Sprawl Dynamics

“its drivers, and where to intervene”

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Chapter 1: Introduction

1.1 Background

The inspiration behind this work was spurred by my stint as an intern at the OECD with the Climate Change Mitigation Team of the Environment Directorate, which coincided with the writing of this thesis. The team had created a climate policy oriented report on transportation and mobility, *Transport Strategies for Net-Zero Systems by Design* (OECD, 2021). Drawing on the scientific literature and using qualitative systems approaches, they detailed how decades of policies focused on *mobility*, rather than *proximity,* has fostered car dependency and the erosion of public transport and other sustainable modes in and around cities.

A large part of their argument centres around *urban sprawl* and how it is interlinked with transportation (OECD, 2021, pp. 97-118). In the literature urban sprawl has been proven hard to define (Rubiera-Morollón & Garrido-Yserte, 2020, pp. 2-3), which warrants a discussion all of its own further on (see: section “1.2.1 What is urban sprawl?”). For the nonce, the phenomena can simply be explained as the outward geographic expansion of cities (Rafferty, 2021). This process creates larger distances between people and places of interest and a more dispersed population. Public transport is typically less efficient within such a sprawled urban form because each train station or bus stop caters to fewer people, and thus people must rely on cars for a larger portion of their trips (OECD, 2018, p. 129). That of course means that people will drive further on average than those who live in denser urban environments. The increasing distances between people and places one might go are generally not conducive to active modes of transport like walking and cycling either (OECD, 2018, p. 124). The increasing traffic volume that follows creates the pressure to continue expanding the road network, thereby opening more of the hinterlands for suburban development and creating a viscous cycle that reinforces car dependency (OECD, 2021). Since cars are generally more polluting than public transport, and active modes, this dynamic is less than favourable from an environmental perspective.

Upon the completion of *Transport Strategies for Net-Zero Systems by Design* (OECD, 2021), the chosen next step for the Climate Change Mitigation Team was to create a second report exploring residential sectors and their emissions, and delving deeper into the dynamics of urban sprawl by building on the insights from the completed report on transport. I was brought on board at the preliminary stages of this work with the express intention to integrate system dynamics more deeply into their process. That was the impetus for this thesis.

Two core influences on the thesis must also be mentioned before moving onto the research review. First, one of the main reasons for creating the reports just discussed is so that they can serve as toolkits for real-world policymaking through "case studies" carried out for, and with, OECD member states. Such a case-study was commissioned by the Irish Climate Change Advisory Council (OECD, 2022) before I joined the team. That project involved developing policy packages designed to reach the country's climate goals. Being actively involved in the project led to the choice of Dublin as the case for this thesis. The second influence concerns the structural hypothesis of the thesis; the causal loop diagrams (CLD) in *Transport Strategies for Net-Zero Systems by Design (OECD, 2021, p. 100),* and the qualitative modelling exercises the we did for the Irish case study, which greatly influenced the direction of the quantitative model developed for this thesis.

1.2 Research review

1.2.1 *What is urban sprawl?*

The word "sprawl", as Gordon and Richardson (1997) puts it, "conjures up connotations of […] an unaesthetic, lazy and undisciplined form of body expression" (p. 99). Having to describe the urban form as such is inconvenient; a less pejorative, and more neutral term would be preferable in a scientific context. However, the term is at this point thoroughly established in the literature and in policy circles. It has been used as a description of the urban form since 1937, when it was coined by one Earle Draper (Nechyba & Walsh, 2004, p. 177). So, there is no getting away from it at this point, but what is it?

Urban sprawl happens when houses are built further from each other and from the inner city, but it is not simply a loss of population density. Consider a "functional urban area" (FUA) containing an inner city, its metropolitan area, and the furthest reaches of its commuting zone; the inner city can experience densification at the same time as low-density areas are being developed in the periphery. In this way, densification can *hide* urban sprawl (OECD, 2018, p. 12). So, the organisation of economic and residential land-use in an area is more relevant than population density where urban sprawl is concerned.

Given the different uses of the term sprawl over the years any "non-compact" development can qualify (Ewing, 2008, p. 519), but in an attempt to pick up the nuances of urban sprawl the definition by Anderson et al. (1996, p. 12) will be used – with slight modifications to point iv. According to their work the phenomena is the fundamental transformation of a region's urban form characterised by:

i. an outward expansion of the metropolitan (commuting zone) boundary that separates urban from rural land uses;
ii. a general decline in intensity of all forms of land uses, as measured by population and employment densities;
iii. transport networks that provide high connectivity among points, even in peripheral parts of the city; and
iv. the segregation of residential from other land uses, with residences locating increasingly in peripheral areas

