MIND THE GAP

Funding and financing city Investments in the 21st century

Greenwood Strategic Advisors

GREATERLONDONAUTHORITY
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Summary

'Mind the Gap' is a report about Greater London as an urban system, how it responds to public investments, and the long-term socioeconomic ***'cost of not'*** making such investments. The analyses described address a critical investment gap, its consequences, and potential solutions in Greater London.

The gap is caused by a chronic shortage of public funding and financing for city investments.

The consequences of this gap are substantial losses in housing availability, environmental quality, social balance, economic growth and government revenues when investments and the benefits they bring are delayed or prevented by funding and borrowing constraints.

Three important findings emerge from these analyses that inform **potential solutions:**

1) Despite pronounced and persistent public investment shortfalls, London's population has grown and will continue growing.
2) Where public investments can be made, they produce quite large and long-lasting benefits that help to address mounting problems such as the housing shortage and social imbalance.
3) As these benefits are monetised in the form of tax revenues, they can support substantial new flows of private financing for public investment in Greater London.

The report outlines innovative public / private solutions to the challenge of funding and financing public investments in London and other cities.

In 2014 Greenwood began developing technology for simulating the dynamics of cities. Since 2015 Greenwood and the Greater London Authority (GLA) have partnered in setting up and employing the Greater London Simulator, a whole-city 'virtual twin' (computer model) of the London city system and how it responds to investments. In 2016 Greenwood began a similar partnership with Boston (Massachusetts), simulating that city and the rest of Greater Boston. In 2017 Greenwood added simulators of Norfolk (Virginia), and Frankfurt and Coburg in Germany.

The investment analyses described in this report were conducted using the Greater London Simulator, through the support of the Mayor of London (for the London-specific scenario development and analyses described) and with part-funding (for the report) from the European Union's European Multi-Regional Assistance: Revolving Investments in Cities in Europe project.

The Greater London Simulator and its counterparts in other cities are neutral test-beds for urban investments, providing objective measures of their long-term social, economic, environmental and fiscal impacts on these cities and their stakeholders. By measuring how each city-system is monetising non-financial investment outcomes, these simulators more fully value such investments.

The need for innovation - Governments and institutional investors such as pension funds generally agree that the *status quo* in cities and capital markets is broadly failing to deliver what cities and investors need from each other and should be able to provide.

- Cities have huge unmet needs for infrastructure and other investments. Even cities like London are able to fund and finance only a fraction of the investments needed for resilience and sustainability in the face of continued population, job, and economic growth.
- Government tax revenues, funding and borrowing have been insufficient to meet these needs and this is unlikely to change in future.
- Institutional investors have huge unmet needs for safe and long-lived investments, but few public investments are currently available to them.
- The missing link is a framework in which private investors, ranging from individual citizens to pension funds, can play a much larger role in financing public urban investment.

City investments that are delayed or prevented by public funding and financing constraints cause substantial and long-lasting social, economic, and environmental damage in cities, along with lost government cash flows that perpetuate underinvestment in an obvious 'vicious cycle'.

Measuring the whole-city impact of public investments reveals that many have real potential to be self-funding through the economic and fiscal growth they bring. This opens up the possibility of new financing approaches and private investment capital that can help relieve public budgets and borrowing constraints and enable cities to be more resilient and better prepared for sustainable growth.

Funding and financing solutions can convert the vicious cycle of under-investment into a virtuous circle, in which city investments increase growth and bring higher tax revenues that help reduce pressure on Her Majesty's Treasury (HMT).

Simulating Greater London investments - Greenwood and the GLA have used the Greater London Simulator (GLS) to simulate seven prospective public investments, measuring their social and economic impacts and how the city monetises these impacts in the form of government cash flows. The seven investments:

- Three extensions of existing public transport lines (Sutton Tram, Crossrail 1 and Bakerloo Line);
- A major new high-speed commuter rail line (Crossrail 2);
- A major brownfield urban redevelopment (Royal Docks);
- High-speed fibre-based digital access to every building in Greater London;
- Accelerated housing development as targeted in the Mayor's London Plan.

All but one of these investments repurpose land or bring new public transport, supporting residential development that will help relieve Greater London's housing crisis and thereby ease the leading constraint on job creation. Together the five transport and redevelopment investments can sustain London's housing growth close to its recent but insufficient rate of development. The simulated investments in accelerated housing development increase the pace of housing growth first to 40,000 net new units per year and then to the London Plan's annual target of 65,000 units/year.

Impacts from five of these investments - Beginning with the four transport projects and the brownfield redevelopment project, these simulations measure Greater London investment impacts in terms of:

1. Cumulative differences in absolute growth of population, housing and jobs to 2050
2. Increases in the simulated sizes of London's 2050 economy and HMT's 2050 tax take from London.

The high 'cost of not' investing - Simulating Greater London without and then with these public investments demonstrates their importance to the city's health and wellbeing. In the absence of these or equivalent investments, the inter-connected dynamics of London's jobs, population and housing operate in a significantly less balanced and effective way.

- Without these investments Greater London will have 365,000 fewer new housing units in 2050, equivalent to about 10% of London's total housing stock in 2015.
- Without these additional units London housing grows by only 12% to 2050, but the city's population swells by over 17% to 9.9 million people, so the housing crisis worsens steadily.
- Therefore social balance continues to deteriorate as middle-income Londoners shrink from 28% to just 22% of total population by 2050, due to diminishing middle-income housing.
- Because of the housing that isn't built, London's total job growth to 2050 is lower by 16% and economic growth is down by 10%. As a result, HMT's real annual London tax revenues are almost 12% lower in 2050 than they would be with these five investments.

Social and economic impacts from the transport and brownfield investments - Social impacts from these five investments begin with the 365,000 net new residential units they make possible by repurposing or bringing new public transport to land in Greater London (shown in the left-hand bar below).

- The new housing meets pent-up demand, enabling additional population growth of 640,000 new residents to 2050 (as seen in the second bar from the left);
- The investments also enable 913,000 m^2 of new London business space to 2050 (the third bar);
- Together, increased population and business space enable additional job growth of 379,000 to 2050 (in the fourth bar);
- This increases the size of Greater London's 2050 economy (GVA) by £34B per year and enlarges HMT's 2050 London tax revenues by £10B per year (in the fifth and sixth bars, both figures are in real terms).

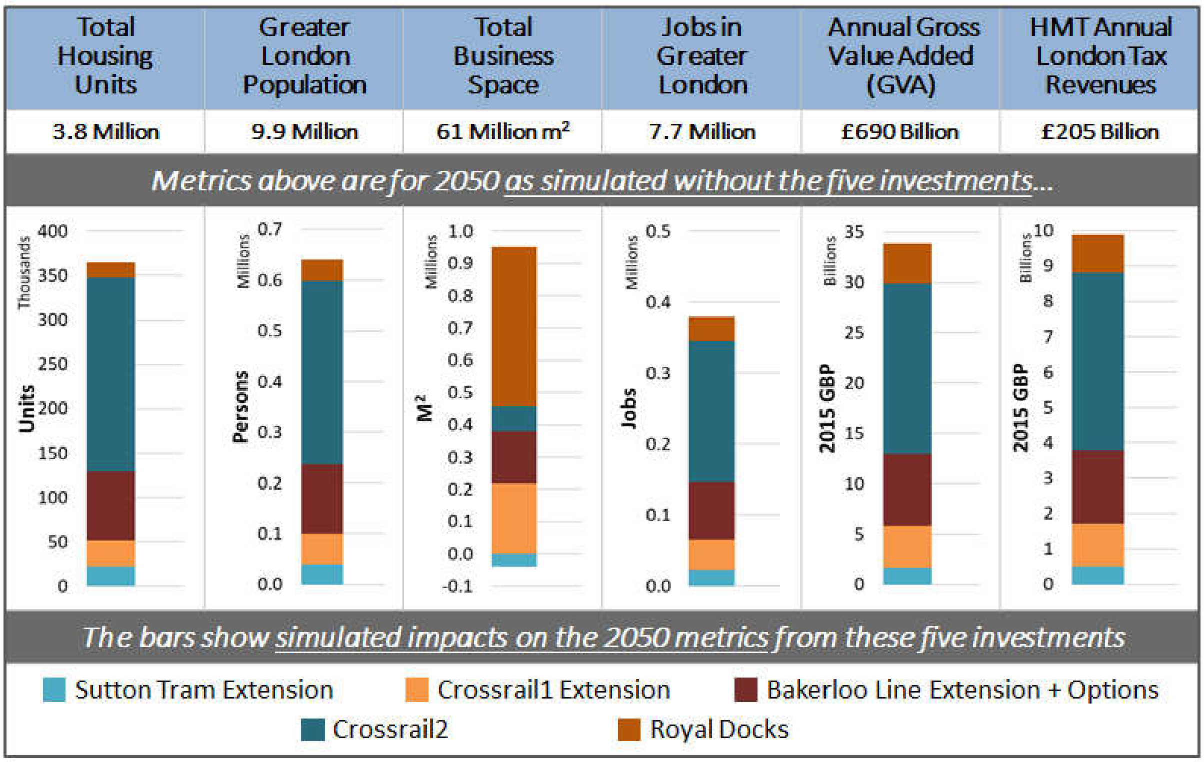

Figure 1 – Social, economic, and fiscal impacts from these public investments in Greater London

The social dynamics of housing, population and jobs are key drivers of the simulated investment impacts, and these elements are highly inter-connected. Their dependence on each other can be seen in two facts:

- The five simulated investments directly add 226,000 new housing units;
- Yet in response to these investments London housing grows by a total of 335,000 units to 2050.

The 'extra' 109,000 housing units are produced by the social dynamics of this housing-constrained city; these dynamics are self-reinforcing over the long term. Public investments that increase housing boost both population and job growth; additional jobs attract still more people, further increasing housing demand and development; the added residents filling these additional housing units enable even more job growth, which attracts yet more people, and so on.

Because these social dynamics are naturally self-reinforcing, energising them by public investment (e.g. that brings increased housing) can deliver disproportionately large socioeconomic benefits relative to investment costs. Simulating these social dynamics in an integrated way is therefore essential to reliably measure the full social, economic, and fiscal impacts of public investments in London and other cities.

Social and economic impacts monetised as fiscal impacts - Greater London monetises the social and economic impacts of these public investments as:

- additional HMT tax revenues from London;
- increased Central Government spending back into a larger London (such back-spending averages about 70% of HMT's London tax revenues);
- increased HMT cash flow from Greater London (the net of additional London tax revenues and increased back-spending into the city).

The Greater London Simulator measures Central Government's fiscal impact from these five investments as HMT's resulting long-term increase in net cash flow from Greater London. It also computes the net present value (NPV) of that cash flow increase so the UK's fiscal gains from these investments can be directly compared to their public investment costs.

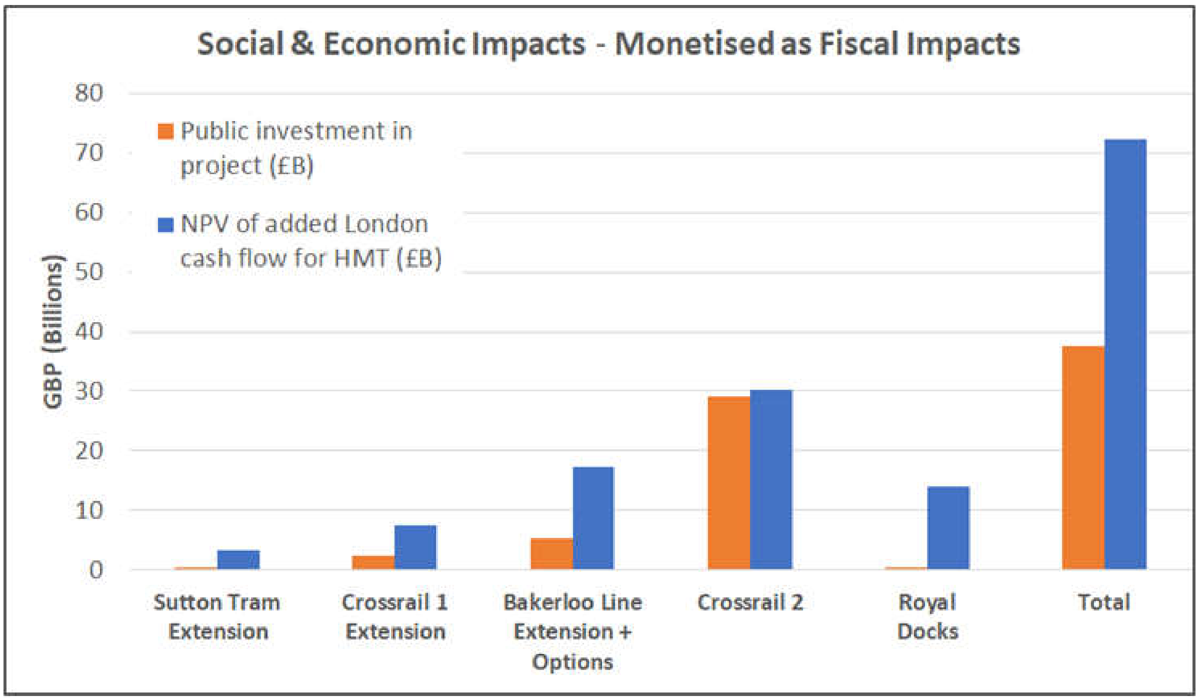

Figure 2 – Social and economic impacts monetised as fiscal impacts

This analysis has not measured other forms of fiscal impact from these public investments, including:

1. Increased cash flows for Transport for London (TfL) from the four transport investments
2. Increased council tax revenues from the new housing these investments bring
3. Potential new tax revenues from sharing in the uplift of land values along the four transport corridors involved.[1]

That said, for each investment the NPV of HMT's added London cash flow is positive and exceeds expected investment cost. In fact, the combined NPVs of the added London cash flows are nearly double

[1] Public sharing via taxation in gains by private property owners that occur when public transport investments increase nearby land values.

the expected investment cost of these projects. This is an evidence-based demonstration that these public investments can generate their own funding and more in the form of increased London cash flows for HMT.

Wider impacts in the UK outside London - HMT's added cash flows from these five simulated investments are worth £72B (in NPV terms), which accrues to Central Government and thus to the UK outside Greater London. This is a quite substantial benefit to the rest of the nation, but these dynamic analyses do not yet account for other potential positive and negative impacts of London investments on other parts of the country. Such impacts are important, for example, to assess whether fiscal benefits from Greater London investments are net additional to the UK economy.

Evidence suggests that fiscal benefits to London from the simulated investments are net additional for the UK as a whole due to:

1. London's openness to and connections with the international economy;
2. Higher economic efficiencies in larger cities (due to agglomeration effects);
3. London's large resulting net tax surplus for HMT;
4. London supply chains that extend throughout the rest of the UK;
5. Strong correlation between growth in London and in the rest of the UK.

Furthermore, dynamic analyses strongly suggest that public investments in other growing UK cities have the same self-funding potential as in London, and can be part-funded with HMT's increased cash flows from public investments in the capital.

Further dynamic analyses are therefore required to measure the social, economic and fiscal impacts on the rest of the UK from public investments in Greater London.

Digital and London Plan housing investments - The simulated digital investment in Greater London spurs job growth that further reduces loss of middle-income households and modestly increases economic growth. Simulated residential development to the London Plan target of 65,000 units annually significantly eases London's housing crisis, strongly boosts social and economic growth, reverses the decline of middle-income households, and modestly increases unemployment.

Environmental impacts - The GLA's ambitious decarbonisation programme aims to reduce London's greenhouse gas emissions by 90% from 1990 levels. Dynamic analysis indicates that London is on track to achieve that target by about 2061 with these seven prospective investments, or by about 2057 without them (due to lower economic growth). Simulating without the decarbonisation programme, a growing London sees rising energy consumption and emissions.

Innovative funding and financing - The potential for city investments that produce their own funding makes private financing of such investments much more feasible. Financing instruments are available that can bring private capital and defer public expenditures until investments are producing their expected social, economic, and fiscal impacts.

Credit Participation Certificates™ are an innovative example of such instruments. UFT Commercial Finance LLC developed and administers the global CPC™ platform, which is open to a wide range of lenders, borrowers and investors. CPCs™ are used in a variety of credit markets including trade finance and private equity, and in multiple jurisdictions including the UK.

The combined capabilities of dynamic city analysis and the CPC™ platform represent a new chapter in public infrastructure finance. Together they can bring new-build city projects to a much broader base of investors (including UK pension funds) and reduce risk by making such investments tradable in liquid markets.

It is expected that these innovations will substantially increase the volume of private financing for public investments while significantly reducing the cost of such financings.

Dynamic investment analysis in other cities - The feasibility and usefulness of dynamic analysis in other cities is demonstrated by its application in five cities ranging from 42,000 to 8.5 million residents and on diverse issues including flood protection, health infrastructure investment, brownfield redevelopment, housing and land use, public transport, and macroeconomic influences. All of these city simulators employ publicly available data for model initialization and testing, and the most recent simulators have been set up and in use in about twelve weeks.

The way forward in London - Dynamic simulation and analysis fills a strategic gap in the GLA's knowledge and understanding of how London (and cities in general) work, namely as systems of inter-connected systems. Planning is in process to enhance the capabilities of the Greater London Simulator and the range and value of dynamic analyses.

- Simulate additional geographic layers including: inner and outer London Boroughs; regions adjoining Greater London and others well beyond the city; and major London transport corridors.
- Extend the Greater London Simulator to measure property values, housing affordability relative to incomes, and potential for value uplift sharing.
- Expand environmental simulation to include air quality and pluvial flooding, their social, health and productivity effects, and mitigation investments.
- Individually simulate Central Government's primary London expenditure categories for more complete analysis of fiscal impacts from public investments.
- Further analysis regarding private financing for large-scale public infrastructure investments.
- Expanded participation by Greater London stakeholders and collaborative solution development.

Conclusion - The GLA now has a tested dynamic analysis platform for integrated measurement of social, economic, environmental and fiscal impacts from public investments in Greater London, along with their monetised values for local councils, Central Government, and the rest of the UK.

The indicated values of such investments are high and mostly insensitive to possible Brexit impacts. There is reason to believe that many such investments can fund themselves and help fund other projects through the economic growth and fiscal benefits they bring.

This development has potential to transform and resolve the UK's public investment funding challenge through innovative private financing.

Greenwood recommends that the Greater London Authority, Transport for London, Greenwood Strategic Advisors, and UFT Commercial Finance work with appropriate lenders in assessing the feasibility of a several-billion-pound CPC™ financing of new public infrastructure in Greater London. The Crossrail 1 extension project to Ebbsfleet in Kent is a good candidate for such a feasibility study.

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Acknowledgements

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Craig Stephens
Project Leader

List of Acronyms

BLE	Bakerloo Line Extension
CAGR	Compound Annual Growth Rate
CBA	Cost-Benefit Analysis
CPC™	Credit Participation Certificate
DC	Dynamic Consequence
DOC	Direct Operating Consequence
FTTB	Fibre to the Building
FTTH	Fibre to the Home
GDP	Gross Domestic Product
GLA	Greater London Authority
GLS	Greater London Simulator
GVA	Gross Value Added
H/M/L	High/Medium/Low
HMT	Her Majesty's Treasury
JLE	Jubilee Line Extension
LIP 2050	London Infrastructure Plan 2050
MRA:RICE	Multi-Region Assistance: Revolving Investment in Cities in Europe
MtCO2e	Million Tons of CO2 Equivalents
N/A	Not Available or Not Applicable
NPV	Net Present Value
U/M/L	Upper/Middle/Lower
VAT	Value-Added Tax

1. Introduction

'Mind the Gap' is a report about Greater London as an urban system, how it responds to public investments, and the long-term socioeconomic ***'cost of not'*** making such investments. The analyses described address a critical investment gap, its consequences, and potential solutions in Greater London.

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Three important findings emerge from these analyses that inform **potential solutions:**

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The first phase of the MRA:RICE programme highlighted the need for cities to be strategic when considering their financial investment portfolios, and acknowledged the inherent difficulty of prioritising within the portfolio when the direct and indirect benefits of individual projects and programmes may differ greatly. 'Mind the Gap' uses dynamic simulations of prospective public investments in Greater London to demonstrate new approaches to analysing and prioritising within investment portfolios based on an integrated whole-city view of social, environmental, economic and fiscal investment impacts. Although these investment scenarios are of interest to MRA:RICE partners, their formation and dynamic analyses has been to support decision-making in Greater London and funding for that work has been provided by the Mayor.

2. Funding and Financing City Investment: a Growing Crisis

Cities are the most socially and economically productive places in the world, which is why they are expected to produce more than three-quarters of future economic growth[2]. City-generated growth provides capacity and resources that are essential for coping with or solving many global challenges:

- Population growth and urbanization
- Aging populations, rising health care needs, underfunded pensions
- Government debt and unfunded liabilities
- Poverty, hunger, disease
- Climate mitigation and adaptation

Cities are critical vehicles for addressing these challenges, both directly and through accelerated growth of personal incomes and public revenues. Public investment has always been essential to the health and well-being of cities and those who live and work in them, and cities have long been among the most productive places for both public and private investment.

Despite these facts and all around the world, cities face a massive chronic shortfall of funding and financing for public investment. It is amazing that such shortfalls of a critical resource could persist and grow over many decades in the primary engines for global social and economic growth. Figure 1 illustrates the magnitude of that gap in the world's financial capital.

Reducing and eventually eliminating this shortage of capital for public investment is crucial to the future of humanity and the planet. This will require innovative solutions including new sources of and approaches to funding and financing public investment in cities.

Greater London's investment shortfall

- *London's infrastructure plan identified £1.45 Trillion of needed new investment, based on expected population growth (LIP 2050)*
- *£850 Billion of that is in transport and public housing…an average of £24 Billion of new public investment needed annually to 2050*
- *This far exceeds past and expected future rates of public investment in Greater London*

Figure 1 – Greater London's investment shortfall

[2] McKinsey Global Institute: https://www.mckinsey.com/~/media/McKinsey/Global%20Themes/Urbanization/Urban%20world/MGI_urban_world_mapping_economic_power_of_cities_full_report.ashx

2.1. The Existing City Investment Framework

Figure 2 diagrams the framework for funding and financing city investments and its the three principle actors. Although specifics differ, at this summary level the framework and its operation are broadly similar in many countries.

In this and succeeding figures, system elements are as labelled and connecting cause-effect relationships are shown as arrows connecting these elements. Textual references to system elements appear in bold-face type (e.g. **Urban communities**).

Urban communities and citizens (that is, local communities within a larger urban area and residents of such communities) produce the majority of national Gross Domestic Product (GDP) and economic growth and generate most tax revenues.

Most tax revenues generated in cities flow to **Central Government** and sometimes to mid-level state and/or county governments between local and national government; higher-level governments then spend a portion of city-generated revenues back into the **Urban communities** from which they flow.

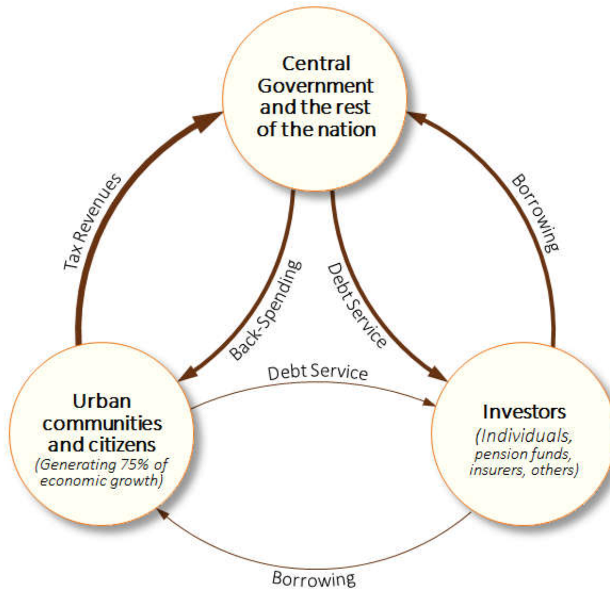

Figure 2 – Framework for funding and financing city investments

This pattern can be seen in many countries.

- In Germany, state and federal governments receive about 82% of tax revenues generated in cities; they then spend the equivalent of about 6% of city-generated tax revenues back into those cities.
- US state and federal governments receive about 89% of all tax revenues generated in cities.
- Britain's Central Government receives about 95% of tax revenues generated in Greater London and spends about 70% of these revenues back into the city (via the National Health Service, operating and capital grants to local councils, etc.). Greater London is the only region in Britain that produces a substantial tax surplus (net of back-spending) for Her Majesty's Treasury (HMT).

Central Government and other higher-level governments do a great deal of borrowing, as evidenced in most countries by their high and rising national debt levels and increasing debt service payments. **Urban communities** borrow as well, although the maturity and depth of municipal finance markets and the volume of local government borrowing vary considerably among nations.

Investors (pension funds, for example) pool money for investment purposes and are primary purchasers of debt from **Urban Communities, Central Government**, and other higher-level governments.

Tax revenues are the primary form of funding for public investments, and public borrowing is the primary form of financing for such investments. A modest fraction of public financing is tied to specific public investment projects. **Central Government** and other higher-level governments typically combine tax revenues and borrowed funds in ways that make it difficult or impossible to determine the mix of funding and financing that is employed for a particular public investment.

2.2. The Public Investment Gap: Origins, Impacts and Solutions

In the public funding / financing framework, investment is constrained by four principle factors:

- Rising operational and service demands on all levels of government;
- Practical limits on taxation and borrowing at all levels of government;
- Government budgeting and borrowing either one year or one project at a time;
- Government borrowing mostly at or close to sovereign rates.

Because most city-generated tax revenues flow to higher-level governments, constraints on public funding and financing heavily affect urban communities.

- Most cities and urban communities are getting only a modest fraction of the public investments that can be justified and are needed for resilience and sustainable social and economic growth (this is the gap referred to throughout 'Mind the Gap').
- The modest amounts of funding and financing available are over-concentrated on a small number of city investments.
- The few investments that receive funding and financing are typically unintegrated and arrive quite late relative to city needs.
- The many public investments that are delayed or prevented cause substantial and long-lasting social, economic, and environmental damage in urban communities.
- These social and economic impacts are monetised as fiscal impacts at all levels of government; they do huge fiscal damage for higher-level governments, perpetuating the funding and financing constraints that cause underinvestment in cities.

Damage from this 'vicious cycle' is not confined to cities. Cities and urban communities are typically the sole generators of substantial net tax surpluses for higher-level governments, and such surpluses are then spent elsewhere in the country (including in cities which do not produce tax surpluses). When urban investments are delayed or prevented in tax-surplus cities, this limits growth of cash flows to higher-level governments. Resulting spending constraints then ripple on to cause social, economic and environmental damage in regions outside the tax-surplus cities and across whole nations.

This broad shortfall of public investment in cities is a relatively recent phenomenon in urban history.

- A thousand years ago city-states began to emerge and thrive in Europe. Their success was propelled by private local financing of both private and public investments in these cities, which accelerated growth and increased prosperity to support yet more investment. This self-reinforcing process began in Italian cities and subsequently sprang up across the Alps, in Germany, and in the Low Countries hundreds of years before empires and (subsequently) nation-states began to coalesce.
- In little more than a century of Industrial Revolution, Manchester transformed itself from a minor Lancastrian town into what Wikipedia terms *"the preeminent industrial metropolis of the United Kingdom and the world."* The city grew at an extraordinary pace to become, by the late 19th century, Britain's third-largest port and the world's ninth-largest city by population. Huge investments propelled social and economic transformation, just as similarly self-reinforcing investments had in European city-states 500+ years earlier. Private financing again played a critical role because in the 19th century funding and financing public investment in cities was not a Central Government function. Manchester was not alone in financing its own public investment; British cities of the time did considerably more public borrowing than Her Majesty's Government.

From the 11th through the 19th centuries private financing of public investment in cities was extraordinarily effective at promoting social and economic growth and advancing urban well-being. But growth patterns changed in the 20th century, as can be seen in population trajectories for Greater London, metropolitan Paris, and the five boroughs of New York (Figure 3).

