	100%	100%

Person Productivity Levels 2020-2071: A Comparison among Scenarios

Convergent high growth would imply not only raised incomes, but also better social inclusion. Through the creation and expansion of new growth areas outside London and the WSE the level of social deprivation would also reduce (see Figure 21).

In a manner of speaking, this is like to move from flying with one big, highly strained engine (London and the South East) to multiple and distributed engines. This would still allow London and WSE to grow sustainably, and at the same time increase the overall capacity for growth. This would significantly enhance the productivity performance of the UK, and ensure better resilience. Similarly, it can be compared refitting the navy with a dependency on a single flagship with limited support vessels to a high-performance complementary fleet with capacity and flexibility to respond to multiple tasks.

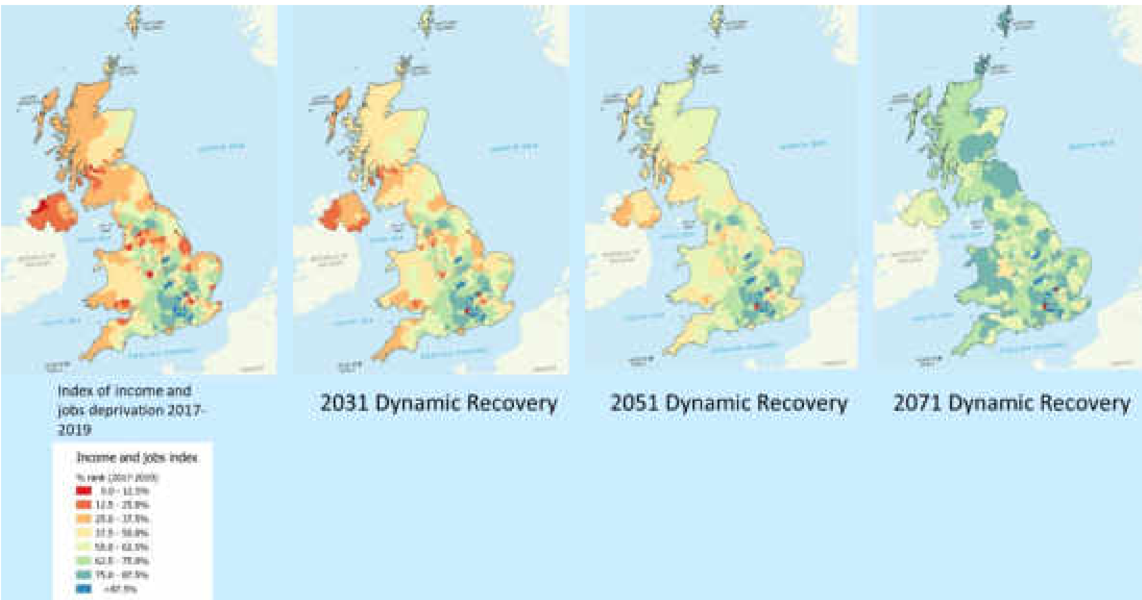

Figure 21 Modelled income and employment deprivation levels: a comparison of the 2020 Base Condition with the 2031, 2051 and 2071 Dynamic Recovery Scenario

5. Conclusions

The new scenario analyses presented in this report update the team's previous research for the UK2070 Commission.

Given all the on-going uncertainties with Covid mitigation, global trade and geopolitical shifts, it is not possible to predict with confidence the UK's short term economic outlook. The scenario tests instead seek to examine the longer-term eventualities. The current, keenly-felt uncertainties have not done away with any of the underlying trends which are expected to continue shaping the UK's constituent countries and regions.

The main finding from the scenario tests is that new, feasible pathways to sustainable and vigorous long-term growth do exist, but this would need to involve a geographic reconfiguration of the patterns of growth in jobs and housing plus coordinated transport investment. In other words, a radical new approach to spatial planning would hold the key to such growth pathways.

Out of a large number of alternative options considered, this report is focused on four distinct spatial planning scenarios that demonstrate that the differences in policy outcomes between them could imply making or breaking the UK. The central idea that emerges from the scenario work is that a regional reconfiguration of jobs, housing and transport, making use of the essential endowment and resources already present in the countries and regions, would not only increase average per person productivity, but also establish new engines of growth and prosperity outside London and the Wider South East.

The findings suggest that this big policy jolt purely on the basis of large scale capital investment in infrastructure alone will not be sufficient. Continued low interest rates may allow to investment in highly productive ventures but alone it would not result in the required growth in productivity. This report therefore examines how areas can raise productivity faster and spread this growth momentum across all countries and regions in the UK. This requires spatial planning drawing upon past experience of what has made areas prosperous.

A comparison among the four main scenarios demonstrates that:

- Irrespective of the underlying rate of economic growth being low or high, a continuation of the current patterns of diverging economic fortunes would result in two distinct realms of regional change that are effectively separated by the Watford Gap: the growth dynamics of London, the wider South East and to some extent the South West would be so different from those for the rest of England and the devolved countries that the two realms may just well be considered as two different nations – this is particularly apparent under Scenario A)
- Under low rates of economic growth, the progress of levelling-up would prove slow and inconsequential (as shown under Scenarios B and C)
- The differences in policy outcomes between them would effectively imply making or breaking the UK's overall growth prospects: London and the South account for half of the UK's economic output, and if this is to be the only area that grows in the future, the hard work of delivering this growth would achieve half of the potential the UK has
- Only with progressively raised per person productivity under Scenario D (i.e. "Dynamic Recovery") could the UK consider an effective convergent regional growth agenda, and a gradual rebalancing between capabilities to deliver housing growth and jobs under this growth scenario could reap significant productivity, social and environmental benefits. This dynamic building of the growth momentum not only generates its own funding streams through raised per worker productivity, but also helps to inspire confidence through the accumulation of initial successes.

The differences in productivity growth that arise from the readjustments to the spatial layout of growth and transport connections, when assessed with HM Treasury and DfT agglomeration elasticities, show the potential to increase longer term average per person productivity by 1.7% per year for the UK as a whole, and more than 3% per year for knowledge-based sectors. This contribution through spatial planning, when coordinated with a forward-looking future jobs programme and wider policies, could thus raise UK's GDP growth from well below 1% today to more than 3% in the longer term.