1.2.2 *Observed sprawl and its effects*

In many countries suburban living was first made possible on a larger scale with the introduction of rail transport in the nineteenth century. Back then, cities often expanded along the newly laid tracks, and this created some of the earliest modern forms of urban sprawl (Lewis, 1991, p. 166). However, not until the 1950s and 1960s did we see *rapid* acceleration in suburbanisation – especially in the United States (Anderson et al., 1996, p. 13). This period saw the popularisation of the private car. Rising incomes and more affordable cars allowed people to move to places further away from their place of work, and for developers to build residential areas with less regard to public transport coverage (Anderson et al., 1996, p. 12). One of the more extreme and interesting manifestations of this can be observed in the American desert. In a lecture he held at the University of Agder, Professor Tor Geir Kvinen (2017) noted after his visit to Phoenix that everyone there lived in a "closed airconditioned system", which could only exist because of the private car!

The last OECD report on the subject of urban sprawl, Rethinking Urban Sprawl (2018), found that out of 29 member countries, population density had declined on average in 14 of them between 1990 and 2014. But as discussed, density does not tell the whole story; there has in the same time period also been "a substantial increase of the share of urban developed surfaces hosting residential areas of very low density" driven by suburbanisation (OECD, 2018, p. 66). This has occurred in 20 out of 29 member states. 18 countries also experienced increased fragmentation of urban areas and in many of those countries sprawl has "co-evolved" with densification; countries like Greece, Ireland, Spain and Sweden and the United Kingdom all saw their low-density areas grow faster than their high density ones (OECD, 2018, p. 12).

1.2.3 The scientific literature on sprawl, its detrimental effects, and drivers

Within the field of system Dynamics there has been little focus spent on urban sprawl – which makes this thesis project an interesting attempt. Searching the database of the System Dynamics Society did not produce a single published journal paper. After extensive searches elsewhere only Eppink et al. (2004) could be found. It explores the interaction between land use and wetland biodiversity. That paper did not explore the drivers of sprawl however, as this thesis is intended to do. Lastly, the conference paper by Sanders and Sanders (2004), *Spatial Urban Dynamics: A vision on the future of urban dynamics* should be mentioned. This paper could not be sourced for this thesis, but according to Eskinasi (2014) they explored adding a spatial dimension to Urban Dynamics by Jay W. Forrester (1969) – similarly to the model developed for this thesis.

The system dynamics literature on housing in general is more impressive. Using system dynamics modelling to explore city development goes back to the 1960s and the fields founder Jay W. Forrester and his aforementioned seminal work, Urban Dynamics (1969). This book remains a cornerstone in system dynamics modelling. The work since then that has embedded system dynamics in housing research has been compiled and catalogued by Martijn Eskinasi in his PhD *Towards Housing System Dynamics* (2014). He makes clear that a system dynamics knowledge base exists on housing, real estate, and urban development, but that unfortunately it is fragmented and not connected to mainstream urban research (p. 45).

Eskinasi (2014) also identifies four "groups" representing four different research streams in the area; the Urban Dynamics Group, the Dutch Housing Group, the Real Estate Dynamics group, and the Isolated Research Group (Eskinasi, 2014, pp. 46-57). The first of which, the Urban Dynamics Group, is the one relevant for this thesis. It builds on Forrester's *Urban Dynamics* (1969). A lot of the work in this group applies the Forrester's model, or modified versions of it, to various cities for policy purposes (e.g., Braden, 1994; Kuroda & Tsaur, 1990) (Eskinasi, 2014, pp. 49-51). This group includes works such as Alfeld and Graham's book *Introduction to Urban Dynamics* (1976) in which they develop URBAN1, a simplified version of Forrester's model. Both the original model by Forrester and URBAN1 has heavily influenced the model developed for this thesis. However, those works were focused on the health of cities from an economic perspective; their modelling work was concerned with indicators of growth, stagnation, and decline. This thesis, as will become clear, includes many of the same mechanisms, but is squarely focused on urban sprawl.

The main source of data and theory comes from the literature on urban sprawl outside of System Dynamics. It's a field that stretches back to Earle Draper and his coinage of the term "sprawl" as it relates to the urban form in 1937. In the mid twentieth century, Jane Jacobs (1961) in her book *The Death and Life of Great American Cities,* was one of the earlier critics of urban sprawl. She called attention to the inefficiencies of scattered and dispersed urban development in North America as she saw it. Jacobs was one of the first to observe and document that the trend towards dispersed suburban development in the periphery of metropolitan areas was accompanied with heavy investments in highways (Rubiera-Morollón & Garrido-Yserte, 2020, pp. 1-2). Historically, the divide in the literature has been between those who see sprawl as unsustainable culturally and environmentally, and those who think it benign. Jacobs was of the former camp believing that sprawl could lead to less creative and more dangerous environments. Perhaps the most well-known critique of this view is the widely cited *Are Compact Cities a Desirable Planning Goal?* (Gordon & Richardson, 1997) which, partly on empirical grounds, discounts the fears of those who would rather see cities become more compact.