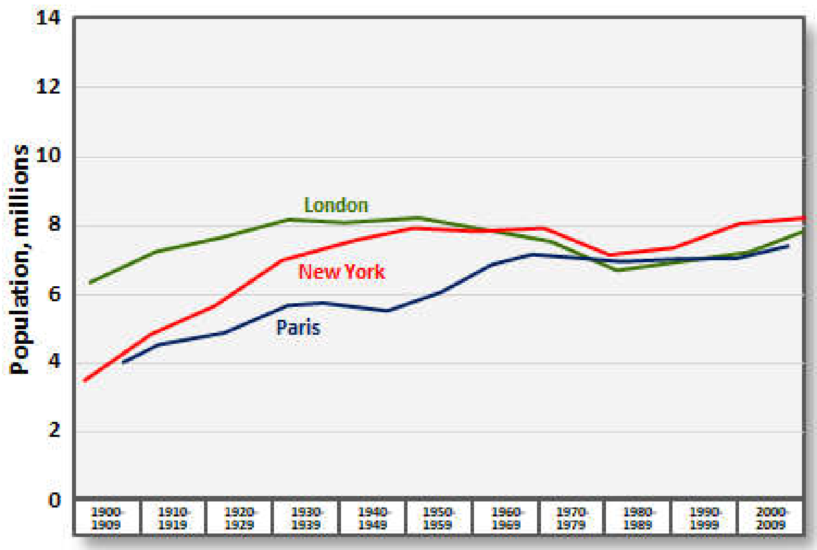

Figure 3 – Growth patterns of London, New York and Paris

Population growth rates in these three cities slowed from 1900 until around mid-century; eventually growth ceased and each city experienced a period of decline until the 1980s. Each city was subsequently rejuvenated and growth resumed, though at slower rates than in the first half of the 20th century. As of 2009 their populations were near but not significantly beyond previous peaks in the 1950s or 1960s.

What brought population growth to a halt in these elite cities, in the national capitals of two great European nations and the financial capital of the world's largest national economy?

One commonly offered hypothesis: by mid-century growth was encountering limits in each city. That is hard to argue given the growth-driving power of jobs and employable people in large concentrations; these engines tend to generate growth until something stops them. 1970s New York was crime-ridden and bankrupt in all but name. London was undergoing prolonged de-industrialization; there were riots in the streets of Paris.

But these problems, though serious, do not seem like fundamental causes of declining growth. Growth began declining many decades before these problems emerged. What was it that caused growth to slow and finally stop in these three elite cities? Had they reached 'natural' limits of geography, or physical density, or absolute size? Probably not: each city was steadily growing well beyond its traditional boundaries, and spatially larger cities with higher densities and much greater populations have sprung up throughout the developing world.

Another hypothesis: growth may have slowed and then stopped because of something that was happening outside these cities and throughout much of the world. The 20th century was marked by a pronounced centralization of power at national levels in Europe, North America, and Asia. Centralization was a significant factor in two world wars which strengthened and perpetuated the centralization process.

As power centralized, higher-level governments gained increased control over public revenues (generated primarily in cities) and therefore over public spending. Figure 4 illustrates control of tax revenues by higher-level governments using US data.

With increasing responsibilities and growing demands on higher-level governments, cities were at the short end of a fast-lengthening spending chain. It was during this period that funding and financing for city investments fell behind what was needed to keep pace with still-expanding populations and economies. The result: insufficient public investment became a growing constraint on social and economic growth and the health and well-being of cities.

Centralized control over public revenues
(Breakdown of 2015 total tax revenues in the US)

• *Federal*	*61%*
• *State*	*28%*
• *All local governments*	*11%*

http://www.taxpolicycenter.org/briefing-book/what-breakdown-tax-revenues-among-federal-state-and-local-governments

Figure 4 – Centralised control over public revenues

This has all the hallmarks of a 'vicious cycle' feedback, that is, a self-perpetuating downward spiral:

- Reduced government funding / financing for public investments in cities causes…
- …reduced growth of city populations, jobs, employment, social mobility, and incomes…
- …and reduced growth of city-generated taxes and tax surpluses for higher-level governments…
- …which further limits government funding / financing for investments in cities.

Two things make this spiral particularly disturbing:

1) It is driven by the power of our own (higher-level) government systems, which means it will likely continue in the absence of bold solutions;
2) Thanks to the attractive power of our most productive cities, they can and will continue creating jobs and drawing in people long after public investment in them has become insufficient to adequately support that growth.

But unlike many man-made clouds, this one has a silver lining: systemically effective solutions can change the 'vicious cycle' into a 'virtuous circle', that is, into a self-reinforcing upward spiral. Given the scale of the public investment gap, the need is for transformative solutions that can be implemented in multiple nations and cities.

Regarding severe and chronic under-investment in cities, four things seem clear:

1) Solutions are unlikely to emerge from increased taxation or increased borrowing by higher-level governments. The chain of causality probably runs in the other direction: solutions to the city investment problem will reduce fiscal pressure on higher-level governments and the need for increased tax rates, borrowing, deficits, or combinations thereof.
2) Solutions are likely to involve an updated version of what worked for city-states and (later) cities from the 11th through the 19th centuries: direct access to private capital for financing local public investment on a much larger scale.
3) Such solutions are quite congruent with the needs of institutional investors who can supply that capital (pension funds and life insurers in particular), and of the middle classes for whose financial futures these firms are responsible. This congruity is not surprising, since both city governments and institutional investors are fiduciaries for citizens.
4) Higher-level governments have important roles to play in these solutions, which will ease budget and balance sheet constraints and make public resources substantially more effective.

Centralized control over public revenues makes it likely that such solutions can be implemented because higher-level governments will be the biggest financial beneficiaries through higher tax revenues that accompany the higher social, economic, and income growth resulting from increased city investment.

3. Valuing and Prioritizing City Investments

3.1. A City is a Socioeconomic System

Impacts from public investments in a socioeconomic system depend primarily on changing conditions within the system. An investment that delivers great benefits under one set of system conditions will fail miserably under different conditions. Understanding conditions within the city system and how they may evolve is critical to valuing and prioritizing public investments. ***This means that systemic analysis capability is essential for reliable valuation and prioritization of urban investments.***

For the purposes of this report, a socioeconomic system is one in which people and institutions interact in attempting to achieve their objectives. Such systems exist in many forms and on many levels: Economic activity, for example, takes place globally, regionally, nationally, and locally (the majority of it in cities). Economic systems are fundamentally social systems; many social systems are themselves economic systems or exist within economic systems.

Markets for goods and services are social and economic systems, as are businesses and governments. A complex development project is a socioeconomic system, whether the end product is a building, computer software, or climate mitigation.

Socioeconomic systems are coupled to environmental systems, which range from the planet as a whole to local micro-environments. Over time socioeconomic systems have caused accumulating environmental change, altering the behaviour of environmental systems in ways that increasingly affect the operation of socioeconomic systems (example: more frequent and severe urban flooding resulting from climate change).

Socioeconomic and environmental systems are fundamentally dynamic in nature, meaning that their behaviour and trajectories change over time and produce changing conditions within the systems. Such changes often occur in response to events or conditions occurring outside of the system; just as often the system produces its own changing behaviour from within, that is, from its own operation and without outside influence. The overall behaviour of the system is a combined product of external influences, the system's own internal dynamics, and how these interact.

'Mind the Gap' is about the behaviour of the Greater London socioeconomic system and resulting conditions within that system. It focuses on how public investments and policies, along with outside events, affect the city's performance and conditions within it and what that suggests for the potential of innovative approaches to funding and financing such investments.

3.2. Components of the City System

There are two types of components in a socioeconomic system (or in any dynamic system): (i) system elements; and (ii) cause-and-effect relationships that connect the elements to form the system.

Component type #1: elements of the city system. The elements of the Greater London system are assets in a very wide range of forms. Many of them are physical: streets, vehicles, power / water / gas systems, buildings, green space, and so on. Many other elements are more than physical: people, businesses, jobs, income balance, social mobility, air quality, life quality.

One can break down and classify the elements of a dynamic system by type. The human body provides a good example, as illustrated by this partial list of element types found in it.

- Organs — Brain, lungs, heart, skin, etc.
- Tissues — Fat, muscle, bone, etc.
- Molecules — Water, protein, fats, carbohydrates, etc.
- Atomic elements — Oxygen, carbon, hydrogen, nitrogen = more than 96% of body mass

There is something notable about this list of human system elements: nowhere in it can we see the system itself. Even a complete collection of human organs would not be a system, much less the whole human system. There are many good reasons to investigate individual system elements, and understanding an element is usually easier than understanding the system as a whole.

Component type #2: cause-effect relationships. The difference between a collection of elements and a system is the network of cause-and-effect relationships that connects the various elements and through which those elements influence each other. These connecting relationships make the system more than the sum of its parts.

Just as an urban system is not defined by component elements alone, neither is it defined by component cause-effect relationships alone. A city system cannot exist or operate without the two component types; both are essential to understanding the system and to anticipating how public investments and changing external conditions will affect the city's performance.

Cause-effect relationships in the urban system arise from the ways that city stakeholders behave, as illustrated in Figure 5. In this and succeeding figures, elements of the city system are as labelled and connecting cause-effect relationships are shown as arrows connecting these elements. As in Section 2.1, textual references to elements of the city system appear capitalized and with bold-face type (e.g. **City Population**).

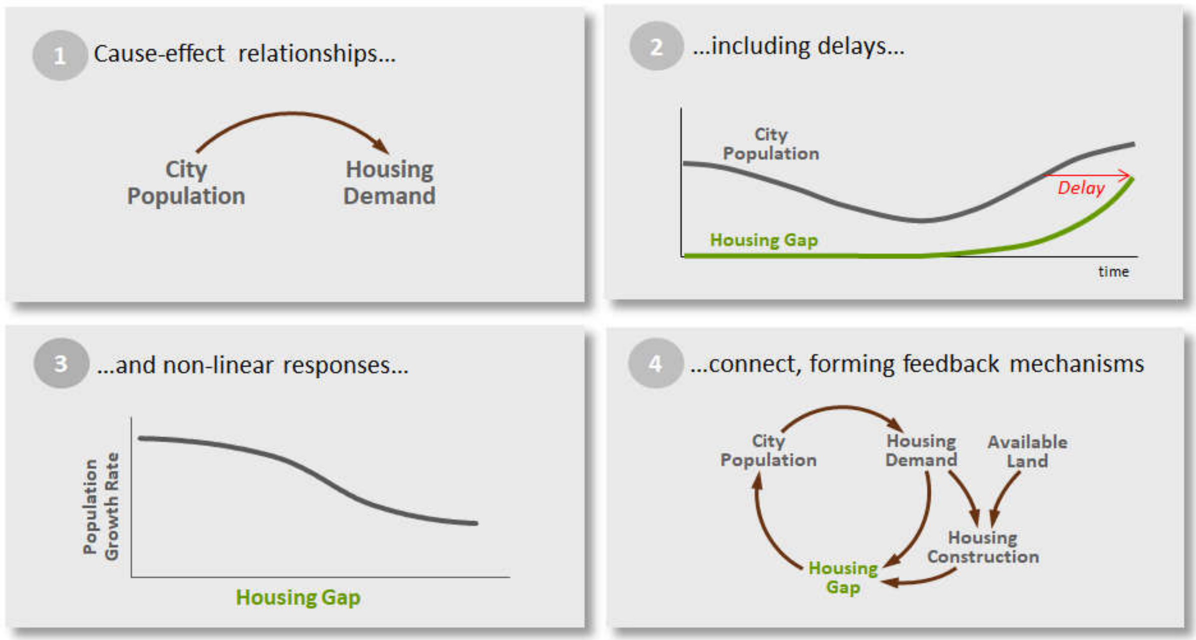

Figure 5 – Illustrative cause-effect relationships in the urban system

1) **City Population** (a system element) influences the level of **Housing Demand** (another system element); that cause-effect relationship connects the two elements.
2) Cause-effect relationships in the system often include significant time lags or delays, as when growing **City Population** gradually results in a **Housing Gap** or shortfall of supply relative to demand (which then emerges as a newly influential element in the city system).
3) Cause-effect relationships in the system often reflect non-linear responses, as when: (i) a small **Housing Gap** has little or no influence on **City Population** growth; but (ii) later on a somewhat larger gap causes a substantial reduction in growth of **City Population**.
4) These cause-effect relationships are linked to each other through common system elements, forming feedback mechanisms or ‘‘loops’’ within the urban system.
   a) The **Housing Demand** feedback loop involves city residents and would-be residents: **City Population** → **Housing Demand** → **Housing Gap** → population growth rate → **City Population**.
   b) The **Housing Construction** feedback loop involves house-builder stakeholders: **City Population** → **Housing Demand** → **Housing Construction** → **Housing Gap** → population growth rate → **City Population**.

These feedback loops cannot act in isolation from each other because they have two elements in common (**Housing Demand** and **Housing Gap**). If **Housing Construction** keeps pace with **Housing Demand**, so that no **Housing Gap** emerges, then **City Population** can grow with no constraint from housing. If **Housing Construction** does not keep pace with rising **Housing Demand** then growth of **City Population** will be constrained at some point.

In a dynamic socioeconomic system there is no guarantee that two connected feedback loops will keep pace with each other. Greater London is one of many cities in which the **Housing Construction** feedback loop has not kept pace with **Housing Demand**. In attractive cities, constraints on **Housing Construction** (e.g. from land availability, or permitting delays) can cause **Housing Gaps** that grow for decades. A large **Housing Gap** slows growth of jobs as well as **City Population**, because the housing shortage makes it harder for employers to attract suitable employees (as in Greater London and Silicon Valley, for example). When that happens, the two diagrammed feedback loops constrain the social, economic, and fiscal growth of the whole urban system and region.

The whole of the city system

An entire city system includes many elements, stakeholders, cause-effect relationships, and feedback loops. Mankind has amassed a great deal of knowledge through long observation of these things. Some of that knowledge is recorded in written forms, and a portion of the written knowledge exists in the form of city data.

With that knowledge we can examine and understand the city system at different levels of detail, either in whole or in part. ***Cities being large and complex, most analyses have tended to focus on specific portions or aspects rather than on the city system as a whole.***

With the objective of better systemic understanding, the following section diagrams the urban system as a whole, in summary form. This involves choosing which elements and cause-effect relationships to include; with appropriate choices we can construct a whole-system diagram that is useful for prioritizing and financing city investments.

In this report the term 'whole-system' refers to system-wide views and representations, in contrast to portions or subsets of the city system. No whole-system diagram can include every element and cause-effect relationship in the city, or it would be as complex as the actual city (and quite unreadable). Neither are we suggesting that whole-system views are superior to those that focus on a particular portion of the city system. Both serve useful purposes and each type complements the other.

These diagrams continue the visual conventions previously established: elements of the city system are as labelled and connecting cause-effect relationships are shown as connecting arrows. Textual references to elements of the city system appear capitalized and with bold-face type.

<u>Seven Primary Elements in a City System.</u> Each of the seven elements shown in Figure 6 can be found in multiple forms and varieties in any city.

Jobs and **People** (i.e. population) are at the heart of every city system. A city can be thought of as a concentration of **Jobs** and **People** in **Space**.

In its broadest sense **Space** means land, but city **Space** exists in various other forms including housing and business buildings. **Available Space** is limited depending on how **Space** is used in each of these categories.

City **Infrastructure** comes in many forms including roads, utilities, commuter rail, and public buildings. Public **Debt** is often the means of financing **Infrastructure** development.

Energy is produced in a variety of forms and consumed in buildings and **Infrastructure**. **Emissions** come in many forms, e.g. noise, physical waste, airborne particulates, and greenhouse gasses.

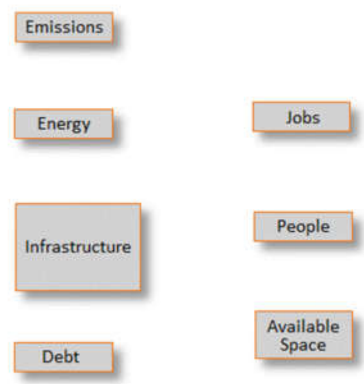

Figure 6 – Seven primary elements in a city system

<u>Jobs, People, and City Attractiveness.</u> The behaviour of employers and **People** creates cause-effect relationships (the arrows in Figure 7) that connect elements of the urban system.

- **People** are attracted to cities by the availability of **Jobs**. This is far from the only such attractor, but it is arguably the most important one.
- **Jobs** tend to grow in cities because they have the largest concentrations of employable **People**. **Job** growth comes as new and existing employers create new jobs and employers move to the city.

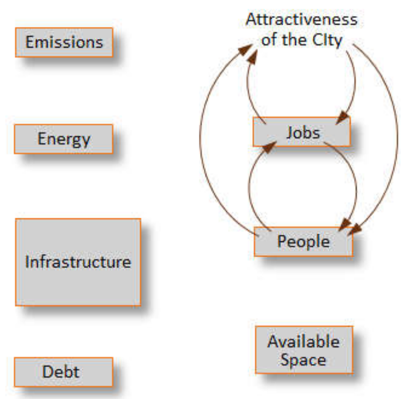

Figure 7 – Jobs, people and city attractiveness

Jobs, employable **People**, **City Attractiveness**, and the cause-effect relationships connecting them are the engine of urban growth and decay. The presence of **Jobs** and employable **People** makes the city attractive, causing growth of **Jobs** and **People** in a self-reinforcing process. The same elements and relationships also drive urban decay; in some Midwestern US cities these feedback loops have generated self-reinforcing losses of **Jobs, People** and **City Attractiveness** in a pattern of spiralling decline. The economic engine that grows cities sometimes operates in reverse.

<u>Jobs and People in Space</u>. **Jobs** and **People** need and occupy **Space** in various forms (Figure 8). As demonstrated by housing crisis in London and other cities, **Jobs** and **People** can increase faster than **Space** for substantial periods, during which **Available Space** declines.

Diminishing **Available Space** makes **Space** more valuable even as it makes the city less attractive. Fortunately, diminishing **Available Space** also prompts other urban stakeholders (e.g. property developers) to engage in **Space Expansion**. Land on the outskirts is repurposed and becomes part of the urban area. Housing and business space are developed on vacant land and redeveloped with increased density on occupied land. These processes increase **Available Space**, helping to sustain **City Attractiveness** and growth of **Jobs** and **People**.

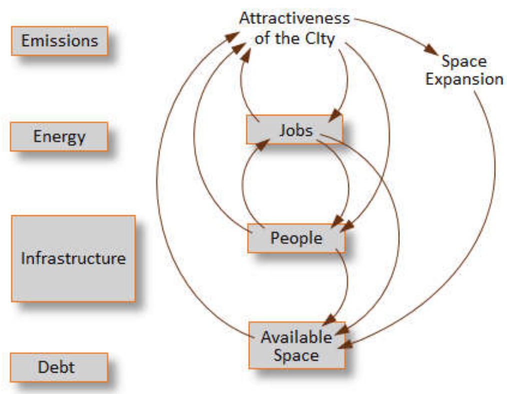

Figure 8 – Jobs and people in space

<u>Public Services and Paying for Them</u>. **Jobs** and **People** require and consume a wide range of **Public Services**, and governments generate **Tax Revenues** to cover associated **Public Costs** (Figure 9). Resulting government **Fiscal Balances** (i.e. the balance of public revenues versus costs of public services) affect **Tax Rates** as well as the level of **Public Services** provided and their **Public Costs** (as when budget restrictions force reduced service levels to control costs).

City Attractiveness can be significantly affected by stakeholders' perceptions of the balance between **Tax Rates** and the level and quality of **Public Services**. Cities with a notably healthy balance are often seen as more attractive. An increasingly unhealthy balance between **Public Services** and **Tax Rates** was a by-product of declining **Jobs** and **People** in Detroit, and that imbalance reinforced the city's downward spiral.

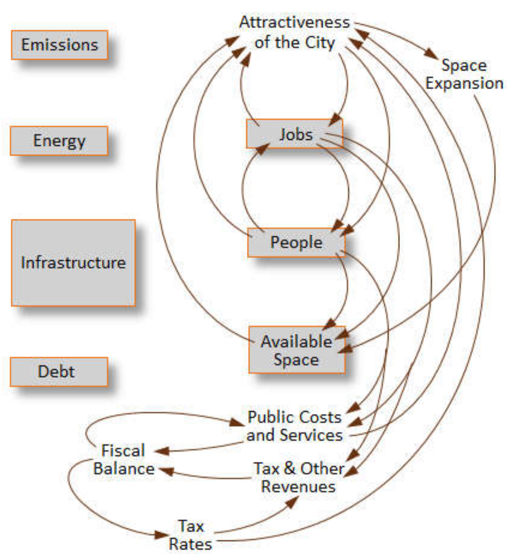

Figure 9 – Public services and paying for them

Public Infrastructure and Debt. **Jobs** and **People** require and use many types of city **Infrastructure** (Figure 10).

Infrastructure tends to consume **Available Space**, and **Available Space** can limit **Infrastructure** expansion. Some forms of **Infrastructure** (e.g. commuter rail) add to **Available Space** by making land in and near the city more accessible to **Jobs**, and therefore suitable for developing housing and business space.

City **Infrastructure** influences the provision of **Public Services** and associated **Public Costs**, and adequacy of Infrastructure influences **City Attractiveness**.

Urban **Infrastructure** investments are often financed with public **Debt**. As the region grows and invests in new **Infrastructure**, public **Debt** tends to grow along with them. With growing **Debt** comes increasing **Debt** service and its influence on the public **Fiscal Balance**.

Public **Debt** tends to grow until it is limited by public borrowing capacity, **Fiscal Balance** or simply by lack of suitable security for further **Debt** financing. Such limits can put a stop to most city **Infrastructure** investment.

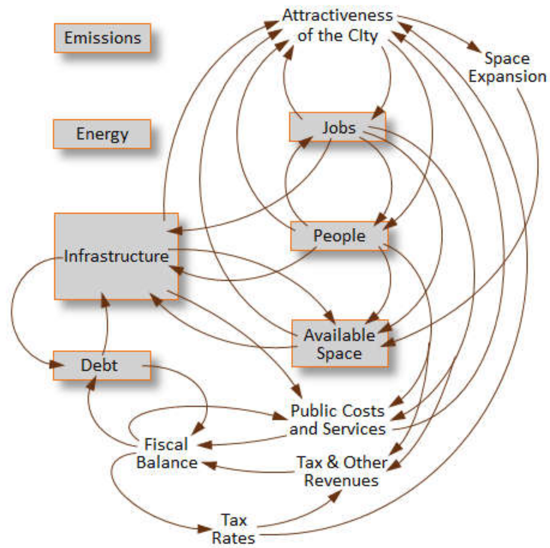

Figure 10 – Public infrastructure and debt

Energy and Emissions. **Jobs**, **People**, and city **Infrastructure** all consume energy and create a variety of **Emissions** (including sewage, NOx, particulates, greenhouse gasses, physical waste, noise). Processes for dealing with **Emissions** usually consume **Energy** (Figure 11).

Both **Energy** consumption and **Emissions** influence **Public Costs** as well as **City Attractiveness**. Severe **Emissions** problems can reduce **City Attractiveness**.

This whole-system diagram is sufficiently complete for the purposes of our report. As the city system is complex, so is the diagram. Yet, on less than a single printed page, it reveals one of the most potent of all man-made dynamic structures. As will be seen in subsequent sections of this report, the dynamic structure shown in this diagram has great power not only in cities, but in quantitative analyses of the city system.

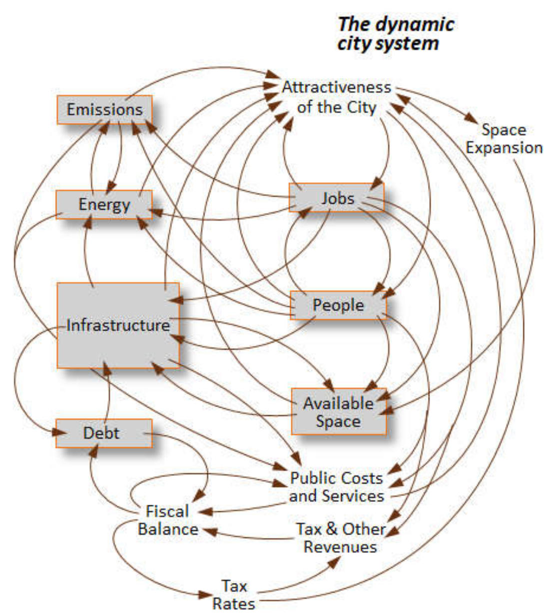

Figure 11 – Energy and emissions

3.3. Understanding the City System

According to Wikipedia: ***"A system is a regularly interacting or interdependent group of items forming a unified whole.*** *Every system is delineated by its spatial and temporal boundaries, surrounded and influenced by its environment, described by its structure and purpose and expressed in its functioning."*

Aristotle wrote that ***"The whole is more than the sum of its parts."***

City elements, bound together by cause-effect relationships, make the city a system that is more than the sum of its parts. That characteristic of systems is vital to understanding cities and how they are affected by public investments. It means that we cannot understand or anticipate how a city system will perform merely by studying the elements included in that system. To study individual elements without their integrative network of cause-effect relationships loses the very system that we seek to understand.

Scientists have been re-discovering this truth about systems and are moving beyond the 'reductionism' that was previously seen as synonymous with science. An excerpt from a recent paper expresses it well (emphasis added).

> *"The French philosopher and mathematician René Descartes (1596–1650) was the first to introduce reductionism to Western thinking and philosophy. According to his view, the world can be regarded as a clockwork mechanism; to understand it, one need only investigate the parts…Newton further advanced the idea of a 'clockwork universe'…The world's apparent complexity can be resolved by analysis and reducing phenomena to their simplest components. "Once you have done that, [the evolution of phenomena] will turn out to be perfectly regular, reversible and predictable…"*
>
> *[But] the reductionist approach is not able to analyse and properly account for the emergent properties that characterize complex systems. The Greek philosopher Aristotle (384–322 BC) had already described emergence in his treatise* Metaphysics *as, "The whole is more than the sum of its parts." Thus, the whole system can neither be reduced nor deduced from the qualities of its individual parts; a view now held in a variety of scientific fields ranging from physics to sociology."*[3]

This is not to criticise reductionist approaches, which have produced a great deal of knowledge about individual elements of the city system. It merely recognizes the limitations of reductionism and its resulting insufficiency for understanding how a city system will perform as a whole. That understanding requires whole-system evaluation capability in both qualitative and quantitative forms.

'Verticals' and the city system

Just as the city system differs fundamentally from its individual elements, so does that system differ fundamentally from the various 'verticals' in city institutions. The term 'verticals' refers to private and public organizations and departments that focus on specific aspects of the city system. For example, the GLA has departments or teams organized around transport, demographics, housing, the environment, city finances, and other vertical disciplines, and these groups have discipline-specific computer models for analysing public investments in Greater London.

Based on knowledge in relevant disciplines, ***institutional verticals are important for analysing, understanding, and managing portions of city systems. Yet verticals are also reductionist by nature and the whole of a city system is more than the sum of its verticals.***

[3] Fulvio Mazzocchi, Complexity in biology. Exceeding the limits of reductionism and determinism… (Science and Society 2008 Jan)

Because institutional verticals focus on different slices of the city system and rely on different disciplines, it is not easy for them to connect and collaborate (Figure 12). Operating and analytical objectives often differ from one vertical to the next, as do knowledge bases, terminologies, data, and methods. These differences make it challenging to join up models, analyses, and understanding across verticals.