The central message is that a regional reconfiguration of jobs, housing and transport, making use of the essential endowment and resources already present in the countries and regions, would not only increase average per person productivity, but also establish new engines of growth and prosperity outside London and the Wider South East. A scaling up of productivity in the currently low productivity areas (which covers three quarters of the population) directly contributes to the overall levels of productivity in the UK; the expanded economic mass will also provide opportunities to extend innovation through a richer and more diverse eco-system and more attraction to external direct investment. The significance of those programmes would ultimately determine the overall potential for the UK's environmental sustainability, wealth and quality of life, and whether the UK's constituent parts could prosper together or diverge in their separate ways.

Additionally, the scenario predictions reported here, particularly those regarding the demand for housing and transport, would help work out the precise specifications of local as well as national investments that collectively achieve the 'big jolt'. Such specifications at the individual site and project level are best worked in a rolling programme: the effects of the initial investments should be assessed against the long term benchmarks in the scenario predictions so that specifications and timescales can be adapted to what is feasible. This rolling programme would seem the most effective for managing the inherent uncertainties going forward.

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7. Study Team, Acknowledgements and Disclaimers

The Study Team for this work comes from the Cities and Transport Research Group, within the Martin Centre for Architectural and Urban Studies, Department of Architecture, University of Cambridge.

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The usual disclaimers apply and the Study Team is solely responsible for the model analyses, views expressed and any remaining errors.

This model appendix is organized as follows. Section A1 introduces the formal structure of the LUISA2.3 model. Section A2 discusses the model solving algorithm in a step-by-step manner. Section A3 summarizes the zoning system in the model. Lists of model variables and behavioural parameters are provided in Section A4. Further technical details are available from the Martin Centre team at University of Cambridge.

A1 Structure of the LUISA2.02 Model

Suppose that the city region is divided into $\mathfrak{J}$ core zones plus $\wp$ peripheral zones. Core zones represent the core study area where detailed policy analyses are conducted with relatively fine spatial granularity; while the peripheral zones represent the wider region outside the core study area which exchanges production factors (e.g. labour) and trades goods & services with the core zones. $\mathbb{N} = \mathfrak{J} + \wp$ thus denotes all modelled zones. Each of the model zones has $r = 1, \ldots, \mathcal{R}$ basic industries and $f = 1, \ldots, F$ consumer types. Table 21 summarizes the model segmentations in the model.

TABLE 21 SEGMENTATIONS IN THE MODEL

	Industry types	Consumer types	Residential floorspace types	Commercial floorspace types
Core zones	$r = 1, \ldots, \mathcal{R}$	$f = 1, \ldots, F$	$m = 1, \ldots, \aleph_1$	$k = 1, \ldots, \aleph_2$
Peripheral zones	$r = 1, \ldots, \mathcal{R}$	$f = 1, \ldots, F$	$m = 1, \ldots, \aleph_1$	$k = 1, \ldots, \aleph_2$

We introduce the following model components in turn: producers, final consumers, location choices, stock constraints and equilibrium conditions.

A1.1 Producers

The producers are represented by a set of production functions that define how they use capital, labour, floorspace and intermediate inputs (raw materials and services). A nested Cobb-Douglas CES (CD-CES) function has been broadly accepted as a standard for this purpose in spatial general equilibrium analyses since Krugman (1991) and Fujita et al. (1999). We follow Anas and Liu (2007) and Jin et al. (2013), and define the production function as a variant of the CD-CES specification.

$$X_{rj} = E_{rj} A_{rj} (K_r)^{\nu_r} \left(\sum_f \kappa_{rfj} L_{fj}^{\theta_r}\right)^{\frac{\delta_r}{\theta_r}} \left(\sum_k \chi_{rkj} B_{kj}^{\zeta_r}\right)^{\frac{\mu_r}{\zeta_r}} \prod_s (Y_{rsj})^{\gamma_{rs}} \tag{1}$$

where X_{rj} is the production output of industry r in zone j; K_r, L_{fj}, B_{kj} and Y_{rsj} are the capital, labour, business floorspace and intermediate input, respectively; ν_r, δ_r, μ_r and γ_{rs} are cost share parameters for the respective input group. This function is Cobb-Douglas and is constant returns to scale by $\nu_r + \delta_r + \mu_r + \sum_s \gamma_{rs} = 1$. The elasticity of substitution between any two labour and building floorspace varieties is $1/(1-\theta_r)$ and $1/(1-\zeta_r)$, respectively. $\kappa_{rfj}, \chi_{rkj} \geq 0$ are input-specific constants for labour and business floorspace varieties, respectively. These constants allow us to specify input-specific preference within each input bundle. A_{rj} is a function of the economic mass for industry r in zone j that represents Hicksian-neutral Total Factor Productivity (TFP) effects resulting from learning and transfer of tacit knowledge (Graham & Kim, 2008; Rice, Venables, & Patacchini, 2006), which is an important component of urban agglomeration effects. E_{rj} is a constant scalar representing any additional zonal effects on total factor productivity. We define $A_{rj} = \underline{A}_{rj}(M_j/\underline{M}_j)^{\pi}$, where $\underline{A}_{rj}$ is a constant representing the baseline agglomeration effects, M_j is a function of the economic mass of zone j, $\underline{M}_j$ is a constant representing the baseline economic mass in j; π is a scale parameter. The function of economic mass builds on the concept of effective density (Graham, Gibbons, & Martin, 2009).

$$M_j = \sum_f \sum_i \frac{L_{fi}}{\chi_{fij}} \tag{2}$$

where L_{fi} is the total size of labour type f in zone i (including zone j) that is relevant to production zone j, and χ_{fij} is the travel time from location i to j for labour type f.

We assume that each firm minimizes the cost subject to the production demand and the price of each input variety. The *conditional input demand* (given target output X_{rj}) of each input factor can be derived as follows:

$$K_r = \frac{1}{\rho} \nu_r p_{rj} X_{rj} \tag{3}$$

$$L_{rfj} = \frac{\kappa_{rfj}^{\frac{1}{1-\theta_r}} w_{fj}^{\frac{1}{\theta_r - 1}}}{\sum_s \kappa_{rsj}^{\frac{1}{1-\theta_r}} w_{sj}^{\frac{\theta_f}{\theta_r - 1}}} \delta_r p_{rj} X_{rj} \tag{4}$$

$$B_{rkj} = \frac{\chi_{rkj}^{\frac{1}{1-\zeta_r}} R_{kj}^{\frac{1}{\zeta_r - 1}}}{\sum_s \chi_{rsj}^{\frac{1}{1-\zeta_r}} R_{sj}^{\frac{\zeta_r}{\zeta_r - 1}}} \mu_r p_{rj} X_{rj} \tag{5}$$