In later years there has been a renewed interest in urban sprawl and the recent literature produced is increasingly siding with Jacobs (Rubiera-Morollón & Garrido-Yserte, 2020). Advancements in digital technologies have allowed much more precise analysis of the phenomenon. Conclusions that had been drawn on a theoretical basis can now be revisited and strengthened or revised with more accurate empirical support. However, the main reason political scientists, urban planners and the like are drawn to study urban sprawl once again can be attributed to the ever-increasing concerns over climate change and environmental impacts of human activity – i.e., "the close relationship that exists between sprawl and the environmental efficiency of cities" (Rubiera-Morollón & Garrido-Yserte, 2020, p. 2). This more recent research seems to have moved the scientific consensus further towards an understanding of sprawl as being an unsustainable dynamic, not only from a cultural point of view, but from an environmental point of view as well. International organisations generally mirror this view (The World Bank, 2020; OECD, 2018; UN, 2012).

1.2.4 The detrimental effects of sprawl

The observation that sprawl is generally undesirable derives from the theoretically proposed and empirically observed negative consequences of the phenomena – some of which will be mentioned here. The first to consider is the aesthetic consequence; the loss of open green countryside and farmland to concrete and asphalt construction that has "hard to measure" effects on well-being (Glaeser & Kahn, 2004, p. 2485). This is not to say that cities or suburban landscapes cannot be beautiful; however, retail parks, malls and highways rarely are, and the construction of these draw people and economic activity out of the city centre (Dwyer & Childs, 2004, p. 154) and robs it of its dynamism.

The loss of inner dynamism is significant, because the cultural, social, and economic dynamism of the inner city is its main draw (Rubiera-Morollón & Garrido-Yserte, 2020, p. 6). Frequent social events, rich cultural offerings and great economic opportunity is less likely to flourish as a population becomes more dispersed. Fundamentally, cities exist and grow as a result of the agglomeration economies that *proximity* yields; when a lot of people live close together, there is more opportunity to pool resources, cooperate, specialise and compete (Giuliano et al., 2019, p. 377).

There are also health concerns related to urban sprawl. Sturm and Cohen (2004) found that sprawl "significantly predicts chronic medical conditions and health related disorders, but not mental disorders" (p. 488). The proposed mechanisms include reductions in physical activity brought on by the increase in car reliance that sprawl brings with it, and the air pollution that the cars produce (p. 494). Air pollution in particular brings us to the main concern that led to this project: Sprawl's effect on the climate and environment.

Cities that are known to have sprawled considerably, e.g. Los Angeles and Houston, have also had big problems with smog (Glaeser & Kahn, 2004, p. 2513), and while Los Angeles' transport emissions per capita is not especially high, Houston's is among the highest in the world (Rubiera-Morollón & Garrido-Yserte, 2020, pp. 9, figure 3). As the population becomes more dispersed, mass transit (a more sustainable mode of transport from an environmental perspective) becomes less and less efficient because each train station and bus stop must cater to fewer and fewer people, and each trip must make more stops as well. This reduction in public transport "adequacy" pushes people towards car usage. This is reflected in global fuel consumption which can easily be seen by comparing the per capita fuel consumption rates of the US (highest), Europe (middle), and Hong Kong (lowest), where the US is generally considered to be the most sprawled, Europe somewhere in the middle and Hong Kong the least (Breheny, 1996, p. 23). The environmental concerns surrounding sprawl also extend to housing itself; generally speaking, the further out from the inner city houses are, the more affordable they become and larger homes can be had for less. Larger detached houses are less energy efficient than the multi-unit buildings common to city centres. In the US for example, one of the main drivers of emissions from the residential sector is the construction of larger and larger homes (Berrill et al., 2021, p. 9).

1.2.5 The drivers of sprawl

Several of the negative aspects to sprawl have been discussed, but that does not mean that there are not positives; there are reasons why people chose the periphery for their dwelling. A lot of people prefer lower density areas (Gordon & Richardson, 1997, pp. 96-97). First, the urban periphery in most cases provide levels of space, comfort, and privacy that the inner city can never match. For example, one can have a larger dwelling, often with a garden, for a relatively lower price than in the inner city. It is also easier to use and own a car in lower density areas; there is generally less traffic, and personal parking spaces are much cheaper. Additionally, both larger homes, and a personal car offers more privacy (OECD, 2018, p. 17).