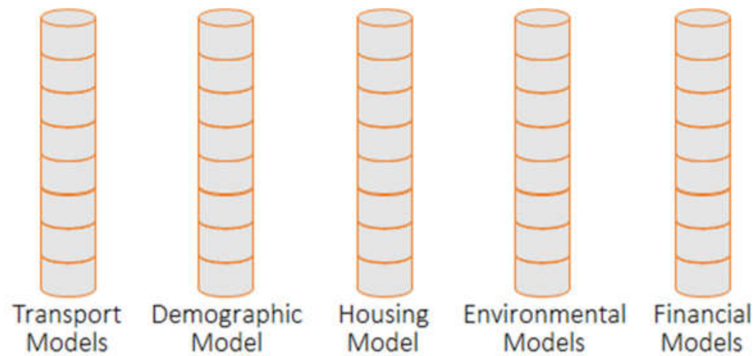

Figure 12 – City discipline-specific models

This point is illustrated by the obvious fact that city jobs, population, housing, and public transport simultaneously and powerfully influence each other, connected and propelled by cause-effect relationships that cut across vertical disciplines and form the city system. It's hard to fully reflect these powerful cross-disciplinary influences in vertical models and analyses. This is not a criticism of such things, which are much needed, but an observation on the inherent nature of limitations that exist in some form in every analytical approach.

Change processes in the city system

This report regularly refers to 'the city system' because the dynamic structure of that system is universal. To be specific, the elements and connecting cause-effect relationships that comprise the city system exist in each of the world's cities.

At the same time, each city's embodiment of this universal structure is unique in two ways.

- Strengths of the component cause-effect relationships are unique to each city. These strengths are the city equivalent of individual human DNA.
- When cause-effect relationships with unique city-specific strengths operate in a dynamic structure that is common to all cities, the result in each city is an ever-shifting mix of jobs, people, infrastructure, space, emissions, etc. that is unique to that city.

Given the universal structure of the city system, one might conclude that ever-changing performance in each city is caused by ever-changing strengths of that city's cause-effect relationships. But, like human DNA, the strengths of each city's cause-effect relationships change much more slowly than does the city's performance over time. In fact, the strengths of the cause-effect relationships in socioeconomic systems are normally quite stable over long periods. Changing city performance comes mostly from shifts in the balance among constituent feedback loops within that city system, while the strengths of the cause-effect relationships in those feedback mechanisms remain constant or very nearly so.

As an example, London's current housing crisis developed quickly, emerging in just 20 years. The root cause of the crisis is the balance (or imbalance) between the feedback loops propelling population growth and those driving housing development. Strengths of the cause-effect relationships in these feedback loops have not changed noticeably during that period, as demonstrated in a subsequent section of this report.

We have arrived at a basic characteristic of dynamic socioeconomic systems (including cities): in them, cause-effect relationships that are themselves quite stable produce changing and even unstable system behaviour. That fact nicely demonstrates these truths: the whole of a system really is more than its parts; and we cannot find out the nature of the system and how it behaves by examining system components.

City system behaviour is continuously changing both from the city's own dynamics and in response to external and other internal changes. People intervene regularly in city systems to bring about change, to improve performance or mitigate problems. These interventions target (i) specific elements of the city system, or (ii) specific cause-effect relationships in the system, or (iii) some combination of the two. Potential solutions for London's housing crisis, now under discussion, offer good examples of these options.

- **Direct change to the housing element of the system:** To mitigate the problem we could add housing units that would not otherwise be built, or that would only be built much more slowly. Alternatively, we could accomplish much the same thing by building commuter rail lines that connect developable land with job concentrations, making housing attractive and economically feasible on that land.
- **Changing the strengths of cause-effect relationships driving housing development:** We could reform the development permitting process and tax undeveloped land to reduce delays and cut down on speculative land-hoarding, thereby increasing the pace of housing development relative to demand.

To evaluate and prioritize such investments and policy changes, it helps to know (i) the stable structure of the city-system and (ii) the mostly stable city-specific strengths of cause-effect relationships operating within that structure. As will be seen in Section 4 of this report, that stable system structure can be used to discover the unique strengths of the cause-effect relationships in each city.

3.4. How Investments Affect the City

An investment affects the city system in two basic ways: (i) through its Direct Operating Consequences (DOCs); and (ii) through Dynamic Consequences (DCs) that are triggered by the Direct Operating Consequences.

Direct Operating Consequences include all the ways the investment will directly affect individual elements and causal relationships in the city system. Examples of expected DOCs from prospective investments in Greater London:

- Crossrail 2 will make developable land in the Upper Lea Valley newly accessible to job concentrations in Greater London, and that land can hold about 134,000 new residential units;
- Research suggests that providing high-speed fibre internet access to every building in Greater London could increase the attractiveness of housing development by about 4.5% on average.

The DOCs of an investment can be identified and characterized, first qualitatively and then in numerical terms, as in the examples above.

Dynamic Consequences (DCs) of an investment include the ways that stakeholders in the city-system react and respond to that investment's DOCs; such reactions are reflected in the cause-effect relationships that connect city elements to form a dynamic system. As will be seen in subsequent sections of this report, the Greater London simulator exists for the purpose of anticipating, analysing, and understanding Dynamic Consequences, whether of investments or of other changes (e.g. Britain's exit from the European Union).

Dynamic Consequences spread through the city's cause-effect network and can go on for quite a long time, emerging as new responses to earlier reactions. Some DCs from the above-listed investments:

- Dynamic Consequences of the Crossrail 2 investment as of 2050 include: (i) 219,000 new residential units; (ii) an increase Greater London's population by 362,000; (iii) an increase in employment by 199,000; (iv) an increase in annual Greater London GVA by 17 billion GBP or 2.4% (in real terms); and (v) an increase in Central Government's annual net tax surplus from Greater London of 5 billion GBP (in real terms) or 2.4%.
- Dynamic Consequences of London-wide 5G service in 2050 include: (i) an increase of 49,000 in Greater London employment; and (ii) an increase in annual Greater London GVA by 3.4 billion GBP or 0.5%.

Most benefits from urban investments come via their Dynamic Consequences, which are powerfully influenced by evolving conditions in the city system. System conditions typically determine whether public benefits will exceed investment costs; and public investments are simultaneously influencing conditions in the dynamic city system.

As a result, public benefits from one investment can be affected by Dynamic Consequences from other public investments, including investments made during different time periods. Cross-influences of investments on each other may act for better or for worse; investment combinations with complementary beneficial influences on city dynamics can increase the potency of public investment funding and financing. The Greater London Simulator and other city simulators help find beneficial synergies among prospective city investments.

3.5. Prioritizing Investments in the City System

Prioritization Challenges

Prioritizing city investments is a challenging task because each investment produces a different mix of responses and consequences in the city system. Some investment consequences can be directly measured in financial terms (changes in incomes or tax revenues), but social and environmental consequences usually involve non-financial metrics. It is generally difficult to combine measures of different types of consequences, even for a single investment. Comparing city consequences across multiple investments, to prioritize them, adds yet another level of difficulty. Sections 4 and 5 of 'Mind the Gap' show new ways of addressing investment prioritisation.

The counterfactual challenge

This section addresses a more basic prioritization challenge: the inherent difficulty of measuring the consequences of a single city investment *even after the fact*. The source of the difficulty is simple: we cannot back up and 'rerun' the city to see how it would have performed without that investment. Such a rerun is often referred to as the 'counterfactual conditional', or counterfactual for short. The counterfactual is the city's condition and performance that would have resulted had we not made the investment in question.

The impracticality of real-world counterfactual experiments has important implications for efforts to prioritize city investments.

- We rarely get a complete, reliable view of consequences from a past city investment.
  - The whole city system shapes and is influenced by the dynamic consequences of such investments.
  - Most analysis methods do not cover the whole system, being vertically focused.
  - Many analysis methods have trouble distinguishing the consequences of a particular investment from those of other city initiatives.
- Given the difficulty of determining the consequences of a past city investment, how can we anticipate consequences from a prospective future investment, or reliably prioritize investments by comparing their expected future consequences?

The answer: we use models to evaluate the likely consequences of investments in comparison to what we can expect from the city without those investments.

City model choices

A model is a representation or imitation of something in the real world. Some models are illustrative, others have analytical purposes. Mental models are by far the most common type for analytical purposes; being accustomed to thinking through options and possible consequences, we rarely stop to consider that this process depends on our mental models of how the world works. Flexibility is a particular strength of mental models, but they are inherently difficult to document and communicate and their reliability is often questionable.

Some mental models take subsequent shape in written or numeric form, and many numeric models are computerized. Computer models exist in a myriad of forms (spreadsheet, econometric, financial, etc.) and have an extremely wide range of subjects, content, and methodologies. Every modelling approach has strengths as well as limitations, which means we must choose model form and content based on what needs to be analysed.

But we cannot choose whether or not to use models; if we are thinking about city investments and their future consequences, we are already relying on (mental) models. Choices thereafter involve the types of models needed and how we should use them.

Section 3.2 briefly discussed vertically focussed computer models in various city disciplines (transport, housing, demographics, etc.). Vertical models are indispensable for deep and detailed analysis work in these disciplines.

Computerized city system models are similarly indispensable for analyses that cross disciplines and measure how the whole system responds to various investments. This purpose calls for a different form of model detail from that found in vertical models. Instead of discipline-specific detail, the whole-system model contains detailed representations of city system components, that is, of system elements and the cause-effect relationships that connect them.

As a whole-system model, the Greater London Simulator is a horizontal, top-down 'virtual twin' of the city's dynamic structure. It integrates the subjects of the various vertical disciplines and represents their influences on each other in the city system. The GLA's vertical models (Figure 13) are appropriately based on deep discipline-specific knowledge and detailed data; in that sense they are 'bottom-up' representations of their subjects.

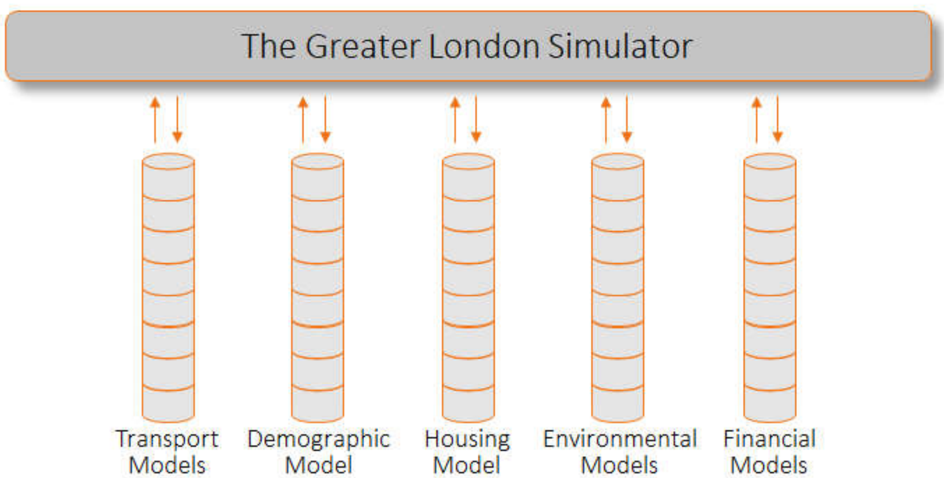

Figure 13 – City-discipline specific models in coordination with the Greater London Simulator

Whole-system and discipline-specific models have different purposes and do not substitute for or depend on one another. These different purposes and model types are inherently complementary. Vertical models reflect important discipline-specific knowledge and detail that would be impractical to include in a whole-system model. Similarly, the system model includes connective whole-city dynamics that extend beyond the appropriate content of a discipline-specific model. Vertical-model analyses can add value by defining and shaping investment scenarios for whole-system analysis; simulations of system-wide investment consequences can add value by more broadly informing the detailed analyses made with discipline-specific models.

Vertical computer models are far more numerous than whole-system models of socioeconomic systems. There are two main types of top-down system-level socioeconomic models; dynamic models like the Greater London Simulator; and econometric models. Of the two types, econometric models are far more widely known and frequently used – most commonly for national economic forecasting.

We are sometimes asked why the Greater London and other city simulators are based on dynamic rather than econometric modelling. The two methods have much in common: both rely strongly on the scientific method and prior knowledge and they share numerous tools and processes, though these are sometimes used in different ways. The two methods have different origins, purposes and strengths which determine their usefulness for evaluating and prioritizing city investments.

- Econometric modelling originated in science and is rooted in mathematics; accurate predictions or forecasts verify model validity and are a primary objective. Econometric models rely heavily on long economic data time series, for model validation among other purposes; such data are readily available for most national economies, but rarely so for cities. The feasibility of econometric modelling diminishes rapidly when available data is short in duration, or interrupted or simply unavailable – as is often the case with city data.
- Dynamic modelling originated in engineering; it focuses on what makes systems behave as they do, and on ways of improving system performance. Its objective is not forecasting, but anticipation, preparedness, and ensuring robust performance under a wide range of possible scenarios. Dynamic modelling makes rigorous use of data time series for model validation. Its dual reliance on wide knowledge of the system structure in combination with data makes dynamic simulation unusually robust in the face of imperfections that are common in city data.
- There are many other analytical methods with which dynamic modelling may be compared, including agent-based modelling, Big Data, AI (Artificial Intelligence), behavioural economics, etc. These generally serve useful but different purposes. Agent-based modelling, for example, is a form of dynamic simulation that focuses on interactions among large numbers of simulated agents (e.g. spectators exiting a stadium). To our knowledge econometrics comes the closest to dynamic analysis in relying on prior knowledge of the system and using historical data for model validation.

4. Simulating Greater London

In 2014 Greenwood simulated Chicago and analysed investments aimed at saving that city from bankruptcy. In 2015 Greenwood and the Greater London Authority (GLA) began working on the Greater London Simulator. In 2016 we began similar work with Boston (Massachusetts), covering that city and the rest of Greater Boston. In 2017 Greenwood added simulators of Norfolk (Virginia) and Frankfurt and Coburg in Germany.

Greenwood's city initiative has three related objectives:

- Understand and anticipate the systemic influence of public and other investments in cities;
- Determine the value (social, economic, environmental, fiscal etc.) of public investments in cities, along with the ***'cost of not'*** making such investments;
- Establish a new framework to bring increased funding and private financing for city investments.

With these objectives in mind, Greenwood developed a software technology platform for city simulation and dynamic analysis. Flexible in its application, this platform enables rapid simulator setup and city analysis at selected levels of detail. The platform uses a common model that is tailored to each city's situation and characteristics and tested for its ability to reproduce that city's history on multiple dimensions.

City simulations and analyses to date have covered the following investment types and public issues.

- Public transport
- Housing and land use
- Brownfield redevelopment
- Flooding impacts / defence
- Quasi-private development
- High-speed internet, smart grid
- Brexit (London, Frankfurt)
- Innovative investment financing solutions

Section 4 reports on the Greater London Simulator and dynamic analyses, including: dynamic structure of the city simulation model; sources and uses of information; simulator testing and validation. Section 5 reports on London investment scenarios for simulation and impacts from these investments.

4.1. Origin of the City Model Structure

Greenwood defined the dynamic structure used in Greater London's simulator well before partnering with the GLA. Two things made that possible.

- First, key system elements and cause-effect relationships are universal, existing in all cities.
- Second, a primary focus on investment in cities enabled us to select appropriate elements and cause-effect relationships for inclusion in the common city simulator.

That selection is a good example of *boundary definition*, a necessary task in developing all types of models. The boundary definition establishes those aspects of the system that will be included in the model. It is impossible to build a model that includes every aspect of most real-world systems. Even if we could build them, such models would be far too complex and cumbersome for effective use. So boundary choices must be made based on the model's purpose and the analysis objectives.

That illustrates a basic tenet of model building and use: *"All models are wrong; some models are useful."*[4]

Models are inevitably 'wrong' because they are deliberately simplified representations of the real world. Mental models can be extreme examples of such simplification, and other model types differ only in degree.

In fact, it is simplification that makes models useful, or potentially so – without simplification our models would be as complicated as the real world and almost as unusable for analysis. ***The usefulness of a computer model depends on the nature of its simplifications of the real world, on what is and is not included and how well the model's content corresponds to its purpose and the analysis objectives.*** The model must have an appropriate boundary, and there must be appropriate content within that boundary – namely, system elements and cause-effect relationships appropriate to the analysis objectives.

Thanks to its boundary and internal content, the common model structure in the Greater London Simulator is suitable for simulating many types of investments and their influence in the city. Moreover, that content can be enhanced when needed for a particular analysis.

The Norfolk (Virginia) simulator is an example of such enhancement; its main purpose is to measure the value of flood-defence investments and the ***'cost of not'*** making such investments. To simulate the physical, psychological, social, and economic damage caused by serial flooding, and how city stakeholders respond to that damage, Greenwood developed a flooding module that connects to the common city model.

The dynamic structure in the new flooding module falls within the original boundary of the common model and connects to existing model content. The module adds details of elements, relationships, and feedbacks that are specific to long-term serial flooding. This added system detail makes the Norfolk model useful for measuring socioeconomic damage from flooding and the value of flood-defence investments.

In future this module may be connected to the Greater London Simulator to analyse socioeconomic impacts from flooding caused by severe rain storms and the value of flood-defence investments.

The structure of the common city model may be usefully explored or audited down to the level of individual equations. For those interested, such a 'drill down' through the structure can be found in Appendix 8.3.

[4] Renowned statistician George E. P. Box

4.2. Information and the Greater London Simulator

Thanks to keen powers of observation and lengthy urban experience, mankind has amassed a great deal of knowledge and information about cities and their component elements and cause-effect relationships. Some of this exists in written form, and a portion of written city information is available as numerical data. These are complementary forms of information, and dynamic simulation makes use of them all.

Four types of information figure prominently in dynamic modelling and analysis of cities. Table 2 and the text following summarize the nature and use of information in simulating Greater London.

	Type of Information	Use in Simulating Greater London
1	Prior knowledge of dynamic structures in socioeconomic systems, particularly cities	Defining the structure of the common city model
2	Information on initial city conditions	Simulator initialization at the simulation starting point
3	Historical information 1995-2016 a) Data time-series b) Characterizations of city conditions and their effects	Testing and validating the simulator; Determining strengths of cause-effect relationships in the city
4	Quantitative characterizations of investments and other scenarios for analysis	Scenario inputs to the simulator

Table 2 – Types of information used in simulating Greater London

1) Prior knowledge of dynamic structures in city systems

A great deal of mankind's knowledge about cities does not exist in written form. This is true of city knowledge in general and of what is known about specific cities and the conditions in them.

There is broad prior knowledge of the elements that exist in and define every city – jobs, people, infrastructure, local government, housing, transport, etc. There is equally broad knowledge of the cause-effect relationships that connect these urban elements to form a city system. We know how such relationships influence the behaviour of various city stakeholders and can assess the relative strengths of these relationships under different circumstances.

Nearly all forms of modelling rely on prior knowledge in some form, and dynamic simulation is no exception. Prior knowledge regarding city systems is seen in the structure of the common city model that is used in the Greater London Simulator, as diagrammed in Appendix 8.3 (Figure 24, Figure 25, Figure 26, Figure 27, and Figure 28).

One cannot assume that any form of city information is correct, including prior knowledge; it is important that all forms of information are tested against each other. Prior knowledge embodied in the structure of the common city model plays a vital role in such testing and is itself tested in that process. This testing is a standard in dynamic simulation, as described in Section 4.3.

2) Information on initial city conditions

Every dynamic simulation of a city starts at some specified point in simulated time. For full information testing that starting point should lie in the past and historical data should be available thereafter.

Greater London simulations currently start at the beginning of 1995, and initial values of the various city elements in the simulator are set consistent with information from the beginning of that historical period, e.g. for London's population, housing, jobs and business space. A total of fifty-four simulated city elements are so initialized, some with multiple initialized sub-categories (e.g. income-based population sub-groups, jobs types, and business types).

3) Historical information 1995-2016

Beginning in 1995 (in simulated time) the Greater London Simulator uses the common city model structure to generate trajectories for population, housing, jobs, business space, and other city elements. These trajectories are created simultaneously and in dynamically connected fashion by the simulated London city-system; they have been extensively tested against London data during the 1995-2016 historical period, as described in Section 3.5.

There are 80 simulated Greater London city elements for which historical information is currently available. Many of these elements are simulated on multiple dimensions (six separate London tax revenue streams, for example). In all, London historical information is currently available for a total of 253 simulated city elements and element sub-groups; this information is available in two different forms.

a) **Data time series.** Time series data exists for 136 simulated city elements and aggregations thereof. Some of these cover the entire 1995-2016 period, many run through 2014, and others cover shorter periods. Available data time series for Greater London are listed in Appendix 8.1.

b) **Characterizations of London conditions and their effects.** Where time series data is not currently available, Greenwood and the GLA conducted structured interviews to access knowledge of London's recent history. As an example, GLA staff were interviewed for their knowledge of factors that have influenced Greater London's attractiveness for in-migration, including availability of jobs and housing. Such knowledge-based characterizations exist for a total of 117 simulated city elements and element sub-groups.

Knowledge gained through interviews is less precise than most of London's data time series. But where important elements and cause-effect relationships are concerned, and data is not available, knowledge from interviews is far better than nothing – especially when that knowledge is rigorously tested against other forms of information. The ability to make seamless, integrated use of hard data and softer knowledge is a notable strength of the dynamic analysis method.

4) Quantitative characterizations of scenarios for analysis

City simulators are platforms for dynamic performance analyses, and scenarios are the vehicles for such analyses. 'Mind the Gap' describes scenarios involving London transport, housing, and internet investments, and refers to scenarios involving Britain's impending exit from the European Union.

For input to the Greater London Simulator, scenarios are characterized in terms of their Direct Operating Consequences (DOCs) for the city system. DOCs express in numerical terms which city elements and relationships are directly affected by a particular scenario, and by how much. Scenario DOCs are simulator inputs; simulating with these inputs shows how the city system as a whole can be expected to respond and perform under that scenario.

GLA subject matter experts specified DOCs for the Greater London simulation scenarios (described in Appendix 8.2) and analyses that are subjects of this report.

As explained in Section 4.3, complementary use of these different information types is of great importance to the reliability of city simulators and simulation analyses.

4.3. Testing and Validating the Greater London Simulator

There are many ways to test a city simulator, and passing such tests provides essential confirmation of the simulator's fitness for purpose and reliability.

Behaviour reproduction is the most important and visible of these tests: Does the simulator reproduce the city's mid- and long-term behaviour, simultaneously on multiple dimensions, over a 20-year period and without accessing or using the historical information over that period?

Most computer models cannot pass a test of behaviour reproduction that is fully independent of historical data, because they use that same historical data as a main model input. Spreadsheet, econometric, financial and many other types of computer models base their structures on historical data, and then enter that data in the model to drive its computations. When historical data drives the model, behaviour reproduction testing can shed little light on the fitness of the model's structure for purpose or reliability.

That is not to criticize these modelling approaches, which have produced a wide array of useful, mostly non-dynamic, analyses. But all modelling methods have limitations and using historical data as inputs means that most computer models have no inherent or testable ability to independently reproduce the history of what is being modelled.

Dynamic simulation works to a different standard. A city simulator that does not independently reproduce the city's own history should not be trusted. Reproducing historical information to close tolerances is a foundational element of the scientific method for testing new theories, and computer models are theories in virtual form.

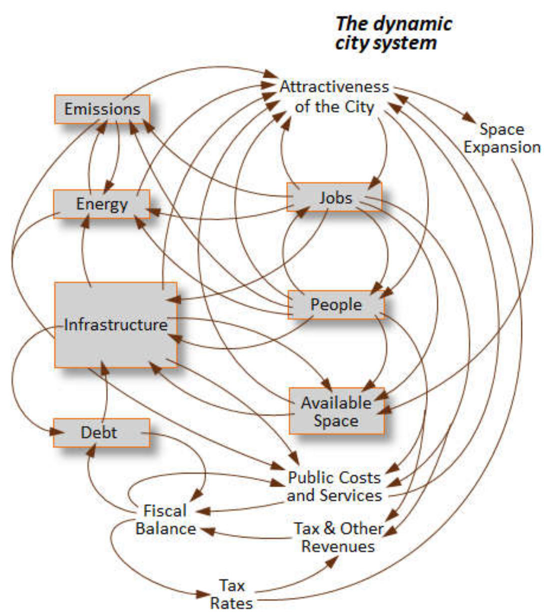

Figure 14 – The dynamic city system

As briefly described in Section 3 of this report, the structure of a dynamic city simulator (shown here) replicates the elements and cause-effect relationships in real cities. In other words, ***the city simulator begins as a 'virtual twin' of cities' dynamic structure instead of starting with historical city information.***

With dynamic city structure as the model's starting point, behaviour reproduction testing becomes both feasible and meaningful. City historical information (including time series data) is used in such testing, not as model inputs, but as a benchmark for behaviour testing, that is, for measuring the fidelity with which the simulator reproduces city history.

A high-fidelity reproduction of history builds confidence in the simulator's reliability and fitness for use. In addition, the process of behaviour testing against history reveals something of great analytical value that would otherwise be unknowable – namely, the strengths of the cause-effect relationships that connect urban elements in a particular city, forming that dynamic city system.

Testing the Greater London Simulator

Although the same foundational cause-effect relationships operate in every city system, the strengths of these relationship will be unique to each city. Unknown when modelling begins, relationship strengths for a particular city can be determined only through testing the behaviour of the model structure against the benchmarks of that city's historical information.

In the first version of the Greater London Simulator Greenwood initialized simulated city elements as described in Section 4.2, based on data from the beginning of the historical period. We initialized simulated cause-effect relationships with placeholder strengths that are typical of cities in general, because we had not yet determined London's unique relationship strengths. It was therefore expected that the first simulation would deviate significantly from London's history on multiple dimensions.

These deviations were useful because each one highlighted discrepancies between the generically initialized strengths of simulated cause-effect relationships and the actual strengths of those relationships in Greater London. The deviations pointed to specific cause-effect relationships that were likely to have the wrong strengths.

For example, in early behaviour testing: (i) the simulated trajectory of London residents was somewhat lower than population data for the historical period; while (ii) the simulated job trajectory closely matched historical employment data. That suggested that cause-effect relationships between jobs and migration in Greater London might be stronger than the placeholder value we had initially used.

When behaviour testing suggests a problem with the strength of a simulated cause-effect relationship, the next steps involve further testing. In this case we increased strength settings for the simulated relationships between jobs and migration, ran another simulation, and again tested London's simulated behaviour against the historical information. The population and job trajectories in this new simulation were much more consistent with London's historical data; at the same time, other dimensions of simulated behaviour had become no less consistent with historical information.

That last point is important, because behaviour testing means simultaneously comparing all simulated elements and relationships with their real-city counterparts, wherever historical information allows. As a reminder Section 4.2 and Appendix 8.1 show that available London historical information directly covers 253 corresponding elements or cause-effect relationships in the Greater London Simulator.

But behaviour testing against city historical information reaches much further than the coverage of historical information alone would suggest. That is because the elements / relationships directly covered by such information connect within the simulated system to many other elements / relationships for which historical information is not available. As a result, behaviour testing reveals and helps resolve problems with the strengths of cause-effect relationships for which historical information is not available.

This capability results from using the known dynamic structure of the city system in combination with behaviour testing against the city's historical information.

Behaviour testing actually tests three complementary types of information against each other:

1) Knowledge of the city system (its component elements and connecting cause-effect relationships)
2) Numerical inputs characterizing strengths of these relationships
3) Historical information for the city being simulated

Because relationship strengths are initially assumed, that is where most inconsistencies with a city's history are discovered and resolved. But behaviour testing regularly reveals non-obvious inconsistencies within the historical information itself and highlights needed structural refinements within the model.

Behaviour reproduction testing is inherently iterative; each test failure indicates needed refinements, which must be followed by another round of behaviour testing and possible further refinement. Such testing of the Greater London Simulator has involved several million simulation / refinement steps. Following each step hundreds of model outputs are compared against historical information and discrepancies quantified using statistical error-rate metrics; these measurements then guide adjustments to relationship strengths (along with any data / model fixes) for the next simulation / refinement step. Greenwood's software automates this process, and the complete behaviour testing and refinement cycle for the Greater London Simulator can be completed in a few days.

The Greater London Simulator has been subjected to many other standard dynamic modelling tests, discussion of which is beyond the scope of this report. Testing will continue in multiple forms as historical information accumulates, information becomes available from earlier historic periods, and the simulator is expanded and refined.