$$Y_{rsj} = \frac{\gamma_{rs} p_{rj} X_{rj}}{p_{rs|j}^*} \tag{6}$$

where p_{rj} is the unit production price of industry r in zone j; ρ is the exogenous price of business capital (i.e. the real interest rate); w_{fj} is the hourly wage of labour type f; R_{kj} is the average rent for business floorspace type k; and $p_{rs|j}^*$ is the average delivered price of intermediate input type s for producing product type r in zone j.
The minimized production price can then be calculated by substituting the above conditional demands into the production function. As zero profit is assumed at any level of output, the minimized price equals the average and the marginal cost, which takes the form:

$$p_{rj} = \frac{\rho^{\nu_r} \left(\sum_f \kappa_{rfj}^{\frac{1}{1-\theta_r}} w_{fj}^{\frac{\theta_r}{\theta_r - 1}} \right)^{\frac{\delta_r \theta_r - 1}{\theta_r}} \left(\sum_k \chi_{rkj}^{\frac{1}{1-\zeta_r}} R_{kj}^{\frac{\zeta_r}{\zeta_r - 1}} \right)^{\frac{\mu_r \zeta_r - 1}{\zeta_r}} \prod_m {p_{rs|j}^*}^{\gamma_{rs}}}{E_{rj} A_j \nu_r^{\nu_r} {\delta_r}^{\delta_r} \mu_r^{\mu_r} \prod_s \gamma_{rs}^{\gamma_{rs}}} \tag{7}$$

A1.2 Final Consumers

Final consumers are categorized into $f = 1, \dots, F$ types according to their employment status and socio-economic level. H_f is the exogenous number of consumers in group f. Consumers in socio-economic group f receive both wage and nonwage income, except group $f = F$ denoting the non-employed consumers who do not have wage income but receive nonwage income through social welfare transfer. The wage income is modelled endogenously subject to equilibrium conditions, while the nonwage income is subject to the *a priori* welfare transfer scheme.
Each consumer makes a set of discrete and continuous choices. For discrete choices, the employed residents decide where to work and where to live jointly from $j = 1, \dots, \mathbb{N}$ employment zones and $i = 1, \dots, \mathbb{N}$ residence zones; the non-employed residents choose their residence location from $i = 1, \dots, \mathbb{N}$ residence zones. Both the employed and non-employed consumers choose where to source goods & services from $z = 1, \dots, \mathbb{N}$ production zones. The remaining choices entail continues variables and are conditional on the above discrete location choices. Consumers then decide on: 1) the annual consumption of each goods & services variety; 2) the quantity of type m housing floorspace to rent; 3) the use of time between work and leisure in the case of employed consumers. All consumers are assumed to maximize their utility from the mixed discrete-continuous choice.

Following the random utility framework (McFadden, 1973), the utility of consumer type f living in zone i and working in zone j takes the form $U_{fij}^* = U_{fij} + e_{fij}$ where U_{fij} is the observable quantity-based utility and e_{fij} is the error term which measures the unobservable utility variance among consumers. The observable utility U_{fij} is given by:

$$U_{fij} = \alpha_f \ln\left(\sum_r \sum_z \xi_{rfz}\left(Z_{rz|fij}\right)^{\eta_f}\right)^{\frac{1}{\eta_f}} + \beta_f \ln\left(\sum_m \iota_{mfi}\left(b_{m|fij}\right)^{\sigma_f}\right)^{\frac{1}{\sigma_f}} + \gamma_f \ln l_{fij} \quad (8)$$

$$\textit{subject to budget constraint: } \sum_{r,z}\left(p_{rz} + c_f 2g_{fiz}\right)Z_{rz|fij} + \sum_m r_{mi} b_{m|fij} + \Delta_f 2Dg_{fij}$$

$$= \Delta_f w_{fj}\left(N - 2DG_{fij} - \sum_{r,z} c_f Z_{rz|fij} 2G_{fiz} - l_{fij}\right) + \mathcal{M}_{fi}$$

$$\textit{and time constraint: } \quad N - \sum_{r,z} c_f Z_{rz|fij} 2G_{fiz} - \Delta_f\left(l_{fij} + 2DG_{fij}\right) \geq 0$$

In equation (8), we assume Cobb-Douglas preference between goods & services $Z_{rz|fij}$, housing $b_{m|fij}$ and leisure time l_{fij}. $\alpha_f + \beta_f + \gamma_f = 1$ are the expenditure coefficients for each consumption bundle. The varieties of goods & services and housing are assumed to be imperfect substitutes (Dixit & Stiglitz, 1977), and the elasticity of substitution is governed by η_f and σ_f for goods & services and housing, respectively. $\xi_{rfz}, \iota_{mfi} > 0$ are the input-specific constants measuring the inherent attractiveness of the goods & services, and housing varieties for consumers type f, which is calibrated empirically.
For the budget constraint in equation (8), the right-hand side of the function is the total income and the left-hand side is the total expenditure. Specifically, p_{rz} is the mill price for goods & services type r produced in zone z; g_{fiz} and G_{fiz} is the expected one-way monetary cost and travel time from i to z for customers type f, respectively[2]; c_f is an exogenous coefficient that measures the cost for delivering a unit of goods & services as percentage of the normal trip cost. r_{mi} is the housing rent of type m in zone i; w_{fj} is the hourly wage rate for labour type f working in zone j. Δ_f is the employment status of the consumer type f. For all employed consumers $\Delta_f = 1$; otherwise $\Delta_f = 0$. $\mathcal{M}_{fi}$ is the nonwage income of consumer type f in zone i. It consists of normal investment returns on real estate in the city region (endogenous in the model) as well as the individual share of social welfare transfer and amenity gains (subject to *a priori* scheme). As for the time constraint, D is the exogenous number of working days per annum; $N = 24D$ is the exogenous total annual time endowment. For the non-employed consumers ($\Delta_f = 0$), the model only accounts for the time for shopping, as they do not commute and have zero value of time for leisure time.
We can rewrite the budget constraint in equation (8) to consider the value of time for shopping travel as a part of the delivered price. The new constraint function is equivalent to equation (8).