There are also the natural amenities that the suburban living often provides. For example, local visibility is better because of fewer tall buildings. For the same reason one can get more exposure to sunlight when tall buildings aren't in the way (OECD, 2018, p. 115). There are also more open spaces to enjoy, which people are willing to pay for (Turner, 2005, p. 20). This is reflected in the observation that land conservation policies indirectly encourage development in surrounding areas (Geniaux et al., 2011; Irwin & Bockstael, 2004). Areas right on the divide between urban and rural areas are especially attractive because one can enjoy the natural world while not being too far removed from the opportunities of the inner city. In this way, the rural-urban fringe has a so called "pull-effect" (Roe et al., 2004). In less densely populated areas families can also enjoy relatively higher environmental quality; there is generally less air, water and noise pollution, and the biodiversity is higher – important factors for many.

Individual preferences like the ones just discussed are considered drivers of sprawl, and so are rising incomes, and government policies (OECD, 2018, pp. 113-122). However, most important are the conditions that allow for these things to manifest themselves as sprawl which are the construction of roads and houses in the urban periphery and the means to use and access them. There may be many drivers of sprawl, but there is one fundamental cause, the automobile (Glaeser & Kahn, 2004, p. 2483). The car, perhaps since the Ford Model T from 1908, became the superior mode of transport (given enough road capacity to use them). The Ford was affordable enough for the factory workers who built them to buy one, and for the first time a middle-class family could go anywhere, at any time, much faster than before, and in more comfort and privacy (the T-Ford was perhaps not especially comfortable, but it did not take long until cars generally were).

As has been discussed in previous sections, the available modes of transport have always been closely linked with the development of the urban form, and the explosion in automobile use and highway expansion in the mid twentieth century onwards is generally acknowledged to have had the largest effect (Anderson et al., 1996, p. 12; Gordon & Richardson, 1997, p. 100; Jacobs, 1961). With expanding highway systems, the barrier of distance increasingly "dissolved" (Gordon & Richardson, 1997, p. 100) and car owners could locate their families further away from their place of work without regard to public transport accessibility (Anderson et al., 1996, p. 12; Webber, 1994, p. 27); for the first time, scattered development could occur on a large scale.

1.3 Relevance of the thesis

With over half the world's population living in cities (UN, 2018), making them sustainable is paramount. Great progress has been made on the technological front; houses are better insulated, and cars are more efficient. However, cities are sprawling; the populations of major urban areas are moving further and further away from the inner city (OECD, 2018). That means a heavier reliance on cars, loss of public transport efficiency, detached and larger homes and thus a less energy efficient residential sector.

High efficiency vehicles, synthetic combustible fuels, and superior insulation are impressive results of reductionistic and analytical sciences. Promoting these technologies and their diffusion are among the most common climate strategies. Their promotion is however, in most cases, a focus on *parts*, and therefore neglect the wider system they are a *part of*. Approaches that don't consider the system often fall prey to "policy resistance" – i.e., the unintended, and unwanted, systemic reactions to one's intervention (Sterman, 2000, p. 11). Consider the rebound effect; As vehicles become more energy efficient – as the result of any mixture of market forces and government policy, say – vehicle costs goes down, making driving more attractive, thereby increasing the total vehicle traffic (Litman, 2017, p. 2)! All else equal, there would be a reduction in emissions proportional to the gains in efficiency, but all else is never equal – the system exhibits delays and feedbacks that *partly* counteracts well-intentioned policies and innovations.

A similar story exists in the residential sector. In their 2021 paper, Berrill et al. looked at the emissions data from the United States residential sector and found total greenhouse gas emissions (GHG) from the sector have decreased by an average annual rate of 2% per year (p. 2). The paper focused on identifying the main drivers of change in energy consumption that could explain this development over time. They found that reductions in the GHG intensity of electricity, partly as the result of changes to primary energy sources, were a powerful downward driver of emissions. However, they also found that reductions in household size and increases in the total floor area per capita were powerful upward drivers (p. 9). This is another situation where a powerful technical solution is opposed by influences elsewhere in the system. So, technical solutions are not enough in themselves if they are offset by high demand, energy intensive modes of living if maximal reductions in total GHG emissions is the goal.

As discussed, these high demand, energy intensive modes of living are partly a result of the sprawled urban form – which produces larger homes, and longer commutes by car. As has been laid out above, this connection is well known. For many decades the effects of local and regional socio-economic developments and transportation infrastructure on land use have been studied. However, simulation modelling of the feedback between these elements is less common (Verburg, 2006, p. 1173). This is an opportunity for furthering the state of the art, as system dynamics is perfectly suited to study the complex nature of "sprawl dynamics".