The common city model used in the Greater London simulator has been further tested by use in simulators of four other cities and on scenarios different from those in Greater London. The ability of this single model structure to simulate quite different cities with equal fidelity validates that model and illustrates the universality of the dynamic structure it simulates.

Simulator validation and validity

A city simulator that does not replicate city history or fails other forms of simulator testing has been shown to be inconsistent with the evidence at hand. Failing that test indicates that the model is not yet fit for use.

When sufficiently refined to closely reproduce the city's history and pass other relevant tests, the Greater London Simulator was thereby validated; that is, substantiated and confirmed as sound, well founded, effective, as having force, cogency, weight. At that point the Greater London Simulator was demonstrably fit for purpose.

The strengths of cause-effect relationships in the London city system are a particularly valuable product of the simulator testing / refinement process because these relationship strengths are, in a sense, the DNA of Greater London – different from the DNA of other cities and slow to change (like human DNA). In combination with the validated simulator structure, these validated relationships are a solid basis for reliable dynamic analysis of investment and other future scenarios in Greater London.

A detailed review of Greater London's simulated history is beyond the scope of this report. Figure 15 on page 39 shows the opening page from the Greater London Simulator's online user interface, and provides an overview spanning the breadth of the simulator.

- The opening page includes 12 summary-level graphs from various model sectors, showing results from simulated scenarios.

- Tabs across the top access 148 graphs showing more detailed simulation results from various scenario simulations.
- The dashed black lines in the graphs show historical data for comparison with the simulator's reproduction of London's history. The Greater London Simulator closely reproduces city history in all respects except unemployment, for which the simulator matches the average level and trend without attempting to mirror the short-term economic cycle. Such cycles are unnecessary for initial investigation of long-term investments and will likely be added as and when needed.

The simulation labelled JLE/Olympics/Crossrail 1 in Figure 17 is the starting point for simulations of the prospective future investments discussed in Section 5 of this report. That simulation includes (i) the Jubilee Line Extension (JLE) investment, (ii) the 2012 London Olympics and Paralympics investments, (iii) the Crossrail 1 high-speed commuter rail line investment scheduled for opening in 2019, and (iv) all other Greater London investments made during the historical period.

Figure 15 – Greater London Simulator recreating London's recent history

5. Dynamic Evaluation of Public Investments in Greater London

5.1. Public Investments and Other Scenarios Evaluated

The GLA has specified and characterised eight public and two mixed public / private investments for dynamic analysis (the BLE project counting as a single investment), as shown in Table 3 below.

GLA Investment Scenarios	Nature of the Investment	Investment Amount (£ Billions)	Expected Construction Time Span	Expected Addition of Housing Units	Expected Added m² of Business Space
Jubilee Line Extension (JLE)	Transport	3.5	1994-2000	28,250	2,695,000
London Olympics and Paralympic Games	Redevelopment	9.3	2005-2012	63,200	1,700,000
Crossrail 1	Transport	14.8	2009-2019	57,000	3,325,000
Sutton Tram Extension	Transport	0.35	2022-2025	10,700	N/A
Crossrail 1 Extension	Transport	2.5	2023-2028	15,000	225,000
Bakerloo Line Extension Phase 1 (BLE) (to Lewisham, 27 trains per hour)	Transport	3.6	2023-2029	25,000	215,300
BLE Phase 2 Option A (to Hayes & Beckenham Jct, 27 trains/ hour)	Transport	0.5	2029-2033	6,500	N/A
BLE Phase 2 Option B (to Bromley North, 27 trains/hour)	Transport	1.2	2023-2033	2,500	N/A
BLE Phase 2 Option C (to Slade Green, 27 trains/hour)	Transport	0.8	2029-2033	8,000	N/A
BLE Phases 1+2 High Capacity (33 trains per hour)	Transport	1.0	2023-2033	7,500	N/A
Crossrail 2	Transport	29.0	2023-2036	134,000	72,315
Royal Docks	Redevelopment	0.39	2016-2037	25,900	641,000
Digital (FTTH/FTTB for every London Building)	Internet	N/A	2018-2028	N/A	N/A
London Plan Housing	Housing	N/A	2019-2050	65,000 net added units/year	N/A

Table 3 – GLA investment scenarios

These include the three past or current investments shown and briefly described in Section 4. 'Mind the Gap' is focused on the seven prospective future investments:

- Four TfL transport investments including extensions of the Sutton Tram, Crossrail 1, and Bakerloo lines, and the proposed Crossrail 2 high-speed commuter rail line;
- The Royal Docks brownfield redevelopment project;
- Digital investment (mixed public / private) to make high-speed fibre-based internet service accessible in every building in Greater London;
- Accelerated housing development (mixed public /private) consistent with the Mayor's London Plan.

TfL is exploring multiple options for the scope and capacity of the BLE, and each listed option has been simulated. BLE simulations shown are for the combination of Phase 1, Phase 2 Option C, and increased BLE capacity from 27 to 33 trains/hour because this option produces the best ratio of investment costs to resulting benefits.[5]

Public cost data is available for the four transport investments and the Royal Docks redevelopment, as shown in the table. Public cost data is not yet available for the simulated Digital and London Plan housing investments, both of which are expected to involve substantial investment by private firms.

Increased housing is a key objective. The five prospective public investments repurpose land or bring new public transport to land that is suitable for development of new housing and business space.

These investments are aimed in part at relieving London's housing crisis. Housing is an expected high-leverage point in Greater London, a node in the dynamic system where investments are likely to deliver substantial social, economic, and fiscal gains.

That is why the Mayor's London Plan calls for building 65,000 net new residential units each year, about 2.5 times the recent rate at which housing has been growing in Greater London.

It is expected that the four prospective transport projects and Royal Docks development prospective investment projects will directly result in about 228,000 additional new housing units to 2037. That would sustain London's housing growth at its recent rate of about 26,000 units annually, well short of the Mayor's target.

The GLA's London Plan scenario injects additional housing growth sufficient to meet the overall target of 65,000 net new units annually, a total of just over 2 million net new units to 2050. In keeping with the Mayor's plan, this scenario has half of all new units being developed for lower-income residents. The simulation is a test of Greater London's dynamic response to a sustained increase in the rate of housing development and does not test the feasibility of achieving that rate.

The GLA's Digital scenario measures the consequences of bringing high-speed fibre-based internet access to every building in Greater London. With expected 30% service uptake by businesses and residents, this investment is expected to boost the attractiveness of housing and business construction, job creation, and local tax revenues (by 4.5% each), with lesser increases for in-migration attractiveness and other local government revenues.

Simulating these investments in Greater London reveals how the city responds as a whole, including resulting growth of population, jobs, and housing that may differ substantially from the direct consequences of the investments.

[5] Results for the individual BLE Phases and combinations of Phase 1, Phase 2 Option A or B respectively, and increased BLE capacity are available in Appendix 8.2.6.6.

Two additional simulation scenarios measure environmental consequences of these various investments in the form of greenhouse gas emissions, both with and without the GLA's ambitious decarbonisation programme.

Two additional simulation scenarios test Brexit's potential influence on these various investments and their consequences in Greater London. The magnitudes of these social and economic influences are set for broad consistency with recent Brexit forecasts by Cambridge Econometrics.[6]

Numerical simulator inputs for these scenarios can be found in Appendix 8.2 of this report. The simulation with the three past and present investments (JLE, Olympics, and Crossrail 1) constitutes the starting point for simulating the prospective future investments and Brexit.

Each prospective London investment is simulated at least twice: once by itself; and the second time in combinations with the other investments. Comparing London outcomes from these simulations reveals the existence of synergies (positive or negative cross-influences) between the various investments.

5.2. Greater London Investment Impacts and Insights

Impacts from these prospective investments are reviewed below in the following sequence.

- Transport and redevelopment investments
- Adding Digital and London Plan housing investments
- Emissions impacts from investments
- Investment synergies and the influence of Brexit
- A summary of investment impacts in Greater London

Simulated consequences are measured and investments are evaluated on social, economic, environmental, fiscal, and other dimensions.

What follows is a summary of simulated investment consequences consistent with the scope of this report; we have used the simulation software to review the simulations in much greater detail than could be presented here.

It is important to be clear about what the following simulations are and are not.

- These simulations are systematic explorations of London's responses to particular investments and other scenarios, made with a London-tailored whole-city model validated against the city's recent history.
- These simulations are not predictions of Greater London's future performance. Such predictions would require guessing which of these and many other investments will actually be made, along with similar guesses regarding numerous other scenarios (including but not limited to Brexit).

[6] No EU funding was used in conducting any simulation analyses involving Brexit.

Transport and redevelopment investments

Figure 16 on page 44 gives an overview of multi-dimensional consequences from the five public investments, beginning with the Sutton Tram Extension and concluding with Royal Docks.

Five broad insights emerge from the simulations shown in the Figure 16 overview.

1) London would still be a growth city even without these prospective future investments (as seen in the orange lines for the JLE/Olympics/Crossrail 1 scenario).
2) That said, these prospective investments boost London's simulated population/job/economic growth beyond what the simulated public investment process would otherwise deliver. Higher growth also results in greater energy consumption and slightly higher emissions, as one would expect.
3) In part these prospective investments are responses to Greater London's past growth, and they also increase Greater London's future growth. In the city system, public investment fuels growth and growth demands and incentivises further investment.
4) There is a significant ***'cost of not'*** making these prospective investments: (i) there are fewer future jobs and less income, yet (ii) the prospect of jobs still swells London's population despite the fact that (iii) there isn't as much housing or infrastructure in absolute terms, and (iii) relative availability of housing and infrastructure are reduced as population is still growing.
5) In the past it was hard to measure the long-term ***'costs of not'*** investing in a comprehensive and therefore reliable manner. Dynamic city analysis has changed that.

The simulations measure impacts from these investments in terms of:

- Cumulative differences in absolute growth of population, housing and jobs to 2050;
- Increases in the simulated sizes of London's 2050 economy and HMT's 2050 tax take from London.

Simulating Greater London without and then with these five public investments demonstrates their importance to the city's health and wellbeing and objectively measures damage on multiple dimensions if they are not made. In the absence of these or equivalent investments the inter-connected dynamics of London's jobs, population and housing operate in a significantly less balanced and effective way.

- Without these investments Greater London will have 365,000 fewer new housing units in 2050, equivalent to about 10% of London's total housing stock in 2015.
- Without these units London housing grows by only 12% to 2050 while the city's population swells by over 17%, so the housing crisis worsens steadily.
- Therefore social balance continues to deteriorate as middle-income Londoners shrink from 28% to just 22% of total population by 2050, due to diminishing middle-income housing.
- Less housing makes employees harder to find, so London's total job growth to 2050 is lower by 16% and economic growth is down by 10%. As a result, HMT's real annual London tax revenues are almost 12% lower in 2050 than they would be with these five investments.

These ***'costs of not'*** are likely to be permanent because lost social, economic, and fiscal growth is quite difficult to make up later. When public investments are delayed or prevented, lost growth opportunities leave a lower socioeconomic base as the starting point for subsequent growth.

Figure 16 – Transport and redevelopment investment scenarios simulated

Social and economic impacts from the transport and brownfield investments. Social impacts from these five investments begin with the 365,000 net new residential units they make possible by repurposing or bringing new public transport to land in Greater London (shown in the left-hand bar in Figure 17 below).

- The new housing meets pent-up demand, enabling additional population growth of 640,000 new residents to 2050 (as seen in the second bar from the left);
- The investments also enable 913,000 m^2 of new London business space to 2050 (the third bar);
- Together, increased population and business space enable additional job growth of 379,000 to 2050 (in the fourth bar);
- This increases the size of Greater London's 2050 economy (GVA) by £34B per year and enlarges HMT's 2050 London tax revenues by £10B per year (in the fifth and sixth bars, both figures are in real terms).

Greater London Population	Jobs in Greater London	Total Housing Units	Total Business Space	Annual Gross Value Added (GVA)	HMT Annual London Tax Revenues
9.9 Million	7.7 Million	3.8 Million	61.3 Million m^2	£691 Billion	£205 Billion

Metrics above are for 2050 as simulated without the five investments...

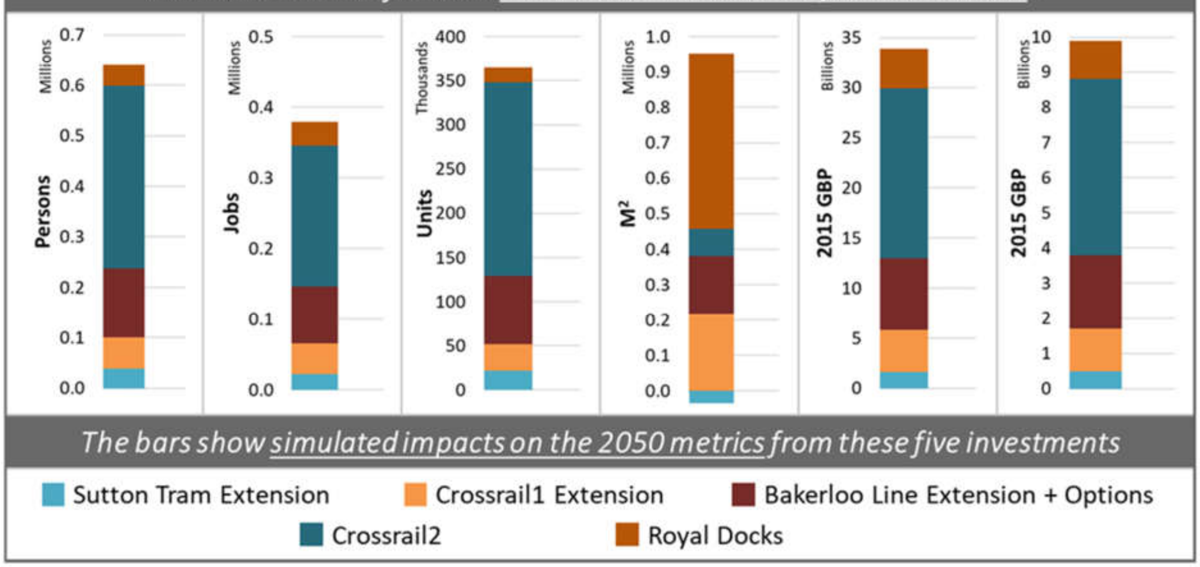

Figure 17 – Social, economic, and fiscal impacts from these public investments in Greater London

The social dynamics of housing, population and jobs are key drivers of the simulated investment impacts, and these elements are highly inter-connected. Their dependence on each other can be seen in two facts:

- The five simulated investments directly add 226,000 new housing units;
- Yet in response to these investments London housing grows by 335,000 units in total.

The 'extra' 109,000 housing units are produced by the self-reinforcing social dynamics of a housing-constrained city; these dynamics are self-reinforcing as long as the housing shortage persists, as follows.

1) Public investments that increase housing boost both population and job growth.
2) Additional jobs attract still more people to Greater London, further increasing housing demand and development.

3) The added residents filling these additional housing units enable even more job growth, which attracts yet more people, and so on.

These social dynamics are naturally self-reinforcing because of the ways that London stakeholders respond to public investments that increase housing during a housing crisis. This self-reinforcement confirms that housing is a high-leverage point for public investment, a node in London's dynamic system where investments deliver disproportionately large socioeconomic benefits relative to investment costs.

Simulating these social dynamics in an integrated way is therefore essential to reliably measure the full social, economic, and fiscal impacts of public investments in London and other cities.

Social and economic impacts monetised as fiscal impacts. Greater London monetises the social and economic impacts of these public investments as:

- additional HMT tax revenues from London;
- increased Central Government spending back into a larger London (such back-spending averages about 70% of HMT's London tax revenues).

The Greater London Simulator measures Central Government's fiscal impact from these five investments as HMT's resulting long-term increase in net cash flow from Greater London. It also computes the net present value (NPV) of that cash flow increase so the UK's fiscal gains from these investments can be directly compared to their public investment costs.

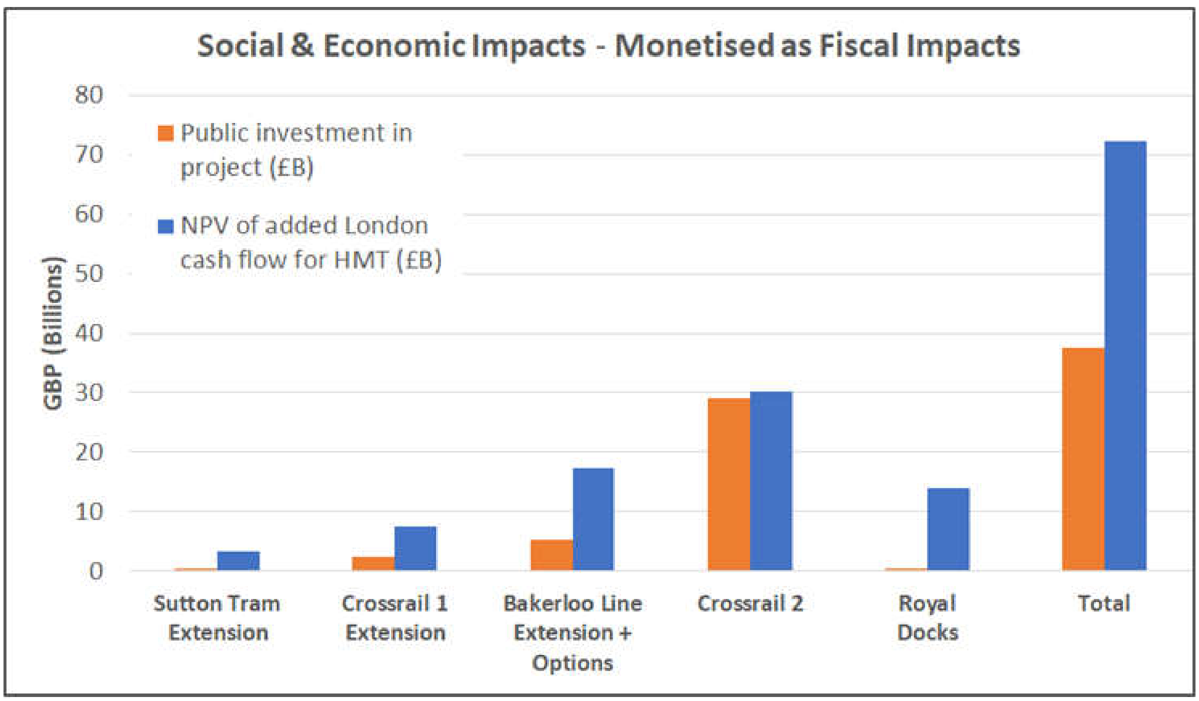

Figure 18 – Social and economic impacts monetised as fiscal impacts

This analysis has not measured other forms of fiscal impact from these public investments, including:

- Increased cash flows for Transport for London (TfL) from the four transport investments
- Increased council tax revenues from the new housing these investments bring
- Potential new tax revenues from sharing in the uplift in land values along the four transport corridors involved.[7]

That said, for each investment the NPV of HMT's added London cash flow is positive and exceeds expected investment cost. In fact, the combined NPVs of the added London cash flows are nearly double the expected investment cost of these projects. This is an evidence-based demonstration that these public investments can generate their own funding and more in the form of increased London cash flows for HMT.

Wider impacts in the UK outside London. HMT's added cash flows from these five simulated investments are worth £72B (in NPV terms), which accrues to Central Government and thus to the UK outside Greater London. This is a quite substantial benefit to the rest of the nation, but these dynamic analyses do not yet account for other potential positive and negative impacts from London investments in other parts of the country. Such impacts are important, for example, to assess whether fiscal benefits from Greater London investments are net additional to the UK economy.

Evidence suggests that fiscal benefits to London from the simulated investments are net additional for the UK as a whole due to:

- London's openness to and connections with the international economy
- Higher economic efficiencies in larger cities (due to agglomeration effects)
- London's large resulting net tax surplus for HMT
- London supply chains that extend throughout the rest of the UK
- Strong correlation between growth in London and in the rest of the UK.

Furthermore, dynamic analyses strongly suggest that public investments in other growing UK cities have the same self-funding potential as in London, and can be part-funded with HMT's increased cash flows from public investments in the capital.

Further dynamic analyses are therefore required to measure the social, economic and fiscal impacts on the rest of the UK from public investments in Greater London.

Table 4 below breaks out summary measures for key social, environmental, economic, and fiscal impacts from these investments, as of or in 2050.

- Impacts from these investments on London's population, housing, job, business space, emissions, and social balance are measured by simulated differences as of 2050 (a convenient point at which to quantify impacts of long-lived investments).
- Investment impacts on the Greater London economy and Central Government's tax take from it are measured by simulated differences in their annual magnitudes during 2050.
- Fiscal impacts from these investments reflect how Greater London monetizes their social and economic impacts and are measured by cumulative simulated differences in tax surplus and cash flows from Greater London for Her Majesty's Treasury (HMT).

[7] Public sharing via taxation in gains by private property owners that occur when public transport investments increase nearby land values.

Investment Impacts in and from Greater London	Sutton Tram Extension	Crossrail 1 Extension	Bakerloo Line Extension[1]	Crossrail 2	Royal Docks	Totals
Investment type	*Transport*	*Transport*	*Transport*	*Transport*	*Redevel-opment*	
Social, Environmental, and Economic Impacts in London	***Simulated differences resulting from these investments as of or in 2050***					
Population	+39,000	+62,000	+136,000	+362,000	+41,000	+640,000
Housing units	+22,000	+30,000	+77,000	+219,000	+17,000	+365,000
Jobs	+22,000	+43,000	+81,000	+199,000	+34,000	+379,000
Social balance	*Reduces by >60% expected losses of middle-income housing & population to 2050*					
Environmental	*Delays achieving the GLA's 2050 emissions target (4.5 MtCO2e, down 90% from 1990 levels) by roughly four years, from about 2057 to 2061*					
Business space (m^2)	-39,000	+217,000	+164,000	+77,000	+494,000	+913,000
Economy (£B/year)	+£1.6	+£4.2	+£7.2	+£16.9	+£4.0	+£33.8
HMT[3] tax take (£B/year)	+£0.5	+£1.2	+£2.1	+£5.0	+£1.1	+£9.8
Social & Economic Impacts Monetized in Fiscal Impacts	***London fiscal differences for HMT from these simulated investments, cumulatively over 50-year economic lives*** *(£B)*					
Increase in London net tax surplus for HMT[4]	£11.2	£30.8	£67.9	£182.0	£42.7	£306.1
Less added interest[5]	-£0.6	-£4.6	-£10.3	-£56.9	-£0.8	-£73.2
Added HMT London cash flow	£10.5	£26.2	£57.6	£125.1	£41.9	£261.3
London NPV for HMT[6] (£B)	**£3.3**	**£7.6**	**£17.3**	**£30.2**	**£13.9**	**£72.3**
Public investment in project (£B)	£0.35	£2.5	£5.4	£29.0	£0.39	£37.6

[1]Phase 1 to Lewisham plus Phase 2 Option to Slade Green plus capacity increase to 33 trains/hour
[2]Million tons of CO² equivalents
[3]Her Majesty's Treasury
[4]Added HMT tax revenues less increased HMT spending in a faster-growing London (based on Oxford Economics' % spending forecast)
[5]Interest on financing of public investment in the project, at 3.44% recent average 10-year Gilts rate
[6]Net present value, discounted at 3.44% recent average 10-year Gilts rate
[7]The year in which added HMT London cash flow exceeds interest on financing of public investment in the project

Table 4 – Greater London investment impacts

Recall that HMT takes about 95% of all tax revenues generated in Greater London. HMT's net tax surplus is the sum of six individually simulated London tax streams minus HMT's spending back into Greater London (the latter based on Oxford Economics' projections of HMT's future back-spending percentage in London[8]). Annual interest (at Gilt rates) on the public project cost is deducted from the added tax surplus resulting from these simulated investments to arrive at HMT's added cash flow resulting from the investments and compute the Net Present Value (NPV) of that added cash flow.

Several new insights emerge from this view of investment impacts, to be added to the list.

6) Public investments that take advantage of self-reinforcing feedback in London's dynamics can deliver quite substantial social, economic, and fiscal returns.

[8] https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Pages/London%27s-Finances-and-Revenues.aspx

7) In this land-constrained city, investments that increase housing can reduce development of business space. The 913,000 m^2 of simulated business space added to 2050 is less than the 1,153,000 m^2 that is expected or targeted to directly result from these investments; that's because the self-reinforcing dynamics of increased housing consume larger amounts of scarce developable land and thereby restrain development of business space.
8) The housing added by these five investments prevents almost two-thirds of middle-income housing and population losses that can otherwise be expected, as shown in Figure 19 below. Without them the city loses over 200,000 more middle-income people by 2050, while the larger upper- and lower-income populations continue growing. This decline is not because of jobs (middle-income jobs are growing throughout), but because middle-income housing continues to disappear in Greater London (down another 13% by 2050). ***Continued loss of social balance is a substantial 'cost of not' making investments that increase London housing.***

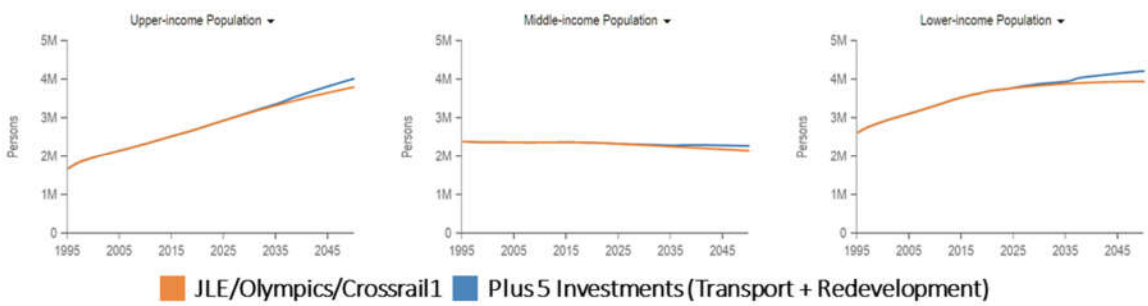

Figure 19 - Upper-, middle- and lower-income population trajectories with the investments in question

9) The five simulated investments produce fiscal gains that make them self-funding in terms of increased London cash flow for HMT. Over time these increased cash flows are sufficient to cover investment costs and to generate cash flow surpluses for Britain.
10) Investments that can more than fund their own project costs and interest are win-win-win solutions for all Greater London stakeholders. Everyone loses if self-funding investments are delayed or prevented by near-term budgeting and funding challenges, and HMT is the biggest financial loser by far.
11) Budgeting one year or one project at a time tends to limit funding for public investments in a self-reinforcing and self-perpetuating cycle. Near-term funding problems delay or prevent investments and associated increases in tax surplus that would otherwise accrue to HMT, thereby ensuring yet more limits on investment funding in subsequent years.
12) Further dynamic analysis is needed to more broadly measure both positive and negative impacts on the rest of the UK from public investments in Greater London.

Chronic funding scarcity forces prioritization to ensure that investment is consistent with near-term constraints. Self-funding potential puts a different light on prioritizing investments; ***investments that can fund themselves should be prioritized to help fund other investments. All city stakeholders lose if investments that can self-fund are delayed or eliminated due to near-term funding constraints, and Central Government and the rest of the UK experience most of the financial damage.***

Adding Digital and London Plan housing investments

Figure 20 on page 51 gives an overview of multi-dimensional consequences from these investments in combination with the previously simulated transport and redevelopment investments.

The five investments previously simulated (transport and redevelopment) result in 365,000 additional housing units by 2050. The Digital investment is described in Appendix 8.2.7. The London Plan housing scenario targets an additional 1.75 million units for a combined total of 2.1 million net new units by 2050 (65,000 units / year for 32 years), half of which are for lower-income residents

There are questions about the feasibility of building 65,000 new housing units annually, about changes that would be needed to build at that rate in Greater London, and about the cost of doing so. These simulations answer a different question: If housing units are built at that rate, what impacts can we expect in the Greater London system?