$$\sum_{r,z} p^*_{rz|fij} Z_{rz|fij} + \sum_m r_{mi} b_{m|fi} + \Delta_f 2Dg_{ij} \quad (9)$$
$$= \Delta_f w_{fj}\left(N - 2DG_{ij} - l_{fij}\right) + \mathcal{M}_{fi}$$

where $p^*_{rz|fij}$ is the full delivered price of a unit of goods & services type r produced in zone z purchased by consumer type f living in zone i and working in zone j. We use the subscript z to denote the production location of goods & services and j as the employment location for employed workers. The full delivered price for final consumers $p^*_{rz|fij}$ is given by:

$$p^*_{rz|fij} = p_{rz} + c_f 2\left(g_{iz} + \Delta_f G_{iz} w_{fj}\right) \quad (10)$$

Accordingly, the full disposable income of the consumer type (fij) net of commuting costs is given by:

$$\Omega_{fij} = \Delta_f w_{fj}\left(N - 2DG_{ij} - l_{fij}\right) - \Delta_f 2Dg_{ij} + \mathcal{M}_{fi} \quad (11)$$

Under the above budget and time constraint, we can then derive the *Marshallian* demand for goods & services, housing and leisure time in Eq. 3.12, Eq. 3.13 and Eq. 3.14, respectively.

[2] The monetary cost and travel time is composite over all available travel modes. For the moment, we do not consider the time-of-day and purpose variations in travel time and cost.

$$\bar{Z}_{r|fij} = \frac{\xi_{rfz}^{\frac{1}{1-\eta_f}} \bar{p}_{r|fij}^{\frac{1}{\eta_f - 1}}}{\sum_s \xi_{rfz}^{\frac{1}{1-\eta_f}} \bar{p}_{s|fij}^{\frac{\eta_f}{\eta_f - 1}}} \alpha_f \Omega_{fij} \tag{12}$$

$$b_{m|fij} = \frac{\iota_{mfi}^{\frac{1}{1-\sigma_f}} r_{mi}^{\frac{1}{\sigma_f - 1}}}{\sum_s \iota_{si}^{\frac{1}{1-\sigma_f}} r_{si}^{\frac{\sigma_f}{\sigma_f - 1}}} \beta_f \Omega_{fij} \tag{13}$$

$$l_{fij} = \frac{\gamma_f \Omega_{fij}}{w_{fj}} \tag{14}$$

where $\bar{Z}_{r|fij}$ is the aggregate demand for product type r for consumer type (fij); $\bar{p}_{r|fij}$ is the probability-weighted average price of product type r faced by consumer type (fij). The formulation of $\bar{p}_{r|fij}$ and $\bar{Z}_{r|fij}$ and the associated discrete-choice probability function will be introduced shortly.

In addition to the *Marshallian* utility function (maximizing utility subject to budget constraints), which is used in base-year model calibration, the model employs the *Hicksian* utility function in forecasts. The Hicksian utility function differs from the Marshallian utility function in that it minimizes the expenditure given fixed utility. The use of Hicksian utility function in forecast mode implies that consumers are assumed to maintain, if not increase, their base-year utility level in future years by altering their locational and consumption choices. Under the same Nested-CES configuration and parameterization, the Marshallian and Hicksian utility functions are consistent in base-year model calibration, in the sense that the derived Marshallian demands (given observed budget constraint) are identical to the Hicksian demands (given the Marshallian utility). In forecast mode, the Hicksian utility function will replace the Marshallian utility function. The implication is that consumers will have to raise the income if the cost of living (i.e. prices of goods & services and housing rents) goes up, in order to maintain the same utility level. The need for increasing income will then be represented by an upward pressure on labour wage. In case the cost of living goes down (e.g. abundance of housing supply), the model assumes that the local wage level would not decrease subject to global price adjustment. Nonetheless the resulting extra utility gain will be competed out in spatial equilibrium as more residents move into the area, which in turn drives up the cost of living. For the Hicksian utility function, the minimized expenditure given the utility U_{fij} is defined as:

$$\Omega_{fij}^{Hicksian} = \alpha_f^{-\alpha_f} \beta_f^{-\beta_f} \gamma_f^{-\gamma_f} \left[\left(\sum_r \sum_z \xi_{rfz}^{\frac{1}{1-\eta_f}} \bar{p}_{r|fij}^{\frac{\eta_f}{\eta_f - 1}} \right)^{\frac{\eta_{f-1}}{\eta_f}} \right]^{\alpha_f} \left[\left(\sum_m \iota_{mfi}^{\frac{1}{1-\sigma_f}} r_{mi}^{\frac{\sigma_f}{\sigma_f - 1}} \right)^{\frac{\sigma_f - 1}{\sigma_f}} \right]^{\beta_f} (w_{fj})^{\gamma_f} U_{fij} \tag{15}$$

The total annual labour working time N_{fij} for the employed consumer type (fij) is thus determined by subtracting the total travel time for commuting and shopping, and the annual leisure time from the annual time endowment N.

$$N_{fij} = N - 2DG_{ij} - \sum_{r,z} c_f Z_{rz|fij} 2G_{iz} - l_{fij} \geq 0 \tag{16}$$

The next step is to evaluate the direct utility function (8) to get the price-based indirect utility function $\widetilde{U}_{fij}$, which is given by:

$$\widetilde{U}_{fij} = \ln \Omega_{fij} - \alpha_f \frac{\eta_f - 1}{\eta_f} \ln \left(\sum_r \sum_z \xi_{rfz}^{\frac{1}{1-\eta_f}} \bar{p}_{r|fij}^{\frac{\eta_f}{\eta_f - 1}} \right) - \beta_f \frac{\sigma_f - 1}{\sigma_f} \ln \left(\sum_m \iota_{mfi}^{\frac{1}{1-\sigma_f}} r_{mi}^{\frac{\sigma_f}{\sigma_f - 1}} \right) - \gamma_f \ln w_{fj} \tag{17}$$

Note that the quantity-based and the price-based utility functions are mathematically equivalent in static equilibrium. However, for the purpose of welfare evaluation over time, particularly in long-term forecast that involves macroeconomic changes (e.g. price-level changes due to growth, inflation or deflation), the quantity-based direct utility function offers a more intuitive and straightforward measure than the price-based counterpart. Therefore, we use the price-based utility in static equilibria and the quantity-based utility for welfare analysis.

A1.3 Location Choices

The location choices in the model include: 1) sourcing goods & services for final consumers; 2) the employment-residence choice (or residence location choice if employment is exogenous) for the employed residents. Both location choices are modelled in the spatial equilibrium framework. Another important aspect of location choice modelling is the articulation of travel disutility. We summarize the measure of travel disutility in the model by the end of this section.