Above, people's preferences and behaviour, transport infrastructure, inner city economic opportunities and housing availability have all been mentioned as elements relating to sprawl. It will be shown below that these elements all interact with each other in non-intuitive ways – it's a complex system fraught with non-linearities. Non-linear systems are notoriously hard to reason in and around (see: Meadows, 2008), which is why we use system dynamics, so that we can simulate and test our assumptions and learn where and how to intervene (Sterman, 2000, pp. 37-39). Technological gains are moving the needle on emissions reduction, but sprawl dynamics are holding it back. We need to make certain that we don't offset all the wonderful technological innovations already here, and those on the horizon, with the potential to improve all our lives. To do so we need a deep understanding of the system, and the good sense to challenge our assumptions and behaviours.

1.4 Reference modes and the Irish context

For reasons already explained (see: section 1.1 Background) the Greater Dublin Area has been chosen as the reference case for the simulation model. Ireland has very ambitious climate goals. They aim to reduce emissions from their transport- and residential sectors by 42-50% and 44-56% respectively. They put forth funding for retrofitting homes, building new public transport, and incentivising electric vehicles as main strategies for achieving their desired climate outcomes (Department of the Taoiseach, 2021). I argue that this is a focus on *parts* without considering *systems*. It is interesting therefore to understand how the urban form of the largest metropolitan area of Ireland could develop in the future so that we can better understand in what context these new policies will be applied. Equally interesting to this project is understanding *how* the Greater Dublin Area got to where it is in terms of sprawl.

So, how has Dublin developed over time? Dublin is an old city, a thousand years old or thereabouts (Joyce, 2010). The model will not consider the very large majority of that history but will instead span a time horizon of 36 years, from 1996 to 2032. This time horizon was chosen for three reasons: Data for many important variables did not go back further than 1996; the population projections used for model calibration did not consider further ahead than 2031; and 2032 is ten years away from when this thesis is written (a nice and round number). The relevance of people, road infrastructure, the car fleet, the job market, and housing have been discussed at length already, and the stocks in the model reflect these elements, and so will the reference modes the model has to replicate. The reference modes are based on data on the Greater Dublin Area from the Irish Statistics Office spanning the years 1996 to 2016, except for some of the population data where official population projections until 2031 were available.

The reference modes and the model will consider Dublin's "functional urban area" (FUA) which includes its inner city, its metropolitan area, and the complete commuting zone (Dijkstra et al., 2019). Figure 1 below is a visual representation of a FUA where each level grows concentrically outward from the inner city. Data on population and housing, and the corresponding stocks in the model, will consider each level of the FUA alone – i.e., the inner city, the metropolitan area excluding the inner city, and the commuting zone excluding the metropolitan area and the inner city.

Reference modes and model stocks relating to road infrastructure and car ownership will apply to the whole FUA. Business construction and economic opportunity concepts will only be considered in the inner city. Because of data availability, the different levels of FUA will be separated by county boundaries: Dublin City represents the Inner City, what was previously County Dublin excluding Dublin City (now, South Dublin, Dún Laoghaire–Rathdown and Fingal) represent the metropolitan area and the first commuting belt, and the Greater Dublin Area excluding County Dublin (counties Meath, Kildare and Wicklow) represent the Commuting Zone and the second commuter belt.