With a total of 2.1 million added housing units, London's simulated population grows to 13 million by 2050 (a 53% increase from 2015). 1.1 million of these new units are for lower-income residents, half of all net new units in the period (consistent with the London Plan). One social impact of this new housing: lower-income population increases by 70% to 2050, considerably more than the 53% increase in total population.

Despite the big increase in population made possible by all this housing, London's housing stock grows faster than its population for the first time since 1995 (by 62% to 2050 as versus 12% without these combined investments). As a result, by 2050 average housing occupancy (the ratio of population to housing units) in Greater London is down 10% from its peak, to a level that was last seen in 2000. ***If it were sustained, the London Plan rate of 65,000 new housing units annually could significantly ease Greater London's housing crisis.***

The new housing also eases the largest single constraint on job creation in Greater London. As a result 2050 jobs are up by 72% (from 2015), growing even faster than population thanks to job-holders living outside of Greater London. Yet London's 2050 unemployment remains at the same level as in 2015 (7%) and is 1.1 percentage points higher than without the London Plan housing. ***In a dynamic system, rapid construction of new housing does not guarantee that jobs and employment will grow as quickly as population.***

Figure 20 – Digital and London Plan housing investment scenarios simulated

In addition to its unemployment impact, achieving the London Plan housing target substantially alters Greater London's social balance. As can be seen in Figure 21 below, the social fabric of Greater London can be expected to change substantially whether or not these investments are made, and London Plan housing investment results in quite different changes in social balance.

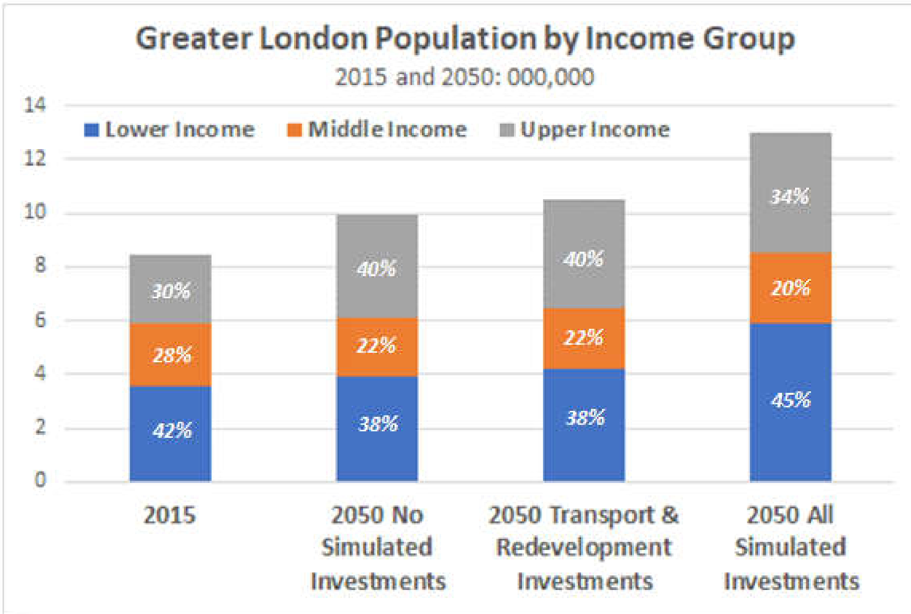

Figure 21 – Greater London population by income group in 2015 and 2050

As a measure of social balance, London's income mix changes significantly even without the simulated investments (No Simulated Investments above). With housing increasing only 12% by 2050, upper-income residents increase most rapidly in both absolute and relative terms (growing from 30% to 40% of population). Lower-income residents increase 12% in absolute terms but decline from 42% to 38% of London's population. Middle-income residents decline in both absolute and relative terms, falling from 28% to 22% of population. ***Without investment that substantially increases housing development, middle- and lower-income Londoners can be expected to decline steadily as a percentage of the city's population.***

The 365,000 housing units added by the simulated transport and infrastructure investments do not change the income mix of London's population from what it would be without those investments.

The additional 1.7 million units added in the London Plan scenario result in sharply increased population growth in all income groups. Lower-income residents get half of all new housing units and grow fastest, increasing to 45% of population by 2050 (up from 40% in 2015). Upper-income residents also grow rapidly, rising to 34% of 2050 population (up from 30% in 2015). Middle-income residents grow in absolute numbers but not fast enough to avoid falling to 20% of London's 2050 population (down from 28% in 2015).

Table 5 below breaks out social, economic, and fiscal impact measures from the Digital and London Plan housing investments. The latter is now broken into two scenario steps: in Step 1 total housing is increased at the rate of 40,000 net new housing units/year (Current Position Housing); in Step 2 it is increased by an additional 25,000 units/year to 65,000 units/year (London Plan Housing). By comparing the impacts from these two steps we can better understand how the Greater London system can be expected to respond to new housing initiatives.

Impacts from these three investments are shown in additive fashion, building on the previously simulated transport and redevelopment investments. The Digital investment appears first with its impacts; then the Step 1 housing scenario and resulting impacts are added and shown; the Step 2 scenario to the London Plan target and its resulting impacts are added and shown next; and the combined impacts from all three investments are totalled.

Greater London Investment Impacts	Digital	Current Position Housing (40,000/year)	London Plan Housing (65,000/year)	Total
Social, and Economic Impacts	***Simulated impacts resulting from each investment as of or in 2050***			
Population	35,000	1,106,00	1,286,000	2,427,000
Housing units	-1,000	559,000	799,000	1,357,000
Jobs	49,000	676,000	706,000	1,431,000
Business space (m^2)	219,000	3,663,000	-33,000	3,849,000
Economy (£B/year)	£3.4	43.2	£20.6	£67.2
HMT[1] tax take (£B/year)	£1.1	£13.5	£8.3	£22.9
Social & Economic Impacts Monetized in Fiscal Impacts	***Simulated 2015-2050 cumulative HMT fiscal impact resulting from each investment** (£B)*			
Added HMT net tax surplus[2]	£18.9	£61.3	£37.4	£117.6

[1]Her Majesty's Treasury
[2]Added HMT tax revenues less increased HMT spending in a faster-growing London (based on Oxford Economics' % spending forecast)

Table 5 – Greater London investment impacts

Digital investment. With 30% assumed customer uptake and a limited time frame, the Digital investment has small impacts on population, housing, jobs and business space to 2050 (the very small reduction in new housing units is due to Digital's favourable impact on development of business space). Resulting expansion of Greater London's economy increases HMT's London tax surplus by almost £19 billion to 2050. Because public investment in this project is expected to be modest (most of it being by private service suppliers), this investment could well be self-funding from a government standpoint.

Housing Step 1: reaching 40,000 new housing units/year. This scenario is the first of two steps, each of which increases the simulated rate of London housing development resulting from the transport & redevelopment investments. The Step 1 scenario increases the simulated rate of total London housing development by about 16,000 units / year on average to meet the targeted 40,000 units/year. 10,000 of these units are affordable to meet the targeted 15,000 affordable units / year.

By 2050 the Step 1 scenario results in an additional 559,000 housing units and 1.1 million London residents. It also eases housing constraints on job creation, resulting in 676,000 new jobs and 3.6m m^2 of new business space by 2050. The 2050 London economy and HMT tax take are substantially increased as a result, as is HMT's cumulative London tax surplus to 2050 (up by £61.3B).

This Step 1 housing scenario has a modest impact on Greater London's social mix in 2050: upper-income Londoners are down from 40% to 37% of population, lower-income residents are up four percentage points at 42%, and middle-income residents are down by one percentage point at 21% (comparisons are to the transport/redevelopment scenarios).

Housing Step 2: reaching 65,000 new housing units/year (London Plan). The Step 2 scenario increases the simulated rate of total London housing development by further 25,000 units / year to 65,000 units/year (the London Plan rate). Almost 16,000 of these additional units are affordable to meet the 32,500 such units / year targeted in the London Plan.

Comparing the different impacts from these two steps reveals non-linear responses from the city system that shape investment returns. The Step 2 scenario adds 43% more London housing units by 2050 than does Step 1 (799,000 versus 559,000). We might expect that resulting Step 2 impacts to 2050 (on population, jobs, business space, GVA, etc.) would also be 43% larger than those from Step 1, but they turn out to be much smaller than that.

- The **resulting Step 2 population increase is only 16% larger** than that from Step 1.
- The **resulting Step 2 jobs increase is only 4% larger** than that from Step 1.
- Step 2 **reduces business space by 33,000 m^2**, as versus the 3.66m m^2 increase resulting from Step 1.
- The **resulting Step 2 GVA increase is 52% smaller** than that from Step 1.
- The **resulting Step 2 increase in HMT's cumulative London tax take is 39% smaller** than that from Step 1.

In other words, the Step 2 increase in housing produces sharply diminishing returns (benefits) in growth of population, job, GVA and tax take relative to Step 1. It also produces a slightly negative return (shrinkage) in business space due to competition for scarce land with the large Step 2 increase in housing.

The chain of causality in these diminishing returns is a consequence of social impacts which are subsequently monetized in economic and fiscal impacts.

- The Step 1 investment results in 1.2 additional jobs for each added unit of housing; Step 2 results in only 0.9 additional jobs for each added housing unit. The main reason for that difference: the 559,000 housing units added in Step 1 eliminate much of the drag from the housing crisis on London job creation. That's why the 43% larger housing increase in Step 2 results in only 4% more added jobs than Step 1 produces.
- As described earlier in this section, the combined Step 1 and 2 increases (to targeted London Plan housing) significantly alter the social balance in Greater London. It similarly alters London's 2050 job balance, producing a 6 percentage-point shift in the mix of upper- and lower-income jobs (from 46%/29% to 43%/32%). Two-thirds of that shift comes with the Step 2 increase in housing, which means that additional Step 2 jobs are at a significantly lower average income than those created with Step 1.

- Step 2 boosts London's GVA by 52% less than the much smaller Step 1 because: (i) Step 2 adds only 4% more jobs than does Step 1; (ii) Step 2 jobs come with significantly lower average income due to the change in job mix; and (iii) Step 2 results in 142,000 more unemployed Londoners, as it grows population by 11% and jobs by only 8.1%. For the same reasons, the much larger Step 2 increases HMT's cumulative London tax take to 2050 by 39% less than does Step 1.

Step 1 and Step 2 have complementary effects in relieving Greater London's housing crisis, as seen in 2050 ratios of population to the number of housing units. The smaller Step 1 increase in housing reduces that ratio from 2.52 to 2.46, the level last seen in 2014; Step 2 then further reduces that ratio to 2.33, the level last seen in about 2000. The added relief from Step 2 is proportionate to its much larger increase in housing.

It is important to note that the substantially diminishing returns to Step 2 do not, of themselves, indicate that the London Plan target of 65,000 net new units/year would be a mistake. The diminishing returns it produces could be eliminated by complementary investments and policies that increase the rate of job growth above what it would otherwise be. Of course that would result in still more population growth and somewhat less relief of the housing crisis.

Additional insights flow from the Digital and London plan investment analyses, for the growing list.

13) Mitigating London's housing crisis will require achieving and sustaining quite a high rate of housing development for an extended period; substantial mitigation can be had at construction rates well below what the London Plan calls for.
14) The ***'cost of not'*** mitigating the housing crisis will be seen the continued erosion of Greater London's social balance as middle- and lower-income residents decline as a percentage of total population. In that respect dynamic analysis confirms what many have already concluded.
15) Housing development is a potent and potentially damaging force, particularly during a housing crisis. An effective amount and mix of new housing must anticipate and maintain a healthy balance among several city elements that are constantly influencing each other: (i) growth rates of total population and income groups; (ii) housing availability and new housing for various income groups; (iii) job availability and unemployment for the income groups; and (iv) London job-holders' residence/commuting choices between Greater London and the near-beyond. This involves too many elements and feedback connections for spreadsheet analysis, and the wrong amount or mix of new housing could damage Greater London's social balance just as powerfully as the housing crisis has (other cities can attest to this, e.g. New York). Investments in transport to the near-beyond are a potential partial substitute for housing investments within London and may be more feasible.

Taking a broader view, every growing city limits its attractiveness in various ways, otherwise it would be overwhelmed by in-migration and job creation. Greater London's housing crisis is a by-product of being overwhelmed in this fashion, and housing has become a potent if unintended limiting factor on the city's ability to attract people and jobs. In other words the city-system tends automatically to protect itself when demand is excessive. With draconian exceptions that are not open to the UK, most growth-limiting factors evolve dynamically and unconsciously, as London's have. Dynamic analysis affords the ability to more consciously choose appropriate limits and balance and means of achieving them.

Emissions impact from decarbonisation and other investments

The GLA has an ambitious Decarbonisation programme aiming at 90% reduction of greenhouse gas emissions by 2050 (relative to 1990 levels). The Decarbonisation programme has been largely responsible for declining emissions in Greater London despite population and job growth (see Figure 20, bottom right corner).

The importance of its Decarbonisation programme can be seen in Figure 22 below; without it energy consumption and greenhouse gas emissions would rise and emissions would be far from the goal of 4.5 MtCO2e.

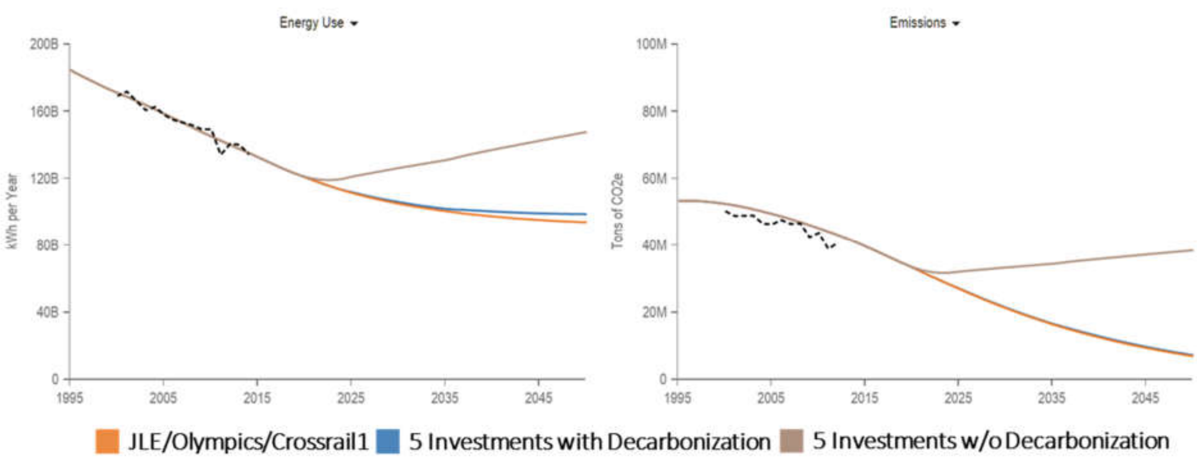

Figure 22 – Energy use and emissions

Without the investments covered in this report, the simulated Decarbonisation programme has London on a trajectory to meet the target by around 2057. Increased growth resulting from the transport and redevelopment investments delays that by about a year, and higher growth resulting from the London Plan housing investment delays reaching the target by roughly three more years.

Increased emissions are social and environmental costs of city investments and the population and job growth they bring, and the Greater London Simulator measures these costs for specific investments.

This prompts two additional insights for the list.

16) Increased city growth increases the necessity for environmental mitigation investment and produces increased tax surpluses from which they can be funded.
17) The GLA's ability to dynamically measure growth-driven environmental impacts from individual investments makes it possible to include mitigation costs in project budgets and in the funding and financing for such investments.

Investment synergies and Brexit

Simulating these investments (transport, redevelopment, Digital and London Plan housing) both individually and in combinations shows minimal synergies between them, either positive or negative. This is not surprising since all but one of the investments is aimed at increasing housing in Greater London. In a housing-constrained city such investments have similar impacts that tend to be simply additive rather than synergistic.

These investment were simulated in combination with a range of possible Brexit influences on Greater London's growth dynamics for population and jobs and investments in housing and business space. The Brexit simulations produce social and economic impacts that are broadly similar to those from recent Brexit-based forecasts made by Cambridge Econometrics.[9]

Simulated investment impacts are mostly insensitive to Brexit; where there is sensitivity it is on the order of 10% or less. As accelerators of Greater London's growth these investments counter potentially negative Brexit consequences.

Summarizing investment impacts in Greater London

Figure 23 on page 58 provides an integrative overview of public investment impacts in London, beginning with the three historical investments that constitute the starting point for the simulations described in this report.

- The JLE (Jubilee Line Extension) to the Tube that made the Docklands development a success
- The 2012 London Olympics / Paralympics, which redeveloped parts of East London
- The Crossrail 1 high-speed commuter rail line scheduled to open in early 2019

The London Plan housing investment is excluded from this view because its large impacts would visually overwhelm the other investments.

Impact metrics appear in the top line of the figure; Annual Gross Value Added (GVA) is the size of the Greater London Economy, and HMT Annual London Tax Revenues is the annual tax take generated for Central Government. The line below that contains simulated 2050 values for those metrics absent all of the investments shown (past, present and prospective future). In other words, those metrics are for pre-JLE London with normal public investment volumes as they would have been without the simulated investments.

The bars show the combined impact of these investments on these Greater London metrics as of 2050, with coloured bar segments showing each investment's contribution to that impact. In each bar the bottom three segments show impacts from the past/present investments and the upper segments show impacts from prospective future investments.

Impacts from past / present investments. The three simulated past / present investments are still generating substantial impacts in 2050, being responsible for approximately half of all population, job, economic growth and HMT tax revenue impacts shown and the vast majority of business space and GVA per capita impacts. ***Public investments like these continue to produce social, economic and fiscal benefits for many decades, and these can now be measured and demonstrated.***

Crossrail 1 and 2 bring the largest population impacts to 2050, though the BLE (Bakerloo Line Extension) is a close third. Crossrail 1 and 2 also result in the largest job impacts to 2050, and Crossrail 2 is the dominant producer of housing impacts. The JLE, Olympics and Crossrail 1 investments produce the

[9] No EU funding was used in conducting any simulation analyses involving Brexit.

largest impacts on 2050 business space, GVA and per-capita GVA. These three, along with Crossrail 2, produce the vast majority of impact on HMT's 2050 tax revenues.

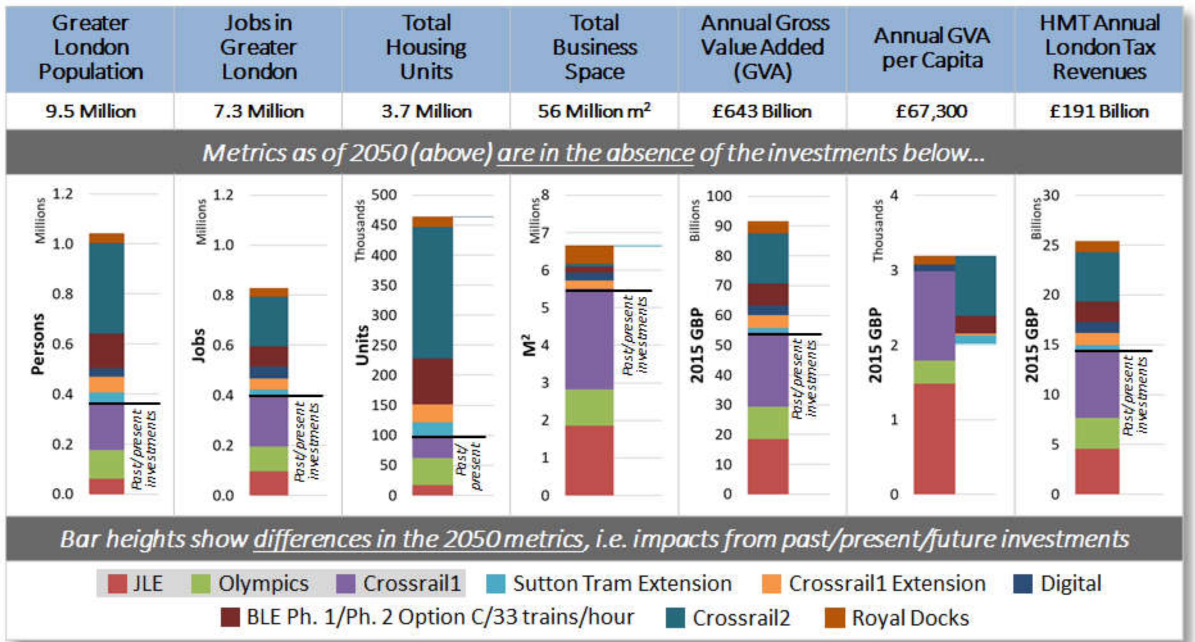

Figure 23 – Infrastructure investment scenarios: deltas in 2050

GVA impacts In total these investments increase the size of Greater London's simulated economy by almost £92 billion in 2050, or by more than 14%. This economic expansion noticeably exceeds the 11% increases in jobs and population to 2050, which means that GVA per capita and per job are increasing because of these past, present and prospective future investments.

Per capita GVA impacts In total these investments increase Greater London's simulated annual GVA per capita by about £2,000 per person or 3% as of 2050. The three past/present investments (JLE, Olympics and Crossrail 1 increase annual GVA per capita by about £3,000 per person, or more than 100% of the total increase from all the investments combined. The increase they produce is partly offset by most of the other investments, which together reduce annual GVA per capita by a little over £1,000 per person. Investments that reduce GVA per capita are shown on the right side of that bar chart.

The cause of these directional differences can be seen by comparing how the Crossrail 1 and Crossrail 2 investments affect 2050 annual GVA per capita. Crossrail 1 boosts simulated GVA by 3.9% and population by 2.0% in 2050, thereby increasing annual GVA per capita. Crossrail 2, on the other hand, increases simulated GVA by 2.6% and population by 3.8% in 2050, thereby reducing annual GVA per capita.

HMT annual London tax revenue impacts In total these investments increase HMT's simulated annual tax revenues from Greater London by over £25 billion in 2050, or by more than 13%. That is the combined effect of the simulated investments on six Central Government tax streams: income tax, national insurance, VAT, corporate tax, business rates and other taxes.

The way forward in Greater London

For the GLA, the Greater London Simulator is filling *"…a strategic gap in its knowledge and understanding of how London (and cities in general) work, namely as systems of inter-connected systems…"* [10] The GLA intends to broaden use of the simulator as a neutral test-bed for evaluating new investments, policy options and changing conditions (e.g. Brexit). Analyses regarding private financing for large-scale infrastructure investments are a priority.

To facilitate broadened use the GLA wants to enhance simulator capability in a number of ways, including the following.

- Simulate additional geographic layers including: inner and outer London Boroughs; regions adjoining Greater London and others well beyond the city; and major London transport corridors.
- Extend the Greater London Simulator to measure property values, housing affordability relative to incomes, and potential for value uplift sharing.
- Expand environmental simulation to include air quality and pluvial flooding, their social, health and productivity effects, and mitigation investments.
- Individually simulate Central Government's primary London expenditure categories for more complete analysis of fiscal impacts from public investments.
- Conduct further analysis regarding private financing for large-scale public infrastructure investments.
- Expand participation with Greater London stakeholders and collaborative solution development.

[10] See: http://ted.europa.eu/TED/notice/udl?uri=TED:NOTICE:513776-2017:TEXT:EN:HTML&WT.mc_id=RSS-Feed&WT.rss_f=Computer+and+Related+Services&WT.rss_a=513776-2017&WT.rss_ev=a

6. Innovative Approaches to Prioritizing and Financing City Investments

6.1. The Need for Innovation

The investment gap in cities emerged and grew as global population increased and urbanized but funding and financing for city investments failed to keep up.

This raises an important question: Why have funding and financing not grown in pace with the need for city investment? Based on conversations with knowledgeable government people and investors, the cause seems to be both structural and perceptual.

The structural aspect of the problem is illustrated by an exchange that took place during a recent conference on impact investment in cities. A senior city manager complained that institutional investors talk a lot about city investments while making very few of them. The CEO of one such investor replied *"We would like to make many more city investments, but there is currently no framework for broader collaboration between cities and capital markets."*

Today governments and investors operate largely within their own 'verticals', having different missions and value systems. These structural realities have made it hard for them to connect across the intervening space, and they shape how governments and investors perceive each other.

Some recent observations by leading players illustrate substantial differences of perception.

From government…

> *"The private sector wants to avoid risk and maximize returns."*
>
> *"As part of government, why would we borrow at other than sovereign rates? Doing so saves taxpayers' money."*

From investors…

> *"Cities and higher levels of government have plenty of money, they just need to spend it differently."*
>
> *"Governments can have all the financing they want if it's at market rates."*

Each of these comments reflects a quite incomplete picture of the other party and their circumstances.

Two other observations (from leading private investment firms) are largely inarguable:

> *"There is absolutely zero correlation between the scale of need for infrastructure and addressable opportunities for the private sector."*
>
> *"It is really a public policy obstacle. [Infrastructure] needs to be paid for, and governments need to find a revenue stream. If there were a sustainable financial and fiscal framework, funds and debt would be there overnight."*

Governments and institutional investors such as pension funds generally agree that the *status quo* in cities and capital markets is broadly failing to deliver what cities and investors need from each other and should be able to provide.

- Cities have huge unmet needs for infrastructure and other investments. Even cities like London are able to fund and finance only a fraction of the investments needed for resilience and sustainability in the face of continued population, job, and economic growth.
- Government tax revenues, funding and borrowing have been insufficient to meet these needs and this is unlikely to change in future.
- Institutional investors have huge unmet needs for safe and long-lived investments, but few public investments are currently available to them.

- The missing link is a framework in which private investors, ranging from individual citizens to pension funds, can play a much larger role in financing public urban investment.

City leaders and investors are equally in the dark as to the nature of this framework, and how to establish it. But, as described in Section 5, there is broad historic precedent for a sustainable, collaborative framework between cities and investors. The absence of such a framework is a fairly recent aberration; we probably need to restore and update a framework that worked well in the past.

Updating that collaborative framework calls for innovation in two areas that are highlighted in the MRA:RICE programme, namely prioritizing and financing city investments.

6.2. Innovation in Valuing and Prioritizing City Investments

Most city investments bring a mix of social, economic, environmental, fiscal and other outcomes. Measuring them all is a significant challenge, in part because these various outcomes influence each other through the many cause-effect relationships in the city system. Establishing their public value is even more challenging because city investments have such a variety of impacts, some of them financial in nature and many others not. These challenges make it difficult to measure the public return on city investments and to make comparisons across investment options. Measurement and comparison difficulties increase uncertainty and risk for cities and for those providing investment funding and financing, both governments and private sector investors.

Traditional Cost-Benefit Analysis (CBA) is useful and often required, but there is growing awareness that CBA alone does not sufficiently measure or properly value the full array of dynamic cross-influences and consequences from city investments. Determining the cost of such investments is straightforward, but it is much harder to measure and value their full social, economic and environmental consequences and how these are monetised. As a result, public investments are typically undervalued on important non-financial dimensions, which tends to increase perceived risk, skew investment comparisons and prioritization, and disqualify investments that could otherwise be justified.

Whole-system analysis goes beyond CBA by taking advantage of the many cause-effect relationships in city systems. Dynamic analysis simulates these connections to make integrated measurements of investment outcomes across the city's many facets and dimensions.

- Many social, environmental and other non-financial outcomes of city investments cannot be directly measured in financial terms (population, housing, etc.).
- Whole-system analysis delivers financial measures of non-financial outcomes by tracking their numerous cause-effect influences on financial elements of the city system (incomes, economic growth, tax revenues, expenditures, etc.). <u>It explicitly measures both financial and non-financial investment outcomes with common, integrated financial metrics</u>.
- These common metrics are not proxies or substitutes for non-financial measures of non-financial investment outcomes; nor are they based on simplistic financial valuations (e.g. the estimated value of a human life) superimposed on non-financial outcomes.
- Instead they measure how the city-system as a whole is monetising non-financial investment outcomes. To put it another way, they measure the city's ongoing translation of non-financial investment outcomes into related financial outcomes.
- As a result, whole-system valuations are much more complete and reliable. They are flexible as well: investment outcomes can be measured for a single city investment and for multiple investments in combination, or for specific city elements or stakeholders.