A1.3.1 Sourcing goods and services

In the model, consumers do not only decide the quantity of each product to purchase, but also where to source them. The former decision is based on average delivered price of each product thus is continuous in nature; while the latter choice is discrete involving limited number of location alternatives. We represent this mixed discrete-continuous choice problem by combining two different choice models. For the continuous choice on quantities, a nested CES function is applied to consider the substitution effects within the consumption bundle. For the discrete location choice, the sourcing pattern is modelled with a multinomial logit probabilistic model. The probability of obtaining product type r from zone z to consumer type f living in zone i (and working in zone j, if employed) is given by:

$$P_{rz|fij} = \frac{S_z \exp\left(-\lambda_{f|r}(p_{rz} + c_f \chi_{fiz} + \psi_{riz} - E_{rfz})\right)}{\sum_n S_n \exp\left(-\lambda_{f|r}(p_{rn} + c_f \chi_{fin} + \psi_{rin} - E_{rfn})\right)} \quad (18)$$

where S_z is a size term that corrects for the bias introduced by the uneven sizes of zones in the model (Ben-Akiva & Lerman, 1985); $\lambda_{f|r}$ is the dispersion parameter. c_f is a coefficient measuring the cost for delivering a unit of goods & services as percentage of normal trip cost; χ_{fiz} is a travel disutility function; ψ_{riz} are observable non-monetary barriers for trading between i and zone z; E_{rfz} is the residual attractiveness term which is calibrated empirically. In the model, consumers will shop to all potential production zones, rather than the zone with the cheapest delivered price only[3]. A similar probability function can be applied to model the sourcing of intermediate inputs for producers.

With the above probability, we can derive the weighted average price of product type r faced by consumer type (fij). Note that this weighted average price considers the consumption inputs from all possible production locations, thus the dimension is $[r]$.

$$\bar{p}_{r|fij} = \sum_z p^*_{rz|fij} P_{rz|fij} \quad (19)$$

where $p^*_{rz|fij}$ is the full delivered price including the value of time for travel. The purpose of deriving $\bar{p}_{r|fij}$ is to link the discrete location choice with the continuous choice of consumption quantities. For residents living in zone i, they first choose how much to consume for each product type $(\bar{Z}_{r|fij})$, regardless of the their production locations. This continuous choice is made based on the weighted average price $\bar{p}_{r|fij}$ through CES functions. The discrete-choice probability in Eq. 3.17 then distributes the aggregate demand $\bar{Z}_{r|fij}$ to each production location z. This distribution process is given by:

$$Z_{rz|fij} = P_{rz|fij} \bar{Z}_{r|fij} \quad (20)$$

This function is used to derive the total production demand for product type r in zone z.

A1.3.2 Employment/residence location choice

In the model, we differentiate the location choice of employed residents and the non-employed. For employed residents we assume that they respond quickly to the utility changes and are mobile in terms of employment-residence relocation in static equilibria. By contrast, the relocation of non-employed residents is inertia-prone, i.e. there may be a lag of many years between a utility change and household relocation. We thus deal the relocation of non-employed households outside the equilibrium framework through recursive dynamic model or model assumptions. This section first introduces the discrete choice model for employment-residence

[3] By “shop” we refer to any non-work trip that involves the purchase of goods and services. We ignore trip chains and travels that do not originate from home.

joint choice. The residence location choice model as an abridged version the former model will be discussed afterwards.
For the employment-residence choice of employed residents, a multinomial logit model is developed. The probability of consumer f working in zone j choosing to live in zone i is defined as:

$$P_{fij} = \frac{S_{ij}\exp\left(\lambda_f v_{fij}\right)}{\sum_{m,n} S_{mn}\exp\left(\lambda_{fI} v_{fmn}\right)} \quad (21)$$

where

$$v_{fij} = \widetilde{U}_{fij} - d_{fij} + \psi_{fij} + E_{fij} + e_{fij} \quad (22)$$

S_{ij} is the a size term that addresses the size of residence/employment opportunities in zone i/j; $\lambda_{f|I}$ is the dispersion parameter; $\widetilde{U}_{fij}$ is the consumption utility of consumer f living in zone i and working in zone j; d_{fij} is the travel disutility of travelling from zone i to j; E_{fij} is the residual attractiveness of location pair (i,j), and e_{fij} is the unobserved error term.
For the residence choice of employed residents, the probability of consumer f choosing to live in zone i, given the employment location j, is defined as:

$$P_{fi|j} = \frac{S_i\exp\left(\lambda_{f|I} v_{fi|j}\right)}{\sum_m S_m\exp\left(\lambda_{f|I} v_{fm|j}\right)} \quad (23)$$

where

$$v_{fi|j} = \widetilde{U}_{fi|j} - d_{fi|j} + \psi_{fi|j} + E_{fi|j} + e_{fi|j} \quad (24)$$

$v_{fi|j}$ is the residence location utility of zone i for resident type f, given the chosen workplace j; $\lambda_{f|I}$ is the dispersion parameter. The other variables follow the same definitions as in function v_{fij}, except that the employment location j is given.
A1.3.3 Travel disutility
In the model, the χ_{fij} function is introduced to represent the attributes of travel for traveller type f from i to j. We differentiate the χ_{fij} function for different uses throughout the model. In this section, we summarize the use of the χ_{fij} function. For measuring the economic mass (as in Eq. 2), we define $\chi_{fij} = 2G_{fiz}$, which is the round-trip travel time (in hourly term) between zone i and j for traveller type f.
For sourcing goods & services (as in Eq. 18), we define $\chi_{fiz} = 2(g_{fiz}/\varsigma_f \overline{w}_{fi} + G_{fiz})$, where $\overline{w}_{fi}$ is the average hourly wage of type-f employed residents living in zone i[4], and $\varsigma_f \in (0,1]$ is a decay coefficient, implying that the shopping trip being partly voluntary thus its value of time is not fully valued by the traveller. The front multiplier transforms the one-way cost into round-trip cost (de Dios OrtÃozar & Willumsen, 2011). The above formulation adopts the time unit (hour), and considers both the travel time and the monetary cost. The monetary cost is transformed into time unit by dividing it by the value of time $\varsigma_f \overline{w}_{fi}$. Note that this time-based travel disutility is only used for modelling location choices. The actual transport costs, including the value of time, are measured in monetary unit in the equilibrating process.
For the employment-residence location choice, it is important to consider the realistic commuting patterns within a large city region. City regions with reasonably self-contained commuting catchment today tend to have a radius of 50km or more. At this metropolitan scale, extensive analyses of travel choices data show that a d_{ij} function (as in Eq. 22) that is linear to travel costs and times will have great difficulties in representing realistic demand elasticity throughout (Jin et al., 2013); a non-linear transformation of utilities is required (Gaudry & Laferriére, 1989). Fox et al (2009) devise a log-linear transformation that is a close equivalent to the Box-Cox function whilst being easier to calibrate. This function is given by:

$$d_{fij} = a_{f|d}\chi_{fij} + \left(1 - a_{f|d}\right)\ln \chi_{fij} - a_{f|d} \quad (25)$$

where $\chi_{fij} = 2DG_{fiz}$, i.e. the annual total commuting time between zone i and j for labour type f, and $a_{f|d}$ is a log-linear parameter. The reason why we do not account for the monetary cost is