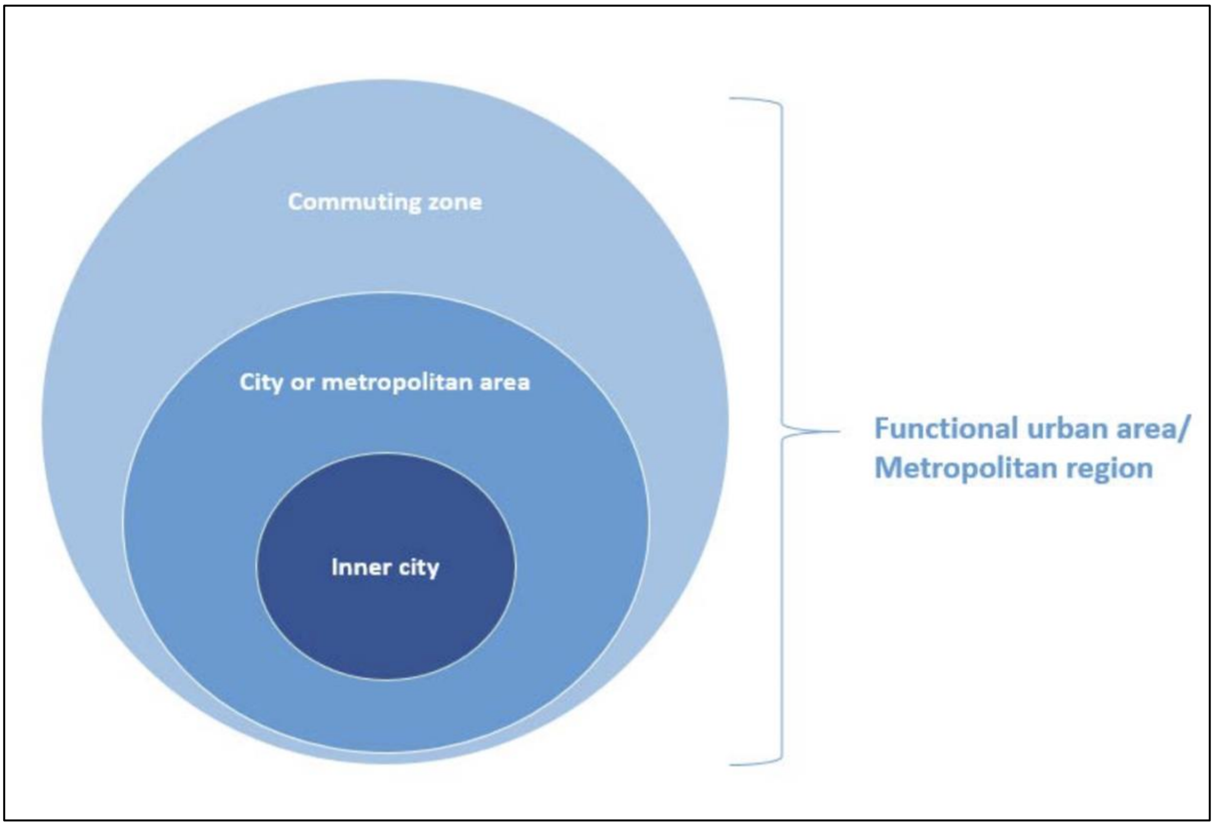


Figure 1 - functional urban area visual representation (Figure 4.7 of OECD, 2021, p. 108)

Quantitative data were found for all the reference modes, but only for specific years. In the reference mode graphs below the raw data will be shown as "dots" with "dotted lines" of linearly interpolated data connecting them. While some the interpolations seem to reveal specific behaviour modes (goal-seeking, s-shaped, etc,) the relative scarceness of data makes it inappropriate to draw any inferences from it. The logic of the structural hypothesis, and the simulation results it produces, will give us firmer ground on which to claim what historic and expected future behaviour modes might look like.

It is the construction of housing – specifically *where* it is constructed – that is most interesting, since that will be our measure of sprawl. Below, in figures 2, 3, and 4, data on the housing stocks of Dublin City is presented. We see that for all three regions of the FUA, the housing stock has increased. However, looking at Figure 5 we see that the two outer commuting belts, the outer metropolitan area, and the commuting zone have grown considerably faster than the inner city.

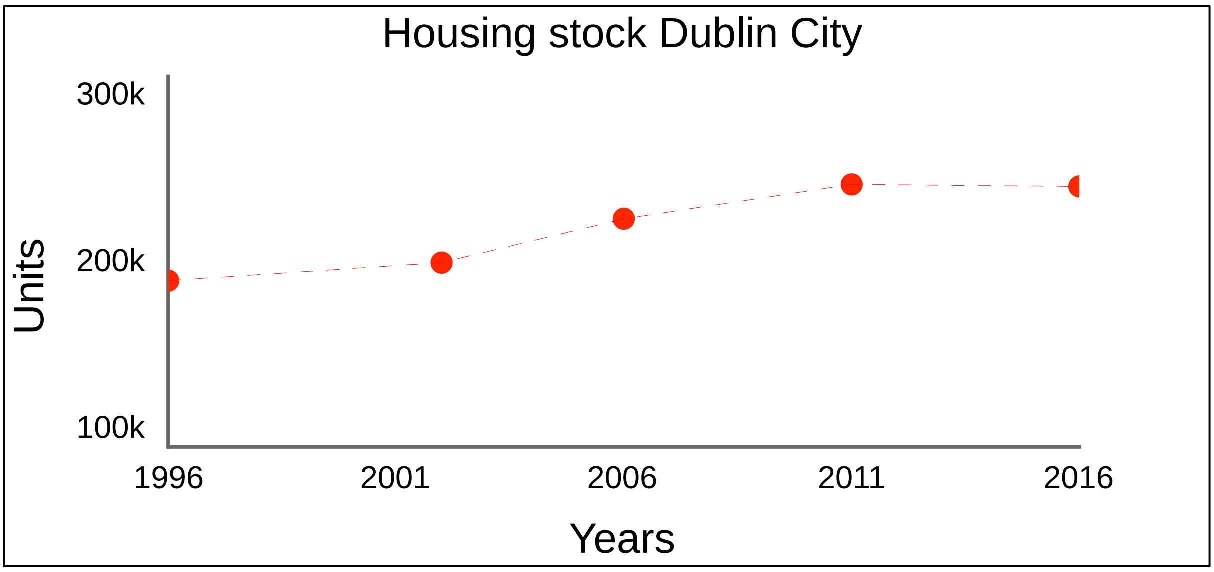


Figure 2 - reference mode: housing stock Dublin City (raw and interpolated data) (CSO, 2016b)