This measurement capability is unique to dynamic city simulation. Measuring outcomes more completely and capturing their monetization by the city makes investments easier to compare and prioritize.

Reflecting risk in prioritizing investments. Dynamic city simulations measure how key risk factors can be expected to affect investment outcomes, the city's performance and how these affect each other.

Whole-system analyses explicitly measure impacts from financial and non-financial types of risk with common, integrated metrics. Impacts can be measured from risks that are investment-specific, city-specific, or external to the city (e.g. Britain's impending exit from the European Union), for single risks or for multiple risks in combination. Risk impacts can be measured on multiple dimensions including: for different city elements (housing, GVA, greenhouse gas emissions, fiscal balances, etc.); for various city stakeholders (citizens, specific income groups, business types, local communities, higher-level governments, other investors in city projects, etc.). Risk-mitigation options can be tested for their impact on investment results.

Beyond prioritization, investment assurance. Whole-system analysis enables a new form and quality of investment assurance for cities and their stakeholders. This dynamic assurance process measures, monitors and maximizes socioeconomic and fiscal returns on city investments for key stakeholders: citizens, municipal and higher-level governments and other investors. Such assurance is of particular importance for long-lived infrastructure with lengthy development periods and long-duration social / economic / fiscal benefits.

- Dynamic assurance is based on whole-system analysis of the city and its various investments.
- Assurance analyses are forward-looking and risk-based, conducted ahead of each investment and continually thereafter, covering investment projects, city performance and investment funding and financing throughout their durations.
- In the face of changing conditions and evolving risks, the dynamic assurance process includes:
    - Regular reporting on past and likely future performance of specific investment projects and of the city as it will be affected by them, with updated investment valuations;
    - Advice and recommendations on options for adjusting individual investment projects, their financing and policies to ensure ongoing benefits for all stakeholders in the face of evolving circumstances;
    - Proactive control by city stakeholders working collaboratively, based on such advice and recommendations.

6.3. Innovative Financing for City Investments

As the founder and head of a leading asset management firm recently observed, *"The [unmet] investor demand for long-dated assets is shocking."* Cities own and need to invest in many long-dated assets (urban infrastructure, for example), but such projects have not been available to large investors (such as pension funds) in significant numbers. The long-lived nature of infrastructure investments is well matched to the long obligations of pension funds and other institutional investors, but the *status quo* has broadly failed to deliver what cities and investors need from each other and should be able to provide to mutual benefit.

Then-Chancellor of the Exchequer George Osborne set out to change this in late 2015, when he announced that 89 Local Government Pension Schemes (LGPS) in England and Wales would be required to pool their assets regionally. These defined-benefit pension schemes cover local government employees, and pooling of their assets was intended to deliver cost savings, increased efficiency and scale, and increased investment financing for UK infrastructure development.

In 2016 LGPS assets totalled £217B, constituting one of the ten largest global sources of capital; by 2018 assets of the eight consolidated LGPS regional pools had risen almost 20% to £259B. [11]

While the pools are achieving significant cost savings, increased LGPS infrastructure investment has been slower to materialize. As of April 2018, a cross-pool platform dedicated to infrastructure investment (GLIL) had invested a little under half of its £1.275B in rail, onshore wind, and Anglian Water Group.[12]

Although the increased scale of the LGPS pools is an important enabler of increased infrastructure investment, commentators cite several other factors that are limiting the pace of such investments in England and Wales:

- The illiquid nature of infrastructure investments and resulting risk of losses, which limits the portion of LGPS portfolios that can be allocated to such investments;
- The general dearth of infrastructure investments on offer to private investors;
- Understandable LGPS desire for existing UK investment assets with established revenue streams, and strong competition for such investments from overseas investors;
- The difficulty of investing in new-build infrastructure projects, which are more complex and take longer to deliver cash flows to investors.

These structural challenges are not unique to the UK, and an innovative investment and financing platform has been established to address them. The platform is open to a wide range of lenders, investors, and borrowers and is being introduced in many jurisdictions, including the UK. The financing instruments are called Credit Participation Certificates™ or CPCs™; they can be used to fractionalize almost any type of credit, essentially "slicing up" individual loans into standardized smaller pieces so they can be easily purchased by investors.

The CPC™ platform was developed and is administered by UFT Commercial Finance LLC. The platform and a suite of CPC™ types were designed following the 2008 financial crisis to provide a more reliable, transparent investment alternative to traditional securitizations. CPCs™ are being used in trade finance,

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[11] https://www.lgpsboard.org/index.php/investment-2016; https://www.professionalpensions.com/professional-pensions/feature/3029061/where-are-the-lgps-pools-three-years-on

[12] https://www.institutionalassetmanager.co.uk/2018/04/24/263530/glil-infrastructure-marks-three-year-anniversary;http://www.pensions-expert.com/DB-Derisking/Uncharted-waters-What-lies-ahead-for-LGPS-pools

receivables lending, mid-market credit, and private equity. In combination with dynamic valuation analyses like those described in this report, the CPC™ platform and instruments are equally relevant to infrastructure investments. Infrastructure-linked CPCs™ incorporate a public-private partnership structure with rules that fundamentally and beneficially alter the characteristics of such transactions.

- For an individual city infrastructure investment:
  - CPCs™ make flexible use of globally standardized platform components and processes, which can greatly speed the financing process.
  - No public monies are involved until after the design/build effort, which helps relieve public budget and funding constraints;
  - Investors earn returns throughout the design/build effort, making it much easier for pension funds to participate;
  - Project debt is owned and shared among private sector participants, which helps relieve government balance sheet and borrowing constraints;
  - The infrastructure asset and related debt come onto the public books when the asset's value (as evidenced by increased tax revenues) outweighs the debt being assumed.
- In the broader market for city infrastructure investment financing:
  - CPCs™ are designed to be traded, which enhances liquidity, reduces duration and other risks, expands the investor audience, and ultimately improves market efficiencies that can reduce the cost of private financing for public infrastructure investments;
  - Dynamic analyses like those described in this report provide regular risk-based infrastructure valuations that are critical to CPC™ tradability and market liquidity;
  - UFT has completed preparatory work for the launch of the first global exchange for CPC™ trading -- formal regulatory approval will begin when total CPC™ market volume has achieved target levels (expected later in 2018).

Measuring the whole-city impact of public investments reveals that many have real potential to be self-funding through the economic and fiscal growth they bring. This opens up the possibility of new financing approaches and private investment capital that can help relieve public budgets and borrowing constraints and enable cities to be more resilient and better prepared for sustainable growth.

The combined capabilities of dynamic city analysis and the CPC™ financing platform represent a new chapter in infrastructure finance; together they have potential to make new-build infrastructure projects accessible and attractive to a much broader base of private global investors including pension funds. CPC™ fractionalization enables investors of almost any size to invest in large or small standardized slices of individual infrastructure investments. Standardization, when applied to infrastructure and coupled with reliable asset-level performance data from dynamic city analysis, empowers investors to act confidently in buying and selling infrastructure CPCs™. That confidence is the foundation of greater market liquidity on which the CPC™ exchange, once it is operating, can build a liquid global market for infrastructure investment.

The finance industry includes many platforms and is changing on multiple fronts, and the authors' view of such things is limited. That said, the CPC™ platform provides a unique and concrete example of financing innovation that is relevant to city infrastructure investment.

Greenwood recommends that the Greater London Authority, Transport for London, Greenwood Strategic Advisors, and UFT Commercial Finance work with appropriate lenders in assessing the feasibility of a several-billion-pound CPC™ financing of new public infrastructure in Greater London. The Crossrail 1 extension project to Ebbsfleet in Kent is a good candidate for such a feasibility study.

7. Dynamic Investment Analysis in Other Cities

Some city investments generate revenues and can be analysed almost like businesses (Transport for London's various tube and commuter rail investments, for example); many public investments do not and cannot be analysed. Either way, every public investment has social, environmental, economic, fiscal and other systemic consequences that are difficult to measure and fully value by traditional means alone.

Measuring and valuing these dynamic consequences is a key capability of the common city model used in the Greater London Simulator. With simulators now working for five cities, experience is providing confirmatory answers to questions about such applications.

1) What value are cities getting from this simulation capability?

The GLA's specifications for the Greater London Simulator include an answer to this question:

> *"The GLA identified a strategic gap in its knowledge and understanding of how London (and cities in general) work, namely as systems of inter-connected systems, and determined that the dynamic simulation or system dynamics method offers unique integrative capabilities and benefits in representing and analysing systemic performance. Consequently this method and associated technology complement other approaches already in use and will help the GLA improve its understanding of and ability to manage London from a systemic standpoint."* [13]

Value comes from rapid answers to questions about the consequences of investment and policy options, answers that cross and integrate multiple aspects of the city. There is value in seeing and understanding the dynamics that determine each city's resilience and sustainability, and how these are shaped by public investment and policy choices. Value also comes from comprehensive investment value measurement that includes social and other non-financial impacts and reflects how the city and its stakeholders monetize such impacts. These metrics open up new options for funding and financing much-needed city investments.

2) Every city is unique, how can a standardized model be used in quite different cities?

The key is understanding what is truly unique about each city and what all cities have in common, and then properly modelling these things and validating their representation and simulation. Common elements and cause-effect relationships are used in modelling multiple cities and are tested and strengthened in that process. These structures are modelled to include unique city characteristics, quantified and verified using city-specific data.

The five currently simulated cities vary considerably; they range from Greater London (population about 8.5 million) to Greater Boston (roughly half the size of London), Frankfurt (about 730,000), Norfolk Virginia (about 240,000), and Coburg Germany (about 42,000). The common structure in these five simulators re-creates these cities' different histories with equal accuracy and simulates their quite different future performance trajectories.

[13] See: http://ted.europa.eu/TED/notice/udl?uri=TED:NOTICE:513776-2017:TEXT:EN:HTML&WT.mc_id=RSS Feed&WT.rss_f=Computer+and+Related+Services&WT.rss_a=513776-2017&WT.rss_ev=a

3) How flexible and adaptable is the common model for addressing different issues in other cities?

A focus on city investments and their dynamic consequences begins with dynamic structures at the heart of every city: people, jobs, housing, etc. The city model containing these structures is equally applicable to a wide range of events and conditions, Brexit being an example. The Greater London and Frankfurt simulators are in use determining Brexit's quite different consequences in these two cities.

The common structure is flexibly adaptable to city dynamics at quite different geographic scales:

- In Greater London that structure is representing, in aggregate, all 32 Boroughs plus the City of London – over 8 million people in total.
- In Boston the structure is used twice in the same simulator: once to simulate the city of Boston itself; and a second time to represent, in aggregate, all of the other towns in the Greater Boston region.
- In Frankfurt, Norfolk and Coburg the common structure is used to represent the city as a single municipality. Norfolk's population is smaller than that of most London Boroughs and Coburg has less than a quarter the population of the smallest London Boroughs.
- The GLA intends to begin simulating small groups of Boroughs and single Boroughs in the near future.

Within the Greater London and other city simulators, new layers of geographic detail can be activated by resetting internal switches (subject to availability of comparably detailed data for model initialization, testing and validation). The common model includes built-in structural adaptability on many other dimensions; these are similarly activated based on the city's issues and analysis priorities.

- The Greater London and Greater Boston simulators make extensive use of this flexibility in simulating (for example): three income-based population sub-groups and social mobility between them, along with three corresponding housing sub-markets; three different business types and three types of jobs based on knowledge intensity, along with three corresponding business property sub-markets.
- These detailed dynamic structures are not activated in the Frankfurt, Norfolk and Coburg simulators, though they are likely to be in future. Initial issues for analysis in these cities did not require the granular social detail that was included from the start in the London and Boston simulators.

Flexible switch-modified model structures allow city-specific choices regarding model and analysis granularity on multiple dimensions, depending on the issues to be addressed.

4) What city data is needed and how hard is it to obtain? How sensitive are city models to sparse or poor-quality data?

The five city simulators now in use employ only publicly available data for model initialization and testing. Many of these data time series can be seen in the Greater London Simulator interface shown in Figure 15, and Appendix 8.1 includes a complete list of London data used. Information used in characterizing scenarios for analysis has been readily available from city employees and public sources.

Dynamic city models are less sensitive to data availability and quality than are most types of computer models. That is because city simulators use whole-system model structure in combination with data. The inter-connectedness of that system structure effectively compensates for missing data and often highlights data inconsistencies.

5) How much time and effort are involved in setting up and using a city simulator?

Setup of the Greater London and Greater Boston simulators (in 2015 and 2016, respectively) took about ten months, including testing and validation. In 2017 the Norfolk, Frankfurt and Coburg simulators were each set up in twelve weeks or less.

This reduction is the result of two things: (i) 'industrialization' of the model setup and testing process; and (ii) development of software and supporting technologies to automate that process. These have sharply reduced the time and effort involved and increased model reliability. Today the most detailed city simulators (comparable to those in London and Boston) can be set up in about twelve weeks, and setup times will continue to decline in subsequent applications.

It now takes considerably less time to set up a city simulator than for city staff to become familiar with its use. Using the simulator develops in-house dynamic analysis capability while it is answering questions about city investments.

6) How dependent is the simulation capability on outside experts?

That is changing fast with ongoing software development and automation, and it will change still more as city simulation plays an increasing role in the financing of city investments.

Greenwood's experts have been developing software that makes simulation expertise unnecessary for conducting dynamic city analyses. Boston's research team is now defining their own scenarios and running dynamic analyses of city investments. This follows a twelve-session on-line course on the content and capabilities of city simulators, conducted in 2017 with a similar team from the GLA. In Boston one person works directly with the simulator and is supported by other members of their team and by Greenwood's people. The Boston team had no prior experience with dynamic simulation.

Looking ahead, the ability to reliably value investments in cities and to measure the ***'cost of not'*** making these investments is revealing new funding approaches and opening up new sources of financing. As described in Section 6, dynamic analysis is expected to play a key role in reducing risk and assuring benefits throughout the life of city investments and their financings. As this unfolds, it is expected that the costs of cities' in-house dynamic analysis teams and their outside support will be built into such financings in the mutual interest of cities and those investing in them.

Conclusion

City-simulation technology has developed in living urban laboratories like London and Boston, and its flexibility has been demonstrated in Frankfurt and other cities. The duration and cost of its application have been sharply reduced to the point where almost any city can participate and benefit from it.

8. Appendix

8.1. Historical Time Series Data Employed in Validation of Greater London Simulator

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Attractiveness of Business Construction	Qualitative Data/Interviews	N/A	N/A	N/A	GLA Subject-Matter Experts
Attractiveness of Housing Construction	Qualitative Data/Interviews	N/A	N/A	N/A	GLA Subject-Matter Experts
Attractiveness of Migration	Qualitative Data/Interviews	N/A	N/A	N/A	GLA Subject-Matter Experts
Attractiveness to Business	Qualitative Data/Interviews	N/A	N/A	N/A	GLA Subject-Matter Experts
Quality of Life	Qualitative Data/Interviews	N/A	N/A	N/A	GLA Subject-Matter Experts
Gross Value Added	Historical Data	1997	2014	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/gross-value-added-and-gross-disposable-household-income
Total Population	Historical Data	1961	2014	Boroughs disaggregated	London Datastore; https://data.london.gov.uk/dataset/office-national-statistics-ons-population-estimates-borough
Inflation Multiplier	Historical Data	1989	2015	N/A	Office for National Statistics; https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/d7bt/mm23
National Interest Rate	Historical Data	1975	2016	N/A	Bank of England; http://www.bankofengland.co.uk/boeapps/iadb/index.asp?Travel=NIxIRxRPx&From=Repo&C=13T&G0Xtop.x=1&G0Xtop.y=1

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Total National Government Tax Receipts	Historical Data	2004	2015	N/A	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf
National Government Tax Receipts from Consumption Tax	Historical Data	2004	2015	Boroughs Aggregated	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf
National Government Tax Receipts from Corporate Tax	Historical Data	2004	2015	Boroughs Aggregated	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf
National Government Tax Receipts from Other National Taxes	Historical Data	2004	2015	Boroughs Aggregated	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf
National Government Tax Receipts from Personal Income Tax	Historical Data	2004	2015	Boroughs Aggregated	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf
National Government Tax Receipts from Social Insurance Tax	Historical Data	2004	2015	Boroughs Aggregated	City of London; https://www.cityoflondon.gov.uk/business/economic-research-and-information/research-publications/Documents/research2014/londons%20finance%20and%20revenues.pdf

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Average Commute Time to Job Location All Modes	Historical Data	2002	2014	N/A	TUC; https://www.tuc.org.uk/news/commute-times-increase-uk%E2%80%99s-transport-system-gets-more-crowded
Passenger Kilometre - Bus	Historical Data	1991	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre - Underground	Historical Data	1991	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre - DLR	Historical Data	1991	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre - Tramlink	Historical Data	2001	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre – Overground	Historical Data	2008	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre - Total Public Transport	Historical Data	1991	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Passenger Kilometre - Motor Vehicles	Historical Data	1993	2010	N/A	London Datastore; https://data.london.gov.uk/dataset/travel-patterns-and-trends-london
Total Business Floor Space	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/commercial-and-industrial-floorspace-borough
Retail Floorspace	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/commercial-and-industrial-floorspace-borough
Office Floorspace	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/commercial-and-industrial-floorspace-borough

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Industrial Floorspace	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/commercial-and-industrial-floorspace-borough
Other Floorspace	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/commercial-and-industrial-floorspace-borough
Total Residential Units	Historical Data	1991	2015	Boroughs Aggregated	GOV.UK Tables 100 and 109; https://www.gov.uk/government/statistical-data-sets/ live-tables-on-dwelling-stock-including-vacants
Average Floor Space per Dwelling (m^2)	Historical Data	2008	2014	Boroughs Aggregated	GOV.UK; https://www.gov.uk/government/statistical-data-sets/stock-profile
Total Social Housing Units	Historical Data	1991	2015	Boroughs Aggregated	GOV.UK Tables 100 and 109; https://www.gov.uk/government/statistical-data-sets/ live-tables-on-dwelling-stock-including-vacants
Total Jobs	Historical Data	1996	2015	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/workforce-jobs
London Unemployment Rate	Historical Data	1992	2015	Boroughs Aggregated	Office for National Statistics; https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/ unemployment/timeseries/ycni/lms
National Unemployment Rate	Historical Data	1971	2015	N/A	Office for National Statistics; https://www.ons.gov.uk/employmentandlabourmarket/peoplenotinwork/ unemployment/timeseries/mgsx/lms
Total Municipal Employment Positions	Historical Data	2008	2011	Boroughs Aggregated	Office for National Statistics; https://www.ons.gov.uk/employmentandlabourmarket/ peopleinwork/publicsectorpersonnel/datasets/publicsectoremploymentreferencetable
Fraction of managers, directors and senior officials	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp ?opt=3&theme=&subgrp=

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Fraction of professional occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of associate prof & tech occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of administrative and secretarial occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of skilled trades occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of caring, leisure and other service occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of sales and customer service occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Fraction of process, plant and machine operatives	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Fraction of elementary occupations	Historical Data	2004	2015	Boroughs Aggregated	NOMIS query; https://www.nomisweb.co.uk/query/select/getdatasetbytheme.asp?opt=3&theme=&subgrp=
Total CO2 Emissions	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Emissions from Business Buildings	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Emissions from Domestic Buildings	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Emissions from Transport	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Total Energy Consumption	Historical Data	2000	2012	No	London Datastore; https://data.london.gov.uk/dataset/leggi
Energy Consumption by Business Buildings	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Energy Consumption by Domestic Buildings	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Energy Consumption by Transport	Historical Data	2000	2012	Boroughs Aggregated	London Datastore; https://data.london.gov.uk/dataset/leggi
Total Debt	Historical Data	2009	2016	GLA / Boroughs Aggregated	Financial data provided by GLA

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Net Borrowing Rate	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Additional debt reducing payments from central government	Historical Data	2012	2012	GLA	Financial data provided by GLA
Tax base for Residential Real Estate Tax	Historical Data	2009	2015	Boroughs Aggregated	Financial data provided by GLA
Tax base for Business Real Estate Tax	Historical Data	2009	2015	Boroughs Aggregated	Financial data provided by GLA
Business Tax Rate	Historical Data	1999	2013	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Revenue	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Economic Tax Revenues	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Real Estate Tax Revenues	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Residential Real Estate Tax Revenues	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Grant Revenues	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Grants Earmarked for Housing	Historical Data	2012	2015	Boroughs Aggregated	Financial data provided by GLA
Grants Earmarked for Police	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
GLA Grants to TfL	Historical Data	2009	2015	GLA	Financial data provided by GLA
Other borrowing and credit arrangements not supported by central government	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Business Real Estate Tax Revenues	Historical Data	2013	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Business Revenues	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Investment for Education Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Investment for Housing Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Total Investment for Other Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Investment for Public Safety Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Investment for Public Transport Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Investment for Roads Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Capital Expenditures	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Capital Expenditures for Education Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Capital Expenditures for Housing Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Capital Expenditures for Other Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Capital Expenditures for Public Safety Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Capital Expenditures for Public Transport Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Capital Expenditures for Roads Infrastructure	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Interest Payments	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Depreciation Expense	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Total Operating Expenditures	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Operating Expenditures for Education Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Operating Expenditures for Housing Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA

Data Series	Data Type	Data range start	Data range end	Aggregation of Data Available	Source
Operating Expenditures for Other Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Operating Expenditures for Public Safety Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Operating Expenditures for Public Transport Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA
Operating Expenditures for Roads Service Delivery	Historical Data	2009	2015	GLA / Boroughs Aggregated	Financial data provided by GLA

8.2. Scenario Input Characterizations

8.2.1. Jubilee Line Extension

Direct Operating Consequence	Value
Project Start	1994
Project Completion	2000
Project Budget	GBP 3,500,000,000
Thereof Municipality Budget	GBP 3,500,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	28,250
Density of Additional Residential Units Relative to Greater London Average	1
Expected Addition of Total Business Floor Space (m²)	2,695,000
Density of Additional Business Space Relative to Greater London Average	1

8.2.2. Olympics

Direct Operating Consequence	Value
Project Start	2005
Project Completion	2012
Project Budget	GBP 9,300,000,000
Thereof Municipality Budget	GBP 9,300,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 5% Other Infrastructure: 10%
Expected Addition of Total Residential Units	63,200
Density of Additional Residential Units Relative to Greater London Average	1
Expected Addition of Total Business Floor Space (m²)	1,700,000
Density of Additional Business Space Relative to Greater London Average	1

8.2.3. Crossrail 1

Direct Operating Consequence	Value
Project Start	2009
Project Completion	2019
Project Budget	GBP 14,800,000,000
Thereof Municipality Budget	GBP 9,280,000,000
Thereof Public Borrowing	GBP 6,900,000,000
Project funded by Municipality	Yes
Tax Supplement for Investment Projects	0.79%
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	57,000
Density of Additional Residential Units Relative to Greater London Average	1
Expected Addition of Total Business Floor Space (m²)	3,325,000
Density of Additional Business Space Relative to Greater London Average	1

8.2.4. Sutton Tram Extension

Direct Operating Consequence	Value
Project Start	2022
Project Completion	2025
Project Budget	GBP 350,000,000
Thereof Municipality Budget	GBP 175,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	10,700
Density of Additional Residential Units Relative to Greater London Average	1/3

8.2.5. Crossrail 1 Extension

Direct Operating Consequence	Value
Project Start	2023
Project Completion	2028
Project Budget	GBP 2,500,000,000
Thereof Municipality Budget	GBP 1,250,000,000
Project funded by Municipality	Yes
Project contributes to …	• Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	15,000
Density of Additional Residential Units Relative to Greater London Average	1/3
Expected Addition of Total Business Floor Space (m²)	225,000
Density of Additional Business Space Relative to Greater London Average	1/3

8.2.6. Bakerloo Line Extension

The Bakerloo Line Extension scenario was split into two phases. Phase 1 is an extension from station Elephant & Castle to Lewisham. There are three mutually exclusive options for Phase 2; Lewisham to 1) Hayes and Beckenham Junction, 2) Bromley North, or 3) Slade Green. The two phases were characterized at current capacity of 27 trains per hour. Also characterized was the additional capacity for housing units along the extended Bakerloo Line resulting from a capacity increase from 27 to 33 trains per hour.

8.2.6.1. Bakerloo Line Extension Phase 1 (Core - Elephant & Castle to Lewisham) at current capacity of 27 trains per hour

Direct Operating Consequence	Value
Project Start	2023
Project Completion	2028
Project Budget	GBP 3,600,000,000
Thereof Municipality Budget	GBP 1,800,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	25,000
Density of Additional Residential Units Relative to Greater London Average	1/3
Expected Addition of Total Business Floor Space (m²)	215,300
Density of Additional Business Space Relative to	1/3

Direct Operating Consequence	Value
Greater London Average	

8.2.6.2. Bakerloo Line Extension Phase 2 Option A (Hayes and Beckenham Junction) at current capacity of 27 trains per hour

Direct Operating Consequence	**Value**
Project Start	2029
Project Completion	2033
Project Budget	GBP 500,000,000
Thereof Municipality Budget	GBP 250,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	6,500
Density of Additional Residential Units Relative to Greater London Average	1/3

8.2.6.3. Bakerloo Line Extension Phase 2 Option B (Bromley North) at current capacity of 27 trains per hour

Direct Operating Consequence	**Value**
Project Start	2029
Project Completion	2033
Project Budget	GBP 1,200,000,000
Thereof Municipality Budget	GBP 600,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	2,500
Density of Additional Residential Units Relative to Greater London Average	1/3

8.2.6.4. Bakerloo Line Extension Phase 2 Option C (Slade Green) at current capacity of 27 trains per hour

Direct Operating Consequence	**Value**
Project Start	2029
Project Completion	2033
Project Budget	GBP 800,000,000
Thereof Municipality Budget	GBP 400,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	8,000
Density of Additional Residential Units Relative to Greater London Average	1/3

8.2.6.5. Bakerloo Line Capacity Extension from 27 to 33 trains per hour

Direct Operating Consequence	**Value**
Project Start	2023
Project Completion	2033
Project Budget	GBP 1,000,000,000
Thereof Municipality Budget	GBP 500,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	7,500
Density of Additional Residential Units Relative to Greater London Average	1/3

8.2.6.6. Bakerloo Line Extension – Investment Impacts

Greater London Investment Impacts	Bakerloo Line Extension		
	Phase 1 to Lewisham plus Phase 2 Option to Hayes and Beckenham Junction plus capacity extension to 33 trains/hour	*Phase 1 to Lewisham plus Phase 2 Option to Bromley North plus capacity extension to 33 trains/hour*	*Phase 1 to Lewisham plus Phase 2 Option to Slade Green plus capacity extension to 33 trains/hour*
Investment type	*Transport*	*Transport*	*Transport*
Social and Economic Impacts	***Simulated differences resulting from these investments as of or in 2050***		
Population	132,000	120,000	136,000
Housing units	74,000	67,000	77,000
Jobs	79,000	72,000	81,000
Business space (m^2)	166,000	171,000	164,000
Economy (£B/year)	£7.0	£6.5	£7.2
HMT[1] tax take (£B/year)	£2.0	£1.9	£2.1
Social & Economic Impacts Monetized in Fiscal Impacts	***Simulated cumulative HMT fiscal differences resulting from these investments over 50-year economic lives** (£B)*		
Added HMT net tax surplus[2]	£66.0	£61.0	£67.9
Less added interest[3]	-£9.5	-£10.5	-£10.3
Added HMT London cash flow	£56.5	£50.5	£57.6
NPV for HMT[4] (£B)	**£17.0**	**£15.0**	**£17.3**
Public investment in project (£B)	£5.1	£5.8	£5.4

[1]Her Majesty's Treasury
[2]Added HMT tax revenues less increased HMT spending in a faster-growing London (based on Oxford Economics' % spending forecast)
[3]Interest on financing of public investment in the project, at 3.44% recent average 10-year Gilts rate
[4]Net present value, discounted at 3.44% recent average 10-year Gilts rate

Bakerloo Line Extension Impacts	*Phase 1 to Lewisham*	*Phase 2 Option A to Hayes and Beckenham Junction*	*Phase 2 Option B to Bromley North*	*Phase 2 Option C to Slade Green*	*Capacity extension to 33 trains/hour*
Investment type			*Transport*		
Social and Economic Impacts	***Simulated differences resulting from these investments as of or in 2050***				
Population	90,000	20,000	8,000	24,000	22,000
Housing units	49,000	12,000	4,000	14,000	13,000
Jobs	56,000	11,000	4,000	13,000	12,000
Business space (m^2)	187,000	-10,000	-4,000	-12,000	-11,000
Economy (£B/year)	£5.2	£0.9	£0.3	£1.0	£1.0
HMT[1] tax take (£B/year)	£1.5	£0.2	£0.0	£0.3	£0.3

[1]*Her Majesty's Treasury*

8.2.7. Digital

The GLA provided qualitative High-Medium-Low characterizations for the Digital Scenario's DOCs as shown in the first table below. The GLA also provided percentages defining the ranges for Low (= 0% to 5%), Medium (= 5% to 15%) and High (= 15% to 30%).