[4] To distinguish $\overline{w}_{fi}$ and w_{fj}, the latter is the hourly wage of labour type f at production zone j, while the former is the average wage for labour type-f living in residence zone i, weighted by the modelled labour distribution to all employment locations.

that the monetary cost is already accounted for in the consumption utility function (see the budget constraint in Eq. 8). To avoid double counting, we thus only consider the travel time in the χ_{fij} function.

To demonstrate the non-linear feature of the above function, we plot the log-linear travel disutility versus the linear counterpart in **Error! Reference source not found.**. It shows that the modelled elasticity of the log-linear function varies for different distance ranges. Specifically, the elasticity of disutility with regard to distance is higher for short-distance range (approx. 0-15 km), and becomes lower for long-distance range (approx. > 15 km).

A1.4 Stock Constraints

We define stock constraints to cover land/floorspace and transport infrastructure which may evolve or "churn" slowly. In the model, the stock constraints include: 1) the zonal supply of housing floorspace varieties ($\hat{b}_{mi}$) and business floorspace varieties ($\hat{B}_{ki}$); 2) the expected transport monetary cost (g_{fij}) and travel time (G_{fij}) for consumer type f; 3) the zonal number of non-employed residents (H_F).

In the model, such stock constraints remain exogenous for any static period and will be updated periodically in a non-equilibrium manner. The underlying assumption is that land/floorspace and transport infrastructure respond to demand slowly and indivisibly, subject to regulation, planning, construction, commission and decommission (Jin et al., 2013). User-defined supply scenarios are likely to be the most appropriate in order to reflect policy targets and background changes. As for the relocation of non-employed residents, it is assumed that there is a time lag between a utility change and household relocation.

A1.5 Equilibrium Conditions

The general equilibrium structure of the model requires three sets of equilibrium conditions to be satisfied simultaneously, conditional on the transport conditions $\boldsymbol{g}$ and $\boldsymbol{G}$.

1) All consumers maximize utility subject to budget and time constraint, or minimise expenditure subject to given utility target.
2) All producers minimize cost subject to supply constraint of input factors and technology. Producers are competitive and operate under constant returns to scale. The minimized production price equals the average and marginal cost, implying zero economic profit.
3) All markets clear with zero excess demands. This applies to: a) the residential and business floorspace markets; b) the labour market for each socio-economic group at each production zone; c) the product market of each product type at each production zone.

The above equilibrium conditions are formulated in the model as follows:

A1.5.1 Product markets

The market clearance condition in both zonal and regional product markets prescribes that in each of the $j = 1, \dots, \mathbb{N}$ production zone, the production output of each industry should equal the total production demand plus net export. Let $Y_{rj|sn}$ be the intermediate demand for industry r in zone j for producing product s in zone n and Ξ_{rj} be the exogenous net export for industry r in zone j. The zero excess demands in product markets require:

$$\sum_{f,z} H_{fi} P_{rz|fij} \bar{z}_{r|fij} + \sum_{s,n} Y_{rj|sn} + \Xi_{rj} = X_{rj} \tag{26}$$

A1.5.2 Labour Markets

In each of the $j = 1, \dots, \mathbb{N}$ production zone, the annual labour demand in hourly term for each of the $f = 1, \dots, F-1$ labour group must equal the working hours supplied by the respective labour group, net of the time for commuting, shopping and leisure.

$$\sum_{r} L_{rfj} = \sum_{i} H_{fi}\, P_{fij} \left(N - 2DG_{fij} - \sum_{r,z} c_f Z_{rz|fij} 2G_{fiz} - l_{fij} \right) \tag{27}$$

A1.5.3 Floorspace Markets

We treat the zonal building floorspace as exogenous supply constraints in static equilibria, and update them through Recursive Dynamic models. The market clearance in floorspace markets requires that in static equilibrium, the zonal demand for each type of residential and business floorspace must equal the corresponding zonal supply constraint.

$$\sum_{f,j} b_{m|fij} = \hat{b}_{mi} \quad (28)$$

$$\sum_{r} B_{rkj} = \hat{B}_{kj} \quad (29)$$

where $\hat{b}_{mi}$ and $\hat{B}_{kj}$ is the zonal supply constraint for housing and business floorspace, respectively.

As a summary, the aforementioned equilibrium conditions define the aggregate behavioural rules of agents, and specify how they interact with each other in respective market. In fact, the equilibrium conditions constitute the economic foundation of general equilibrium models, and it is a theoretical necessity to satisfy such conditions in equilibrium analysis.

A2 Model Algorithm

In the previous section, we present the formal structure of the Spatial Equilibrium model. Given the exogenous stock constraints (building floorspace supply, transport infrastructure and non-employed households), the aforementioned equations and variables complete the spatial general equilibrium of the model. Following the convention of spatial equilibrium models, we solve the static equilibrium in a sequential manner, which is specified in FIGURE 22.

The solving algorithm for the Spatial Equilibrium model is as follows:

STEP 0 (Initialization). Arbitrary exogenous vectors of rents $(\boldsymbol{R}, \boldsymbol{r})$, wages $(\boldsymbol{w})$ serve as initial inputs. Given the guessed values, as well as the given transport conditions $\boldsymbol{G}$ and $\boldsymbol{g}$ and all parameters, the following sequentially arranged steps complete a single iteration of the SE model.

STEP 1 (Production prices). The zero economic profit equation (7) is solved for the equilibrium production price $\boldsymbol{p}$, given wages $\mathbf{w}$ and business floorspace rents $\mathbf{R}$.