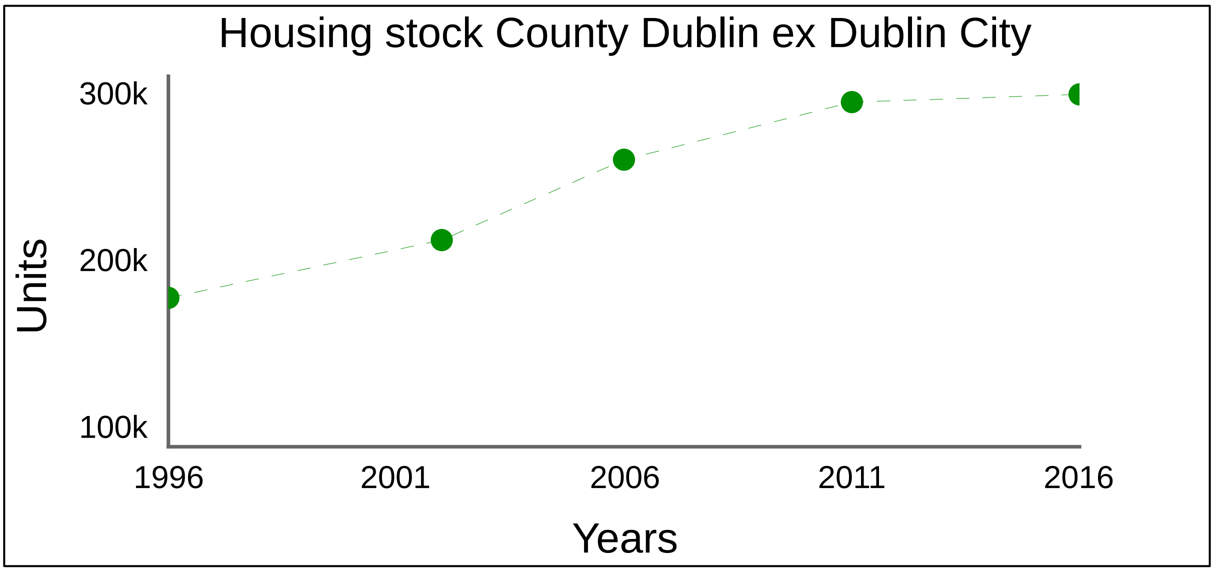


Figure 3 – reference mode: housing stock County Dublin (raw and interpolated data) (CSO, 2016b)

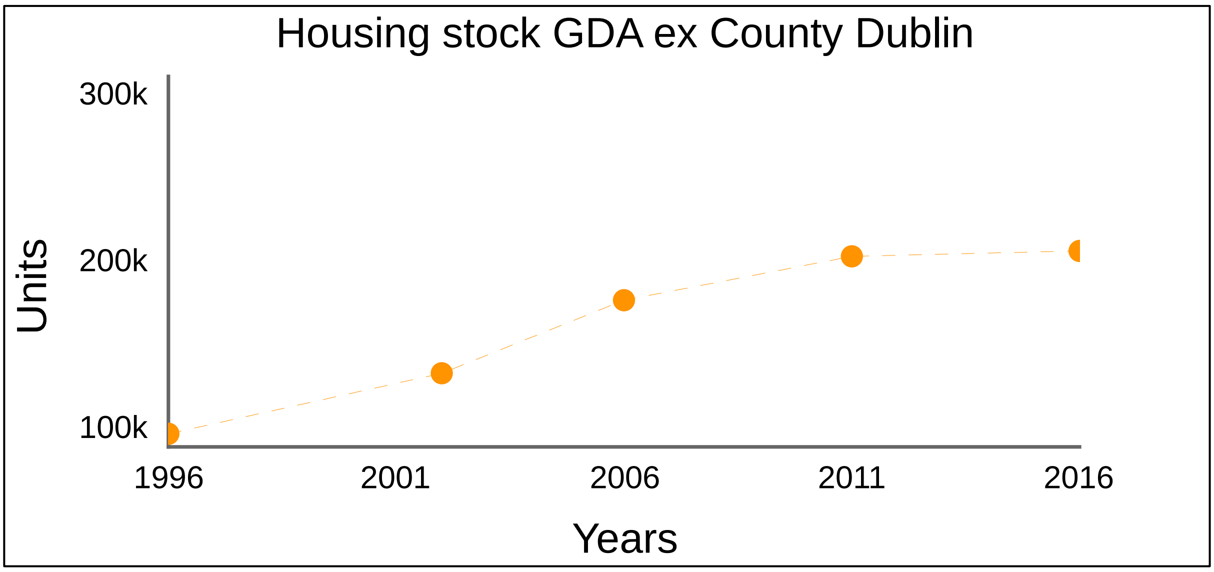


Figure 4 – reference mode: housing stock GDA ex County Dublin (raw and interpolated data) (CSO, 2016b)