Direct Operating Consequences	Qualitative Impact	GLA Source
Attractiveness of business construction	High	CoStar analysis in Boston
Attractiveness of housing construction	High	Rightmove survey found slow broadband 'wiped' 20% of property sale value
Attractiveness of job creation	High	GLA assumption
Attractiveness of migration	Medium	Redrow survey; 100% of people surveyed say that high-speed broadband is important for creating a strong community
Energy consumption by business buildings	Low	GLA assumption – Due to Increased ability to use connected devices
Energy consumption by domestic buildings	Low	GLA assumption – Due to Increased ability to use connected devices
Council tax revenues	High	Same as for attractiveness of business construction
Business rate revenues	High	Same as for attractiveness to business
Business type council revenue	Medium	Study from "Journal of Productivity Analysis" and European Commission quote 7-10% figure
Operating expenditures for other service delivery	Low (reduction)	GLA assumption

The GLA advised that the lower end of the respective range should be used. In addition the lower end is to be reduced to 30% of its value to reflect the assumed uptake of service.

Direct Operating Consequence	Value
Project Start	2018
Ramp up Time in Years	10
Fully Active from	2028
Active through	2038
Increase/Decrease of Direct Impact on	
Attractiveness of Business Construction	4.5% *(= 30% * 15%)*
Attractiveness of Housing Construction	4.5% *(= 30% * 15%)*
Attractiveness of Job Creation	4.5% *(= 30% * 15%)*
Attractiveness of Migration	1.5% *(= 30% * 5%)*
Energy Consumption by Business Buildings	0% *(= 30% * 0%)*
Energy Consumption by Domestic Buildings	0% *(= 30% * 0%)*
Council Tax Revenues	4.5% *(= 30% * 15%)*
Business Rate Revenues	4.5% *(= 30% * 15%)*
Business Type Council Revenue	1.5% *(= 30% * 5%)*
Operating Expenditure for other Service Delivery	-1.5% *(= 30% * -5%)*

8.2.8. Crossrail 2

Direct Operating Consequence	Value
Project Start	2023
Project Completion	2036
Project Budget	GBP 29,000,000,000
Thereof Municipality Budget	GBP 14,500,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Tax Supplement for Investment Projects	0.79%
Expected Addition of Total Residential Units	134,000
Density of Additional Residential Units Relative to Greater London Average	1/3
Expected Addition of Total Business Floor Space (m²)	72,315
Density of Additional Business Space Relative to Greater London Average	1/3

8.2.9. Royal Docks

Direct Operating Consequence	Value
Project Start	2016
Project Completion	2037
Project Budget	GBP 385,000,000
Thereof Municipality Budget	GBP 385,000,000
Project funded by Municipality	Yes
Project contributes to …	Public Transport Infrastructure: 100%
Expected Addition of Total Residential Units	25,900
Density of Additional Residential Units Relative to Greater London Average	1/3
Expected Addition of Total Business Floor Space (m²)	641,000

8.2.10. Current Position Housing

Direct Operating Consequence	Value
Scenario Start	2018
Scenario End	2050
Ensuring net addition of Residential Units per year	40,000
Thereof affordable	15,000

8.2.11. London Plan Housing

Direct Operating Consequence	Value
Scenario Start	2018
Scenario End	2050
Ensuring net addition of Residential Units per year	65,000
Thereof affordable	32,500

8.3. Drilling Down in the City Simulator

The diagram in Figure 24 shows, at summary level, the dynamic structure of the city and of the common model used in the Greater London Simulator. The model can be viewed at five levels of successively greater detail.

1) Summary-level dynamic structure (main elements and relationships) in Figure 24
2) Model architecture (sectors and their interrelationships) in Figure 25
3) Sector-level dynamic structure and interdependencies in Figure 26
4) Detailed model views at equation level (using Vensim simulation software) in Figure 27
5) Model equations (using Vensim simulation software) in Figure 28

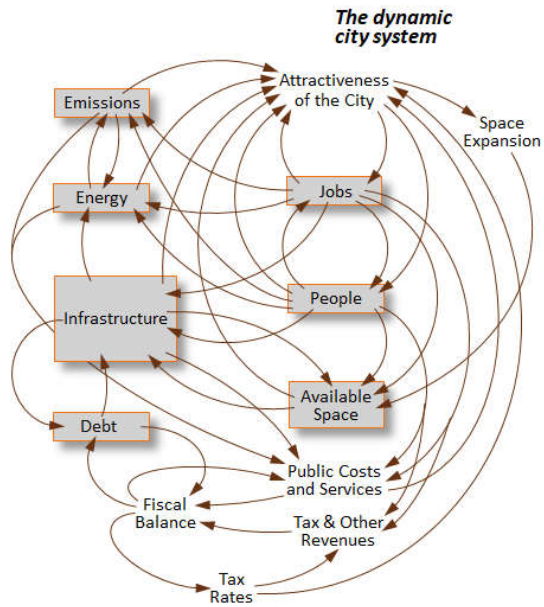

Figure 24 – The dynamic city system

Surveying the full city model structure is beyond the scope of this report, but it is useful to view its structure at the different levels. That means broadly reviewing model sectors (level 2), followed by drilling vertically down through model structure in the Population and Migration sector (levels 3-5).

Despite the simplification involved in modelling, a dynamic model of a large, complex system necessarily includes a great deal of system detail in the form of numerous structural diagrams and equations. Drilling down illustrates the fact that dynamic simulation models are 'clear box' representations which can be examined and audited from top to bottom. This is important for understanding and credibility.

Level 2: Model architecture

Figure 25 is the architecture diagram of the common city model. It is arranged in sectors that represent various city stakeholder groups and their actions, or consequences of those actions. The connecting arrows indicate interrelationships between the sectors.

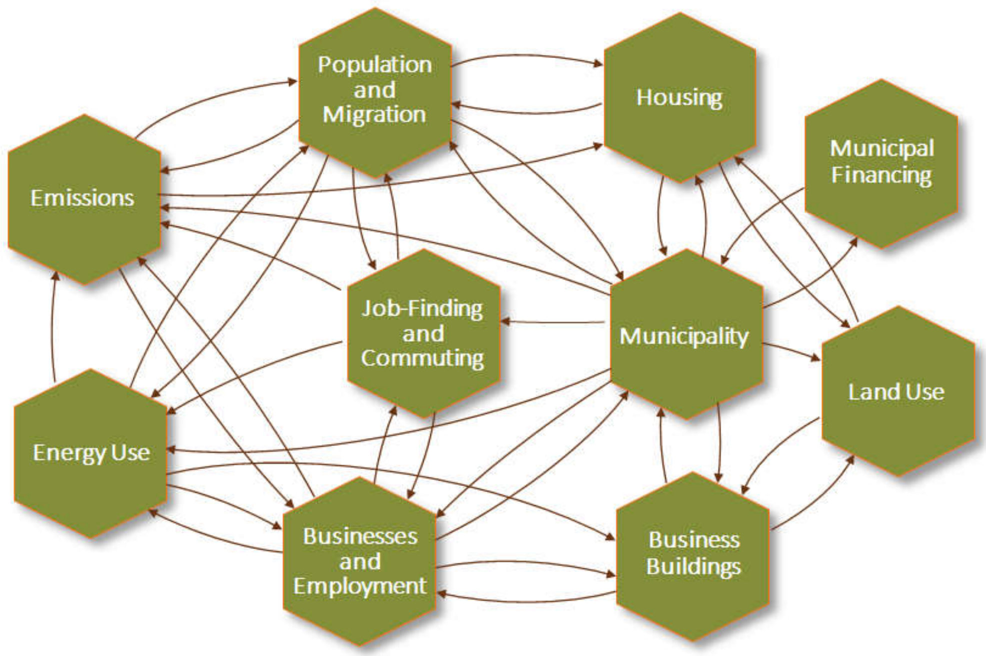

Figure 25 – Greater London Simulator model architecture

Population and Migration	Simulates births / deaths, in- and out-migration, and upward and downward Migration mobility for upper / middle / lower income groups, influenced by job and housing availability and other simulated factors.
Housing	Simulates development and redevelopment of social housing and upper / middle / lower income private housing, influenced by housing demand, land availability, and other simulated factors.
Businesses and Employment	Simulates job creation / destruction and job in- / out-migration in businesses of high / medium / low knowledge intensity, influenced by availability of personnel and business space, and other simulated factors.
Business Buildings	Simulates development and redevelopment of space for businesses of high / medium / low knowledge intensity, influenced by demand for space, land availability, and other simulated factors.
Job-Finding and Commuting	Simulates job-finding, unemployment, and daily travel of employees between residences and workplaces, within Greater London and from and to outlying areas, by private and public transport (car or bus / tube / rail), influenced by housing and workplace locations and commuting times.
Municipality,	Simulates public revenue streams, budgeting, provision of infrastructure and

Municipal Financing	public services, debt repayment, finances and availability of financing, for two levels of local government (the GLA, and all Boroughs in aggregate).
Land Use	Simulates land use, land redevelopment/repurposing, and land availability, influenced by development of housing and business space.
Energy Use, Emissions	Simulate energy use by and greenhouse gas emissions from residences / businesses / transport, influenced by efficiency and emissions-intensity trends.

The common city model is pre-structured for aggregated or disaggregated representations on several dimensions. As indicated in the sector descriptions above, the Greater London Simulator is currently disaggregated as follows.

- Geographically: now used to separately simulate the GLA and the aggregated Boroughs; will be used in future to simulate various Borough clusters (inner city, outer ring, along transport corridors)
- Population income groups: upper, middle, lower
- Housing: upper, middle, and lower income
- Jobs: upper, middle, and lower income
- Businesses, business space: high / medium / low knowledge intensity businesses, and business space; each business type having a different mix of upper, middle, and lower income

Disaggregation choices are made when a city model is first set up or subsequently revised. These choices dictate the levels at which simulated London stakeholders (people and businesses) interact with each other and with other city elements (housing, business space). Disaggregating creates and simulates sub-markets within the overall markets for jobs, housing and business space. For example, disaggregation in the Greater London Simulator has lower-income people competing for lower-income housing and lower knowledge-intensity jobs under dynamically driven conditions that differ significantly from those experienced in the middle- and upper-income groups.

One important note: disaggregating does not increase the accuracy or reliability of the Greater London Simulator; equally high accuracy can be achieved in aggregated and disaggregated whole-system models.

- This is in contrast to most types of computer models; being non-dynamic, these depend significantly on disaggregation (also known as granular detail) for accuracy, reliability and credibility. It is not surprising that the same is expected of dynamic simulation models.
- The accuracy and reliability of city and other dynamic models depend on dynamic whole-system detail, which is very different from disaggregation detail. Dynamic detail means including the system elements and connecting cause-effect relationships that are relevant to the analysis questions being addressed. With the right dynamic feedback structure, a city model can be aggregated or disaggregated with no effect on accuracy and reliability.
- Disaggregation detail in city simulators adds value not by increasing accuracy, but by enabling us to pose and answer more detailed and focused questions. In the Greater London Simulator disaggregation allows us to differentiate (for example) between different income groups and their differing access to housing and jobs and upward mobility.

It is important to remember that the sectors shown in Figure 25 do not exist in Greater London or any other real-world city. The sectors are useful tools for organizing the city model and make it easier to review. But they are a bit like vertical departments in city governments (housing, transport, etc.); the real city system operates as an integrated, dynamic whole and without regard for organizing structures.

Level 3: Sector-level dynamic structure and interdependencies. Figure 26 diagrams dynamic structure in the Population and Migration sector, though it necessarily includes dynamics from other model sectors as well. Similar diagrams showing dynamic structure in the Housing, Businesses, Commuting and Municipality sectors can be found in Appendix 8.4.

These diagrams provide an intermediate-level view of both city dynamics and city model structure, giving a more complete overview than would fit in the summary-level diagram (Figure 24), while leaving out structural detail that appears in equation-level diagrams (Figure 27) and in the equations themselves (Figure 28).

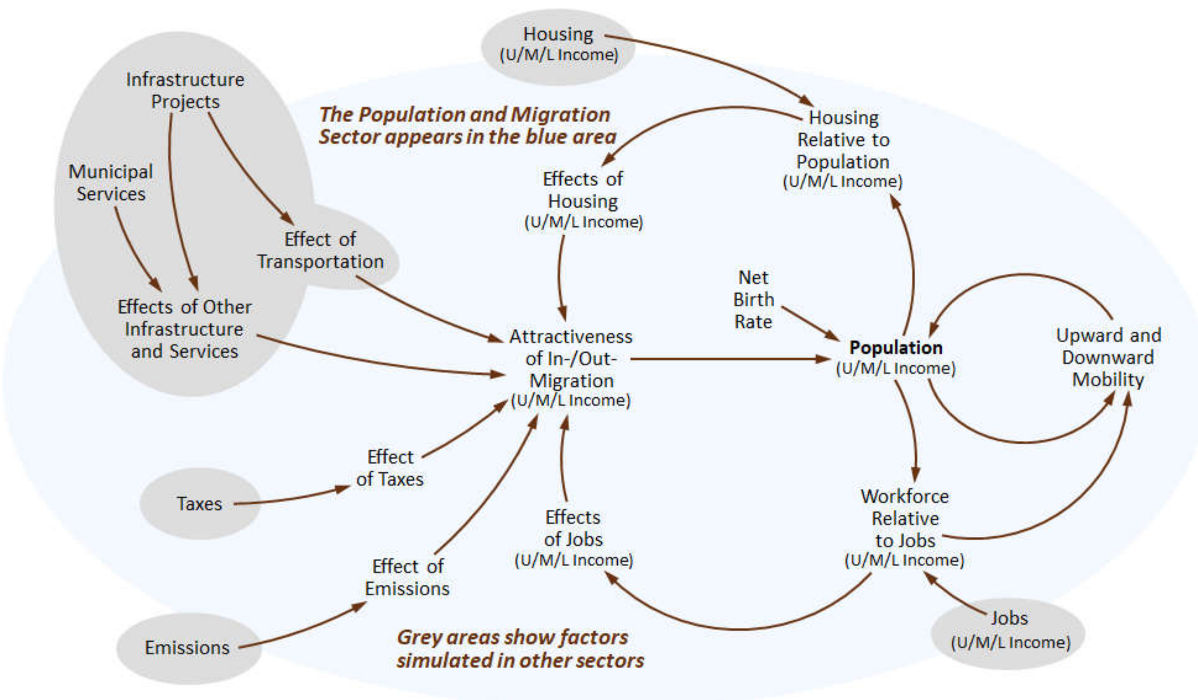

Figure 26 – Sector-level dynamic structure of the population and migration sector

The core dynamics in this sector involve Housing and Jobs, their influence on the Attractiveness of In- and Out-Migration and resulting consequences for Greater London's Population. These elements and cause-effect relationships constitute the two feedback loops at the right centre of the diagram.

- The upper feedback loop includes these elements and relationships: Population → Housing Relative to Population → Attractiveness of In- / Out-Migration (via Effects of Housing) → Population (via migration, which is simulated but not shown in this diagram). This feedback loop was discussed in more general terms in Section 3.2 of this report.
- The lower feedback loop includes these elements and relationships: Population → Workforce Relative to Jobs → Attractiveness of In- / Out-Migration (via Effects of Jobs) → Population.

London's growing population in the face of the housing crisis is evidence that Attractiveness of Migration (on a net basis) has been more powerfully increased by Job availability than it has been reduce by Housing availability. Until that is no longer the case, we can expect London's housing crisis to continue worsening.

One 'obvious' solution is to build more houses in Greater London. Whether we trace that mentally through the core feedback loops in Figure 26 or simulate them in the computer, more housing will make London more attractive for in-migration even as it reduces peoples' primary motive for out-migration. Consequently, London's population will grow by more than it would have without the additional housing.

In other words, in a city where population growth has been constrained by a housing shortage, population 'springs up' if the constraint is partly relieved by increased housing. Thanks to the city's non-linear feedback dynamics, each new batch of housing can be expected to increase population by more than the housing capacity added. That is likely to go on for a long time in an attractor city like London, because it takes a great deal of new housing to catch up with demand that grows because you are adding housing. That dynamic reality is the main reason why close to half of all new London jobs are filled by people who live outside Greater London. As a result, Greater London is already much greater than official boundaries and population numbers would suggest.

The city dynamics diagrammed in Figure 26 are created by people making employment and housing and migration and commuting decisions in cities, and these are not separate decisions. We know that from experience, because they are the sort of social / economic / life decisions. We have all made – weighing prospective jobs and income against the availability and cost of housing and associated living styles and commuting time and expense. We know the elements involved in these decisions and the sort of cause-effect relationships and feedback loops that are formed by tens of thousands of people making and acting on such decisions each year.

Housing and Jobs are far from the only factors shaping peoples' migration decisions and London's population. Transportation and investments in transport infrastructure are major and growing influences as jobs in Greater London are increasingly held by people who live in the outer Boroughs and outside London's official boundaries. Other municipal services (education, social care, public safety) loom just as large in peoples' decision making and must be provided where they are choosing to live. Taxes are weighed against the availability and quality of those services and emissions (waste, noise, air quality).

Individuals in a city will have very different weightings for these decision-influencing factors, but averages across populations will tend to be stable or to change slowly when they do. Peoples' average weightings may differ significantly from one city to the next, especially in the face of local problems (very bad transport or air quality, for example), but city-specific averages can be determined as described later in this section.

The other sector-level diagrams (in Appendix 8.4) portray different aspects of city dynamics, all resulting from ongoing decisions and actions taken by individuals, institutions and other city stakeholders.

The colouring used in Figure 26 shows the limitations of sectoral definitions within a model of a dynamic socioeconomic system. The blue portion of the diagram contains simulated elements and cause-effect relationships which we have assigned to the Population and Migration sector of the city model. The grey portions contain elements and relationships which We have assigned to the Housing, Commuting, Emissions and Municipality sectors. Other diagrammed cause-effect relationships cross the boundaries of these various sectors. All of the elements and relationships in the diagram influence Population and Migration, and the most substantial influences come from the Housing and Commuting sectors. While they are useful for organizing the model, sector definitions have little or no systemic significance.

Level 4: Detailed model views at equation level

Greenwood uses commercially available Vensim software to set up city simulators and run simulations. Among its many capabilities, Vensim produces equation-level diagrams of any compatible simulation model. Such diagrams are very helpful for tracing chains of simulated cause-effect relationships, and for reviewing or auditing model structure and simulation results.

The full equation-level diagram of the common city simulation model would be too large for legible on-screen viewing; if printed at readable scale it would measure about three metres by four. Vensim intelligently divides up models and diagrams them in a series of connecting views, each of which can be printed at readable scale on A4 paper. Each such view covers a portion of the city model at equation level, alongside adjacent views that cover adjoining portions of the model.

The diagram of the common city model includes 167 such views. About 100 of these contain equations for simulating the dynamics of the city system, that is, the operation of the city's component elements and cause-effect relationships. The other views contain equations for various model 'housekeeping' functions.

Figure 27 on page 98 shows the central Vensim view from the Population and Migration sector of the city model. The diagram is what appears on the computer screen when this particular view is accessed via the Vensim software. It is one of 12 Vensim views that, together, diagram the model equations included in the Population and Migration sector of the Greater London Simulator.

The labels in this view show various elements and relationships simulated in that model sector. Each label is the name of an equation that calculates the values of a modelled element or relationship over simulated time.

Specifically, the model computes a new value for each element / relationship at six-week intervals in simulated time. After each such interval: (i) first the new value of each element is calculated, based on previous values of the particular cause-effect relationships that influence that element (from the preceding time interval); (ii) then a new value is calculated for each cause-effect relationship (a value that will prevail during the upcoming interval), based on the just-updated values of the particular elements that influence that relationship.

This interval-by-interval simulation process is much more than a convenient computation method; it deliberately mirrors the operation of real-world dynamic systems. In all such systems the state of system elements constantly shapes the workings of the cause-effect relationships that connect the elements, and, in turn, these cause-effect relationships are constantly influencing the states of the elements they connect. The length of the simulation intervals in the city model is set for consistency with the pace of element-relationship influences in the real-world city.

The rectangle at the centre of Figure 27 (labelled Population SIMULATED) represents the equation that calculates London's population (a city element). Arrows pointing into and out of the rectangle (or both into and out of it) represent the equations for population-altering flows that are shaped by various simulated cause-effect relationships:

- Net Births
- In- and Out-Migration
- Upward and Downward Mobility

To simulate the London sub-populations (upper, middle and lower income groups), Population SIMULATED and its in- and out-flows are separately computed for each of the three sub-populations at the end of each simulation interval. The flows for upward and downward mobility run between the lower- and middle-income populations and the middle- and upper-income populations.

The three population sub-groups are all subject to the same structural influences from various elements and cause-effect relationships. But the states of the elements and strengths of the connecting relationships will be different for these sub-populations and so are separately simulated for each of them, as indicated in Figure 26.

The chains of cause-effect relationships driving changes in London's Population are seen in the arrows that connect to the population-altering flows. Tracing backwards up these chains leads to other elements in the city system that influence population flows: attractiveness of migration, and effects on upward and downward mobility between income groups. These can be seen in the cause-effect relationships and elements diagrammed in Figure 26. In Figure 27 these labels appear in <brackets>, indicating that their equations are located elsewhere in the city model: green hexagons link to equations located in one of the other views of the Population and Migration Sector; grey hexagons link to equations in other model sectors. Some elements shown on the right side of the diagram are also labelled in <brackets> but without hexagons, which indicates that their equations are located elsewhere in this model view.

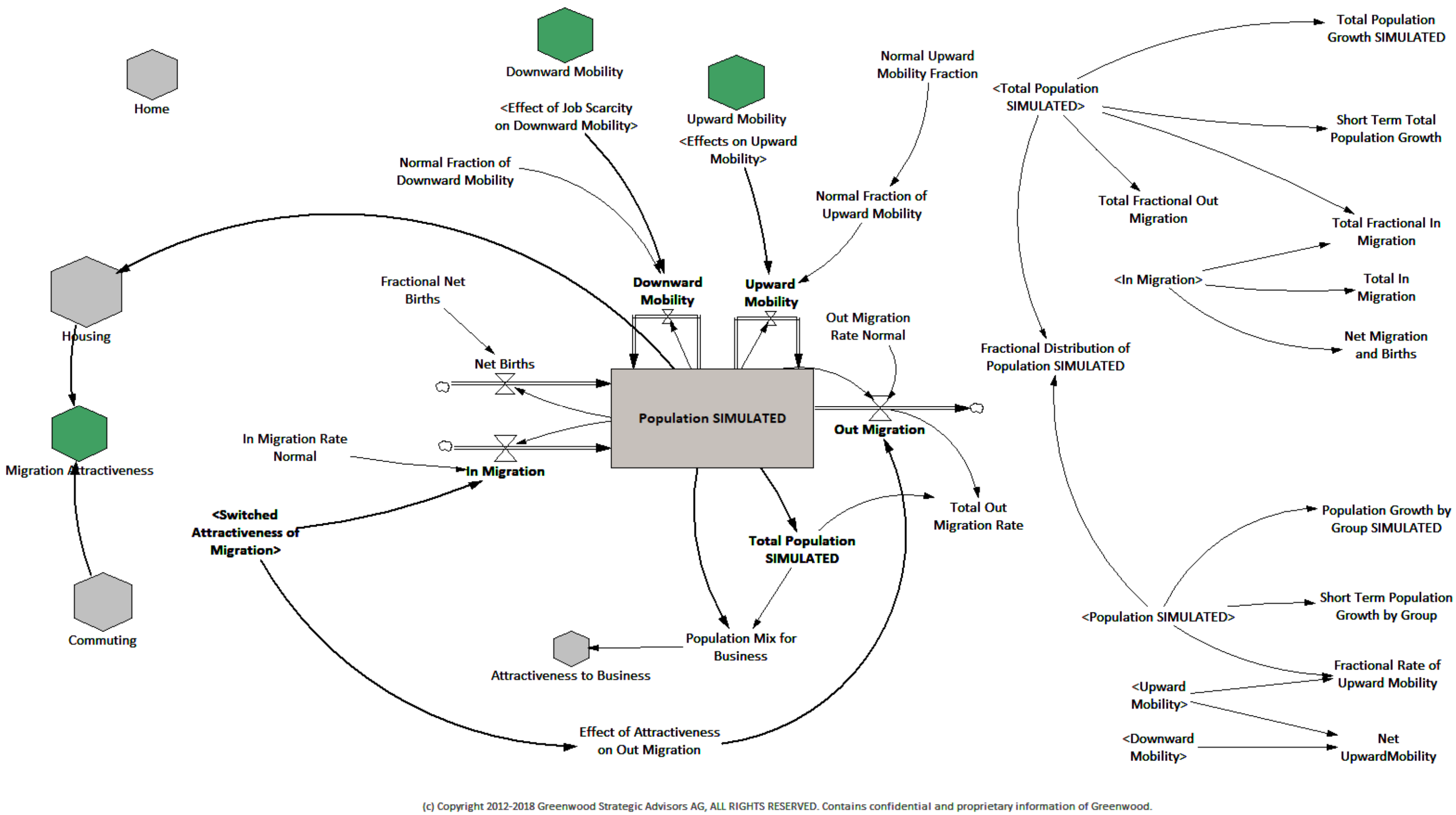

Figure 27 – Detailed model view in population and migration sector

Level 5: Model equations

Within any Vensim view of the city model, clicking on the label for an element or cause-effect relationship reveals the equation which calculates its simulated values over time.

Clicking on Population SIMULATED opens the dialogue box shown in Figure 28 on page 100. In the upper left corner of that box can be found:

- The Name of the element or relationship;
- The type (in this case a Level element that varies with in- and out-flows);
- The units in which this element is measured (in this case, people);
- Whether the element is subscripted (in this case, by population groups; the Upop subscript indicates that this equation calculates population numbers for the upper-income subgroup);
- The type of equation for the element (in this case INTEG, signifying integration of flows to compute Level values over time);
- The list of flows integrated (as shown in the diagram: In Migration minus Out Migration plus Net Births plus Upward Mobility minus Downward Mobility).

If we change the Subscript entry to read Mpop, the equation for the middle-income population subgroup will appear. That equation contains two additional mobility flows, because the middle sub-group experiences upward and downward mobility flows to and from both of the other income groups.

All element and relationship equations can be reviewed in the Vensim software (Figure 28), along with the views that diagram these equations and how they connect in the model’s dynamic structure (Figure 27). That structure can also be reviewed in the sector level diagrams (Figure 26 and Appendix 8.4) and in the summary diagram (Figure 25).