STEP 2 (Location choices). Residents make discrete location choice for sourcing goods & services with equation (18). Employed residents make joint location choices with Equation 21 or 23.

STEP 3 (Outputs). Given the production price $\boldsymbol{p}$ from STEP 1 and the location choices from STEP 2, the final demand for production $\boldsymbol{F}$ can be solved with the *Marshallian* demand function (12) and the zero-excess-demand equation (26). The total production demand $\boldsymbol{X}$, including the intermediate demand, can be derived with the classical input-output solution $\boldsymbol{X} = (\boldsymbol{I} - \boldsymbol{A})^{-1}\boldsymbol{F}$, where $\boldsymbol{A} = [\gamma_{rs}]$ is the matrix of input-output coefficients.

STEP 4 (Rents). Given the production price $\boldsymbol{p}$ from STEP 1 and the production outputs $\boldsymbol{X}$ from STEP 3, the equilibrium rents for business floorspace $\mathbf{R}$ can be solved with the floorspace demand function (3.5) subject to the stock constraints $\hat{\boldsymbol{B}}$. Similarly, the housing rents $\mathbf{r}$ are solved with the *Marshallian* or *Hicksian* demand function subject to the housing stock constraints $\hat{\boldsymbol{b}}$.

STEP 5 (Wages). Given the production price $\boldsymbol{p}$ from STEP 1, the location choices from STEP 2, and the production outputs $\boldsymbol{X}$ from STEP 3, the equilibrium wages $\mathbf{w}$ can be solved with the labour market zero-excess-demand equation.

STEP 6 (Updating). Gathering the results of STEP 1 to STEP 5, the algorithm has determined vectors $\boldsymbol{p}, \boldsymbol{w}, \boldsymbol{R}, \boldsymbol{r}$ conditional on transport matrices $\boldsymbol{G}$ and $\boldsymbol{g}$ and all exogenous variables, constraints and parameters. The algorithm will then check whether these updated prices and the associated quantities are converged and whether they simultaneously satisfy all equilibrium conditions to a desired level of accuracy that is discussed below. If not, then the next iteration is started by returning to STEP 1 with these updated vectors. If all equilibrium conditions and converging criteria are satisfied simultaneously, model iteration stops and writes output files.

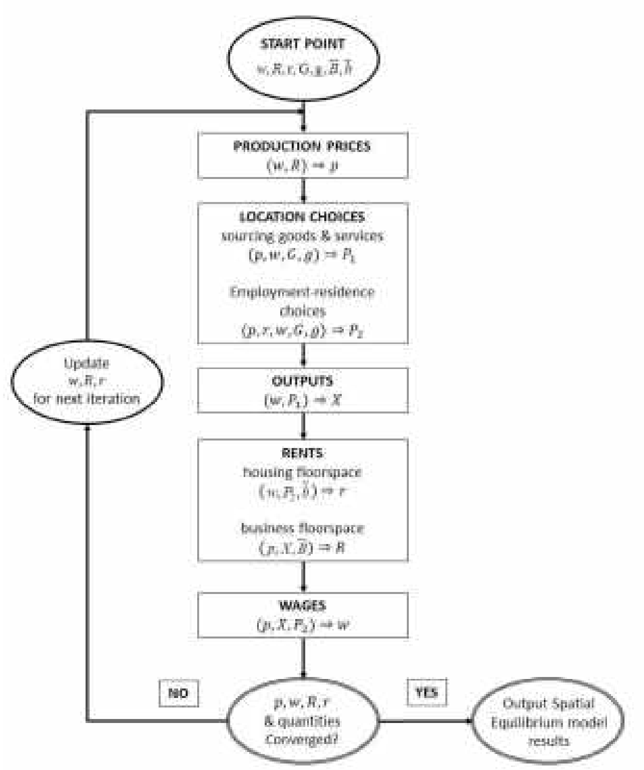

Figure 22 Solving Algorithm for Spatial Equilibrium Model

We define the level of converging accuracy by setting a maximum relative error condition. The Spatial Equilibrium model is considered converged in the *n*th iteration when the following inequality condition is satisfied simultaneously for all prices and quantities concerned:

$$\max_{\forall i}\left(\left|\frac{x_{i|n} - x_{i|n-1}}{\frac{1}{2}\left(x_{i|n} + x_{i|n-1}\right)}\right|\right) < ITERTOL \tag{30}$$

where vectors $x_{i|n}$ include zonal prices $\boldsymbol{p}, \boldsymbol{w}, \boldsymbol{R}, \boldsymbol{r}$ and all the associated excess demands in iteration n, and $ITERTOL$ is a user-specified maximum iteration tolerance. When the Spatial Equilibrium model is initiated with guesstimated starting values, large relative errors between iterations may occur. As the model approaches the equilibrium solution, the relative errors are expected to reduce gradually, yet not necessarily monotonically.

In order to stabilize the equilibrating process and avoid the model from divergence, we need to define how the variables are updated between iterations. Let $Current(X_n)$ be the variable value in iteration n and $New(X_{n+1})$ be the updated value from the solving algorithm for iteration $n + 1$, we set:

$$Current(x_{n+1}) = \varpi(n)New(x_n) + [1 - \varpi(n)]Current(x_n) \tag{31}$$

where coefficient $\varpi(n) \in [0,1]$ is a monotonically increasing function with respect to the iteration number $n \in [1, MAXITER]$. The $\varpi(n)$ function represents a smoothing technique for updating variables between iterations. A smaller step change of $\varpi(n)$ helps to stabilize the equilibrating process but incurs more iterations.