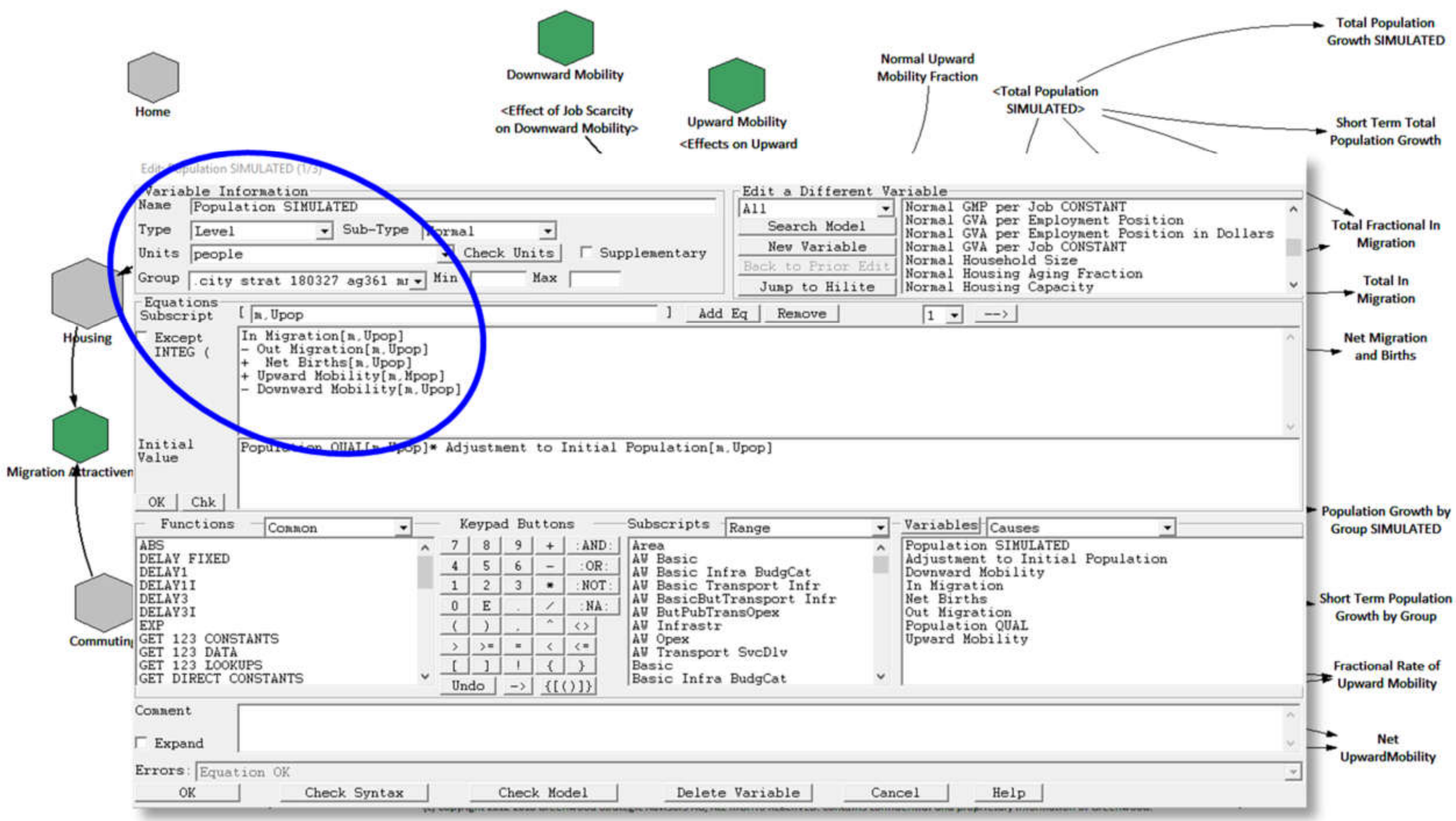

Figure 28 – Detailed equation level view of population

8.4. High-Level Views of Greater London Simulator Sectors

8.4.1. Housing Sector

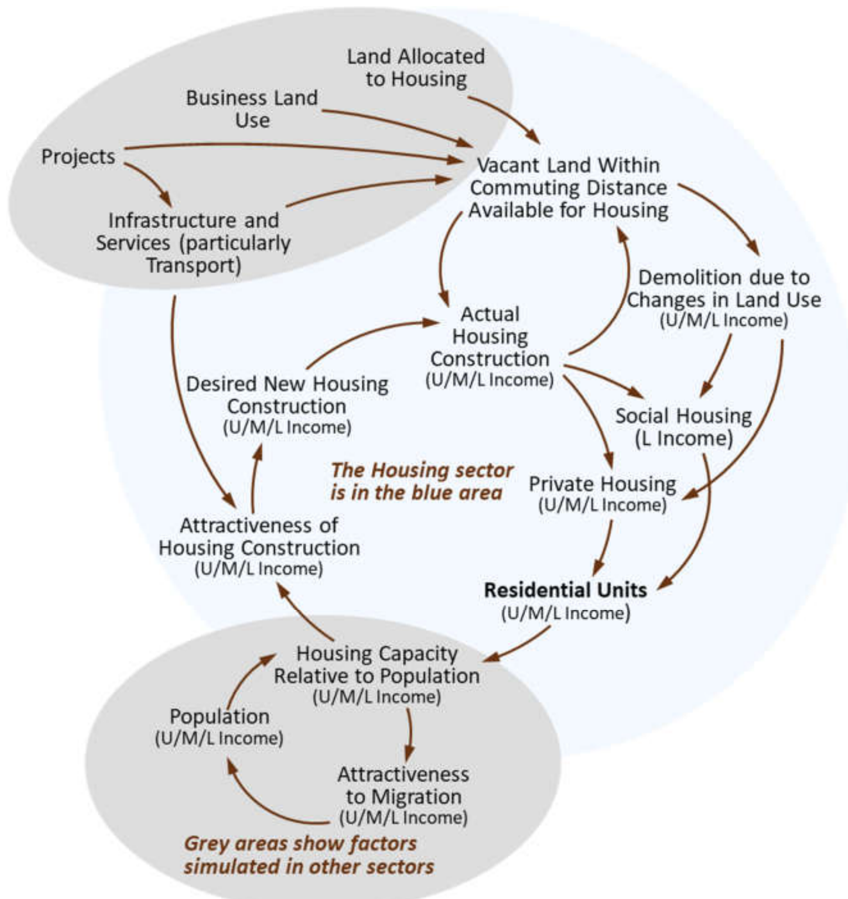

Figure 29 – High-level view of the housing sector

8.4.2. Business Sector

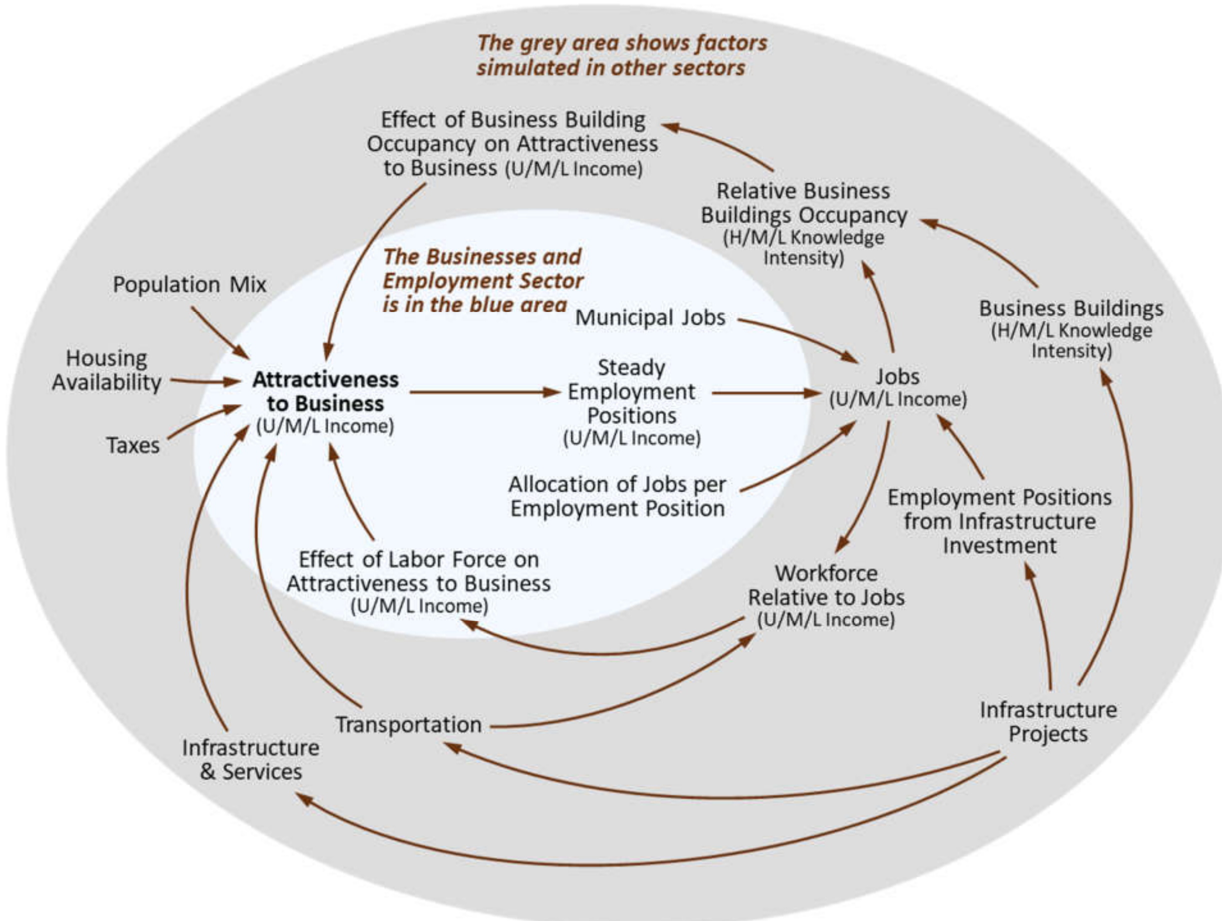

Figure 30 – High-level view of the business sector

8.4.3. Business Buildings Sector

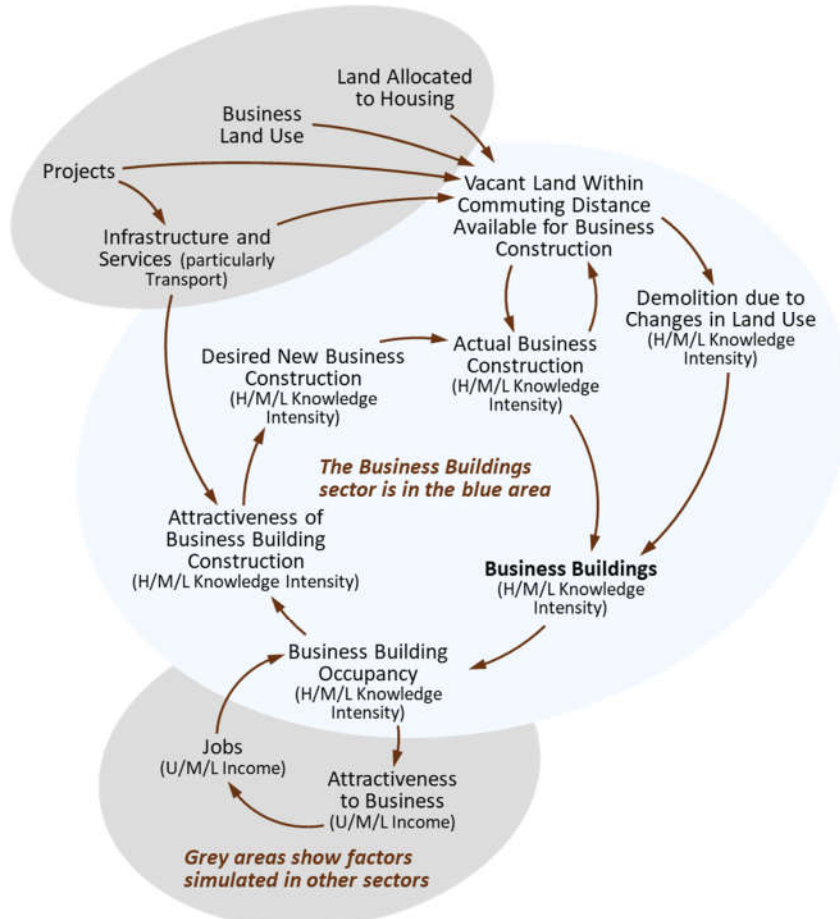

Figure 31 – High-level view of the business buildings sector

8.4.4. Transport Sector

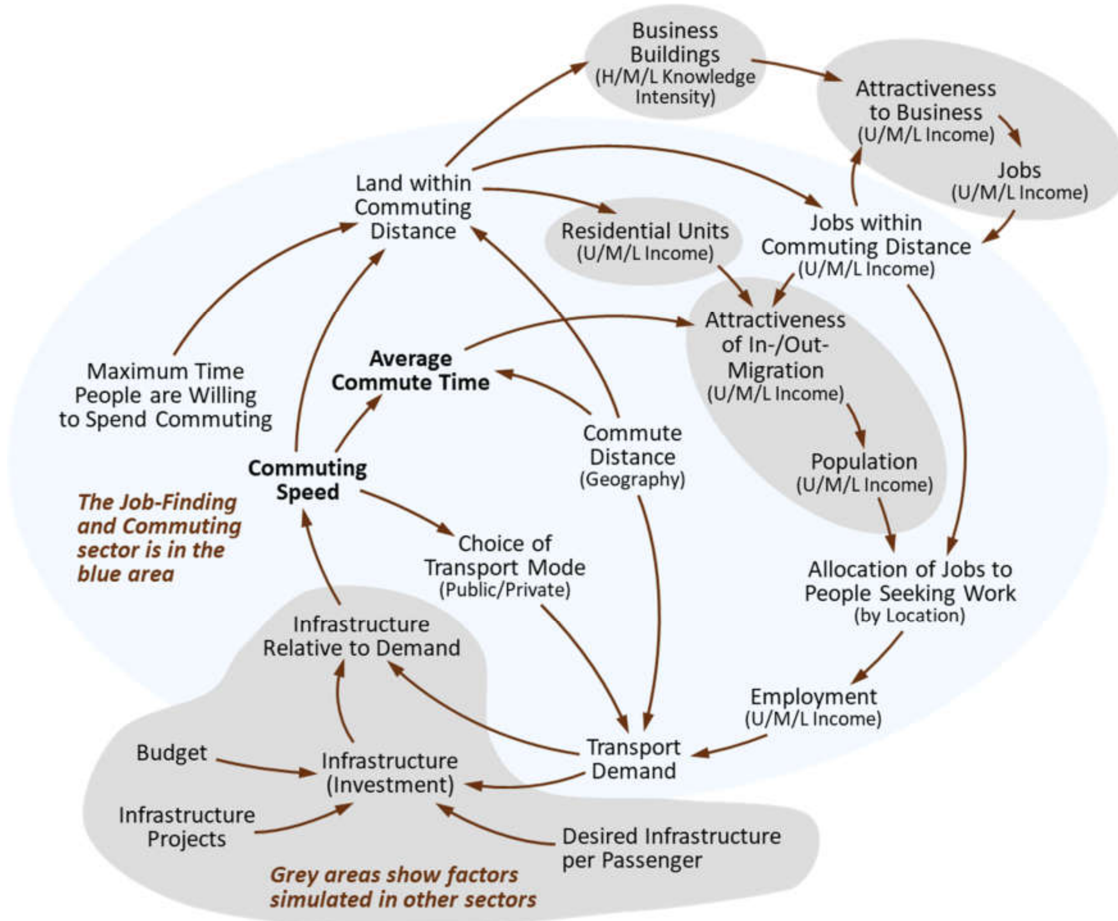

Figure 32 – High-level view of the job-finding and commuting sector

8.4.5. Municipal Sector

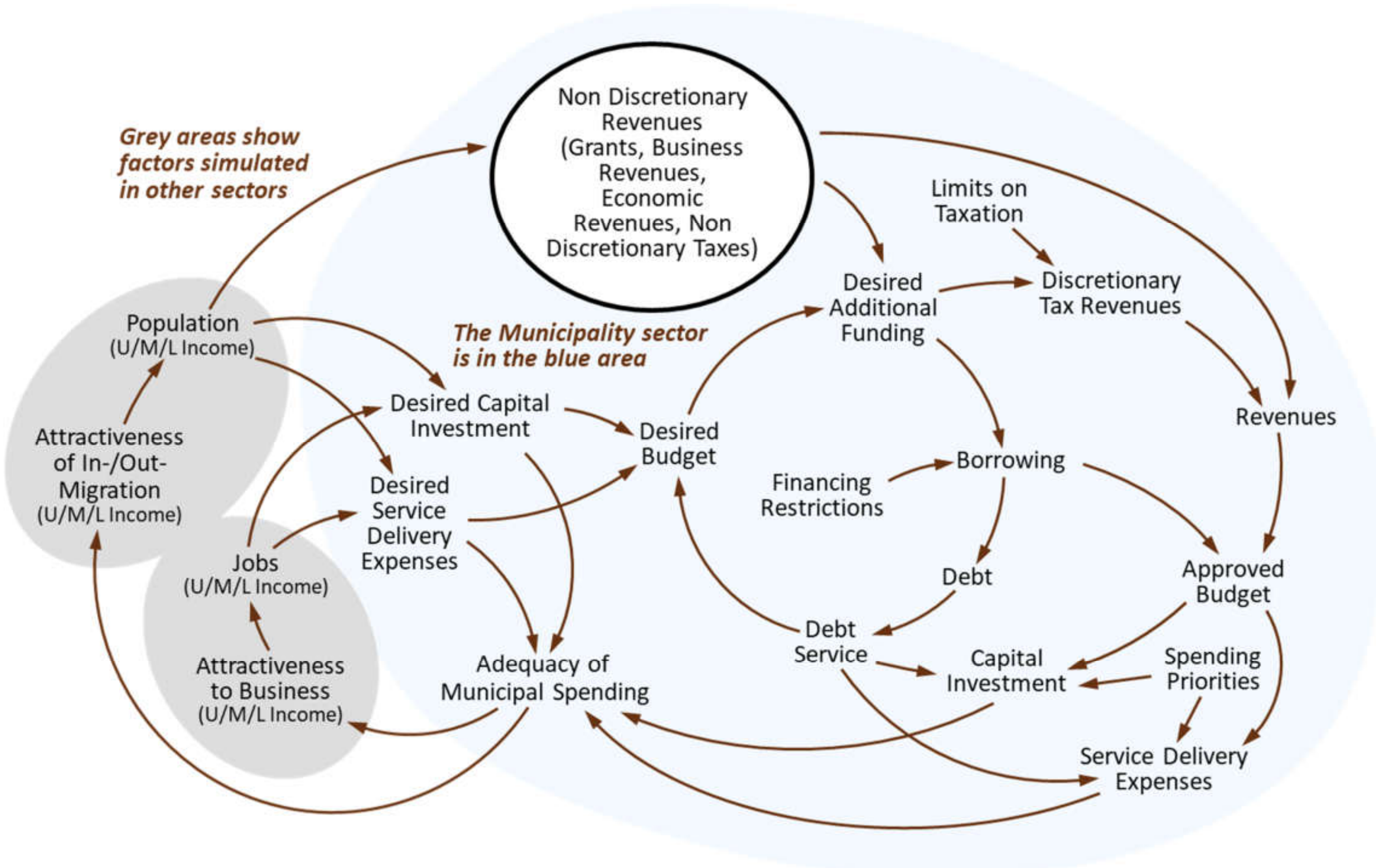

Figure 33 – High-level view of the municipality sector

8.4.6. Emissions Sector

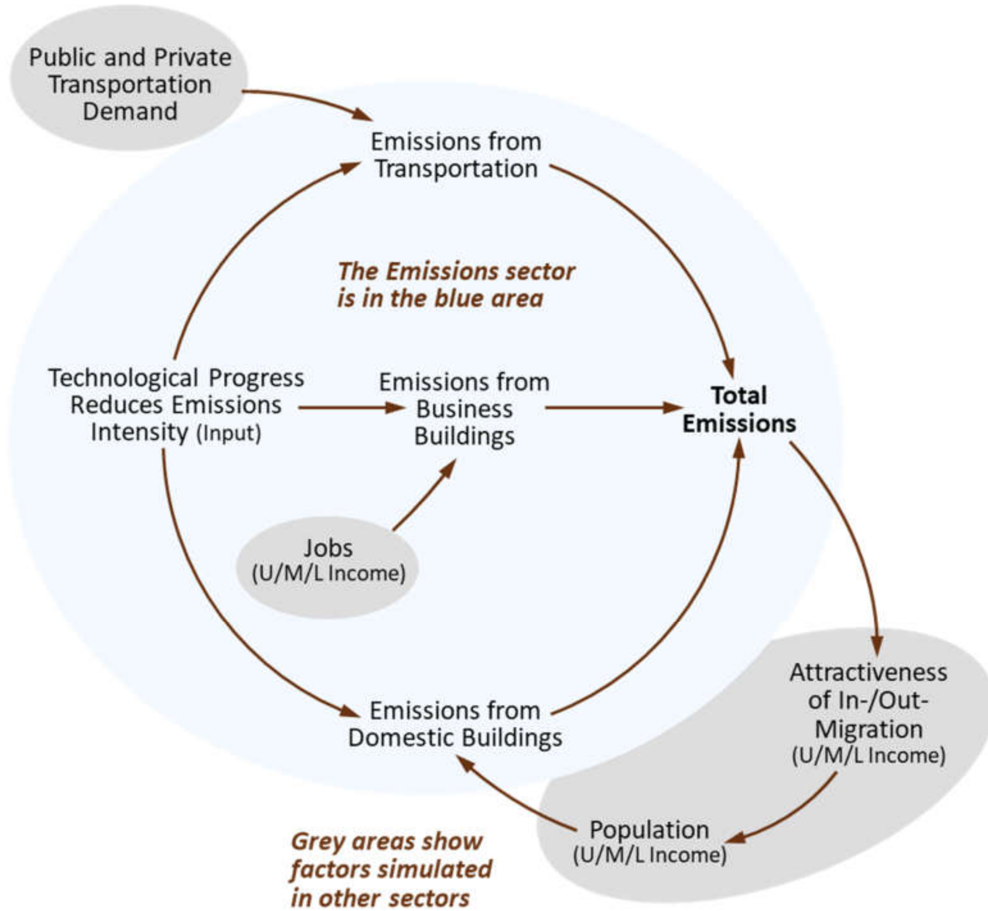

Figure 34 – High-level view of the emissions sector

8.4.7. Energy Sector

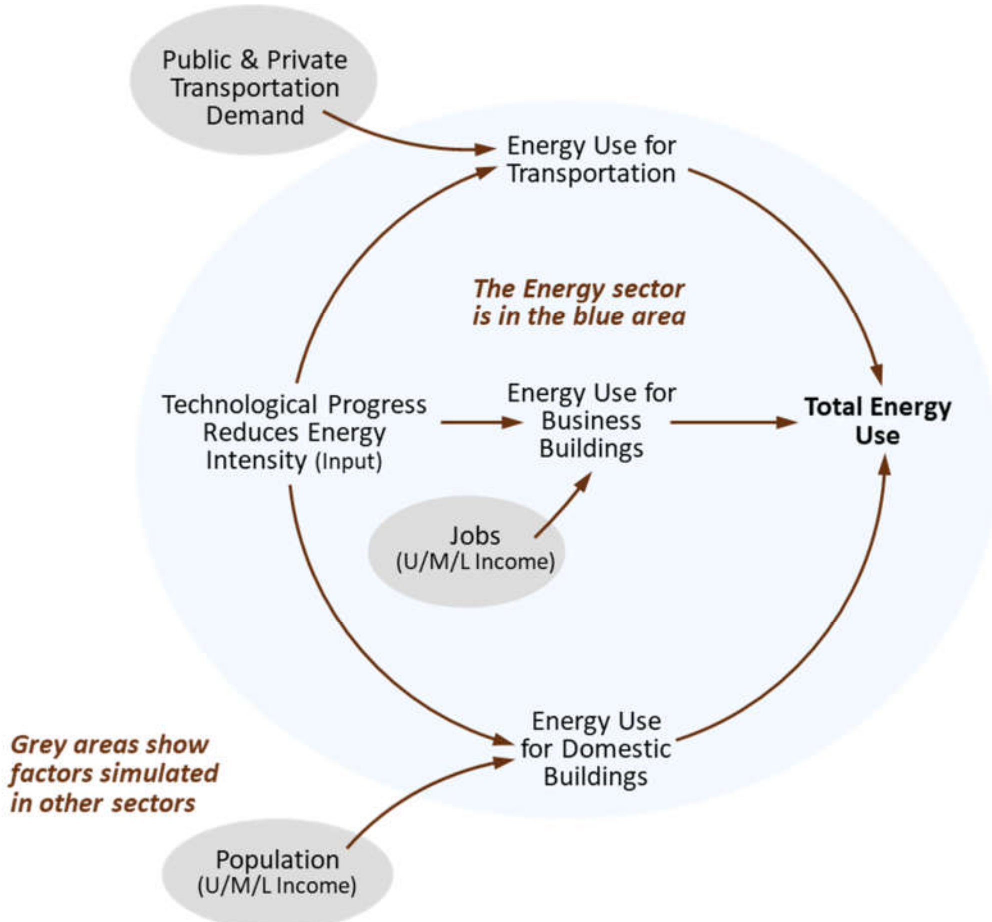

Figure 35 – High-level view of the energy sector

9. Glossary

Technology / Modelling Terms	
AI (Artificial Intelligence)	*Computers operating so as to mimic human intelligence*
Agent-based modelling	*Simulating the actions and interactions of autonomous agents to assess their influence on the system as a whole*
Agglomeration effects	*Benefits that come when firms and people locate near one another together in cities and industrial clusters.*
Behavioural economics	*Application of psychological insights into human behaviour to explain economic decision-making*
Big Data	*Use of advanced analytics to extract value from data*
Brexit	*Britain's exit from the European Union*
Brownfield redevelopment	*Repurposing and redeveloping former industrial sites*
Cost-Benefit Analysis	*A systematic process for calculating and comparing benefits and costs of a policy or project*
Decarbonisation programme	*The GLA's programme aiming at 90% reduction of greenhouse gas emissions by 2050 (relative to 1990 levels)*
Econometric modelling	*Application of statistical methods to economic data to quantify relationships and forecast performance*
Exchange trading	*An exchange is a market for trading securities, with centralized communication of bid and offer prices to all market participants and clearing facilities through which trading activities are concluded*
Fiduciaries	*A fiduciary is responsible for acting on behalf of others based on a relationship of trust and confidence*
Gross Domestic Product (GDP)	*A monetary measure of the value of goods and services produced in an economy in a given period of time*
Gross Value Added (GVA)	*Similar to GDP, equal to economic output minus intermediate or input consumption*
Higher-level governments	*Levels of government above that of local communities*
Institutional investors	*Entities which pool money to purchase assets or make loans*
Liquid and Illiquid assets and markets	*Liquid assets can be sold quickly and without a substantial loss of value due to ready availability of willing buyers; illiquid assets are the opposite. Liquid markets are ones in which ready availability of buyers ensures quick asset sales without substantial loss of value; illiquid markets are the opposite.*
Long-dated assets	*An asset producing a long-duration income stream*
Net Present Value (NPV)	*A measure of profit or value reflecting the time value of money*
Scientific method	*An evaluative procedure characterized by systematic observation, measurement, experiment, and the formation and testing of hypotheses*
Socioeconomic system	A *socioeconomic system* is one in which people and institutions interact in attempting to achieve their objectives
System Dynamics	*A method for understanding and evaluating the behavior of complex dynamic systems through computer simulation*
Vensim	*Commercially available software for developing and running dynamic simulation models*
Verticals; vertical models	*Organizations or departments focused on a specific function or discipline (e.g. housing, transport, demographics); computer and other analytical models that are similarly focused*

Technology / Modelling Terms	
Whole-System Models	*Computer models representing the whole of a dynamic system*