A3 List of Variables in the Model

INDICES FOR DIMENSIONS OF THE MODEL	
$\mathfrak{I}$	Number of core zones
$\wp$	Number of peripheral zones
$\mathbb{N} = \mathfrak{I} + \wp$	Total number of model zones
F	Number of social-economic groups
$\mathcal{R}$	Number of industry types
$\aleph_1$	Number of residential floorspace types
$\aleph_2$	Number of business floorspace types
D	Exogenous number of annual working days
$N = 24D$	Exogenous total annual time endowment
VARIABLES IN SPATIAL EQUILIBRIUM MODEL	
X_{rj}	Aggregate production output of industry r in zone j
E_{rj}	Constant scalar representing any additional zonal effects on Total Factor Productivity (TFP)
A_{rj}	An economic mass function for industry r in zone j that represents the agglomeration effects on TFP
K_r	Capital input for industry r
L_{fj}	Labour input of type f for industry r in zone j
B_{kj}	Business floorspace input of type k for industry r in zone j
Y_{rsj}	Intermediate input of type s for industry r in zone j
M_j	Economic mass of zone j
S_i	Geographic area of zone j
χ_{fij}	Travel disutility function for socio-economic group type f travelling from i to j
p_{rj}	Unit production price of industry r in zone j
ρ	Real interest rate
w_{fj}	Hourly wage of labour type f in zone j
R_{kj}	Average rent for business floorspace type k in zone j
$p^*_{rs\|j}$	Average delivered price of intermediate input type s for producing product type r in zone j
U_{fij}	Observable utility of resident type f living in zone i and working in zone j
$Z_{rz\|fij}$	Aggregate consumption volume for industry r in zone z, given resident type f living in zone i and working in zone j
$b_{m\|fij}$	Consumption volume for housing type m in zone i, given resident type f living in zone i and working in zone j
l_{fij}	Leisure time of resident type f living in zone i and working in zone j
g_{fiz}	Expected one-way monetary cost from i to z for customers type f
G_{fiz}	Expected one-way travel time from i to z for customers type f
$\mathcal{M}_{fi}$	Nonwage income of consumer type f in zone i
r_{mi}	Housing rent of type m in zone i
Δ_f	Employment status of the consumer type f (For all employed consumers $\Delta_f = 1$; otherwise $\Delta_f = 0$)
$p^*_{rz\|fij}$	Full delivered price of a unit of goods & services type r produced in zone z purchased by consumer type f living in zone i and working in zone j
Ω_{fij}	Full disposable income of the consumer type (fij) net of commuting costs

$\bar{Z}_{r\|fij}$	Aggregate demand for product type r for consumer type (fij)
$\bar{p}_{r\|fij}$	Probability-weighted average price of product type r faced by consumer type (fij)
N_{fij}	Total annual labour working time for labour type (fij)
$\widetilde{U}_{fij}$	Price-based indirect utility of resident type f living in zone i and working in zone j
$P_{rz\|fij}$	Probability of obtaining product type r from zone z to consumer type f living in zone i (and working in zone j, if employed)
S_z	Size term that corrects for the bias introduced by the uneven sizes of zones in the model
P_{fij}	Probability of employed resident type f choosing to live in zone i and work in zone j
v_{fj}	Employment location utility of zone j for labour type f
$v_{fi\|j}$	Residence location utility of zone i for resident type f, given the chosen workplace j
$V_{f\|j}$	*Log-sum* or *inclusive utility* representing the expected utility that employed worker type f in zone j would receive from all residence location choices
$\overline{w}_{fi}$	Average hourly wage of type-f employed residents living in zone i
d_{fij}	Travel disutility after Box-Cox transformation for commuter type f travelling from i to j
$\hat{b}_{mi}$	Stock constraints of housing floorspace type m in zone i
$\hat{B}_{ki}$	Stock constraints of business floorspace type k in zone j
H_{fi}	Number of type f residents in zone i
Θ	Exogenous nonwage income from other sources
Ξ_{rj}	Exogenous net export for industry r in zone j
VARIABLES IN RECURSIVE DYNAMIC MODELS	
$\hat{B}_{ki}^{t+1}$	Zonal business floorspace stock of type k at zone i for period $t+1$
$\vec{B}_{k}^{t\|t+1}$	Regional aggregate stock change of business floorspace type k from period t to $t+1$
$V_{i\|B}$	Locational utility of zone j for business floorspace growth
$\hat{b}_{mi}^{t+1}$	Zonal housing floorspace stock of type m at zone i for period $t+1$
$\vec{b}_{m}^{t\|t+1}$	Regional aggregate stock change of housing floorspace type m from period t to $t+1$
$V_{i\|b}$	Locational utility of zone j for housing floorspace growth
$\bar{R}_i^t$	Zonal average business floorspace rent at zone i for period t
$\bar{R}_D^t$	Municipal/provincial average business floorspace rents at D for period t
$\mathcal{D}_i^t$	Zonal building floorspace density at zone i for period t
ℶ$_{i\|B}$	Dummy variable indicating zonal policy trend for business floorspace growth
$\bar{r}_i^t$	Zonal average housing floorspace rent at zone i for period t
$\bar{r}_D^t$	Municipal/provincial average housing floorspace rents at D for period t
ℶ$_{i\|b}$	Dummy variable indicating zonal positive policy trend for housing floorspace growth
⅄$_{i\|b}$	Dummy variable indicating zonal negative policy trend for housing floorspace growth
$H_{i\|F}^{t+1}$	Zonal number of non-employed residents in zone i at period $t+1$
$\vec{H}_{F}^{t\|t+1}$	Regional aggregate change of non-employed households from period t to $t+1$
J_{fj}^t	Number of labour type f in zone j for period t

List of Parameters in the Model

PARAMETERS IN SPATIAL EQUILIBRIUM MODEL	
δ_r	Labour cost share
μ_r	Business floorspace cost share
ν_r	Capital cost share
γ_{rn}	Intermediate cost share
ζ_r	Elasticity of substitution for business floorspace varieties
θ_r	Elasticity of substitution for labour varieties
σ_f	Elasticity of substitution for housing varieties
$a_{f\|\kappa}$	Coefficient for determining the input-specific parameters for labour varieties
κ_{rfj}	Input-specific parameters for labour varieties
$a_{f\|\iota}$	Coefficient for determining the input-specific parameters for housing varieties
ξ_{rfz}	Input-specific parameters for goods & services varieties
ι_{mfi}	Input-specific parameters for housing varieties
E_j	Additional total factor productivity multiplier
π	Economic mass effects on productivity
c_f	Cost for delivering a unit of local services as percentage of commuting trip cost
α_f	Utility coefficient for goods & services
β_f	Utility coefficient for housing
γ_f	Utility coefficient for leisure time
$a_{f\|d}$	Log-linear travel cost function parameter
ς_f	Decay coefficient for value of time (non-commuting travels)
$\lambda_{f\|r}$	Dispersion parameter for sourcing goods & services
$\lambda_{f\|J}$	Dispersion parameter for employment location choices
$\lambda_{f\|I}$	Dispersion parameter for residence location choices
$\psi_{iz}, \psi_{fi\|j}, \psi_{fj}$	Observable non-monetary barriers for spatial interaction
E_{fz}	Residual attractiveness for sourcing goods & services
E_{fj}, $E_{fi\|j}$	Residual attractiveness for residence-employment location choices