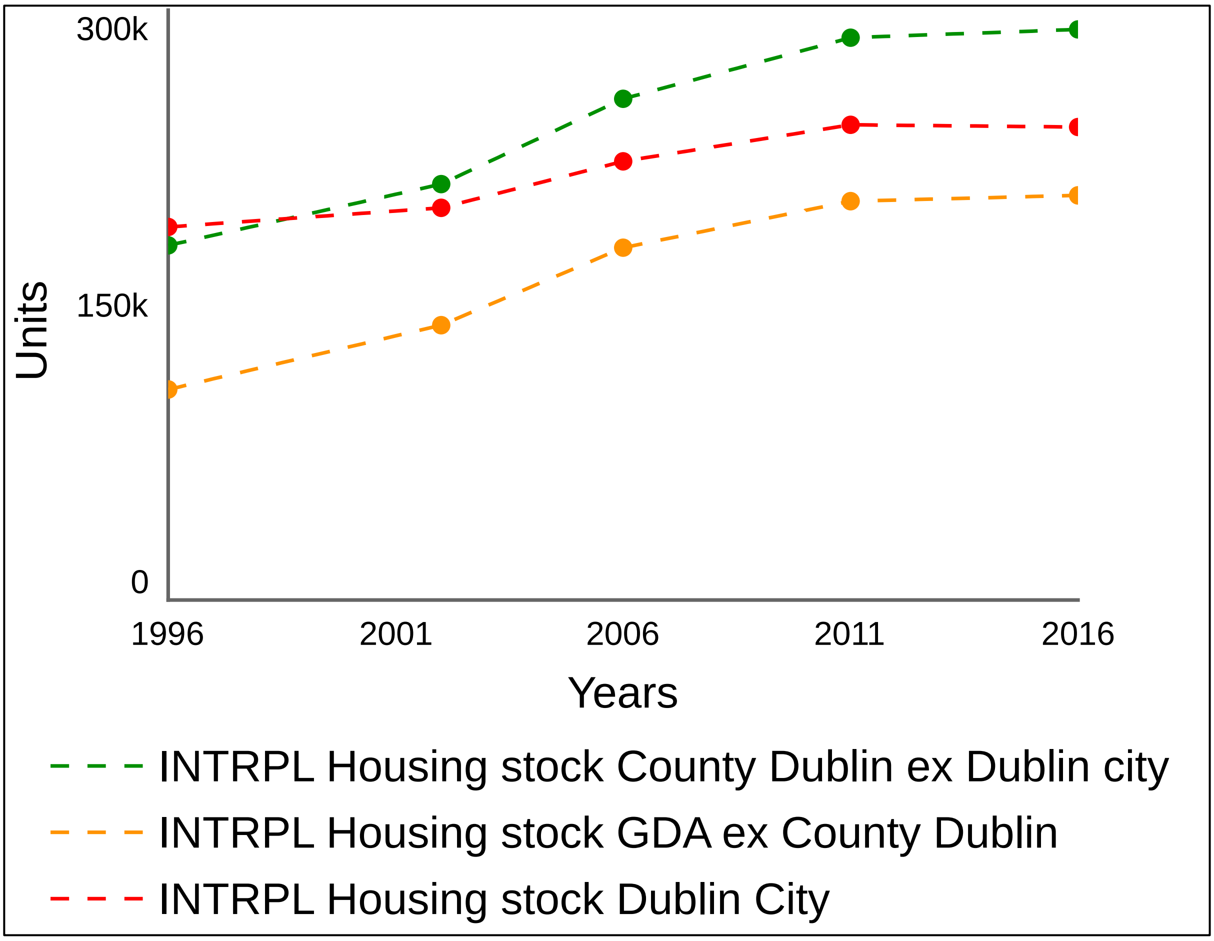


Figure 5 – reference mode: Housing stocks FUA compared (interpolated data) (CSO, 2016b)

So, the Greater Dublin Area is another case of sprawl hiding behind, or at least having coevolved with, densification of the inner city – which is in line with OECD (2018, p. 12) findings. It may seem from the interpolated data in Figure 5 that growth is slowing down for all three regions, but keep in mind that there are only 5 data points for each of the curves, so conclusions are hard to draw on that basis. Looking to the population data and projections we get a better sense of what we can expect in terms of regional development.

Population projections for Dublin City as separate from County Dublin could not be sourced but looking at Figure 6, which includes all of County Dublin including the inner city, we get an indication that the growth in those areas seems to decline based on the population projections for the years 2026 and 2031 (CSO, 2016e). From Figure 7 however, we see the opposite; the outermost commuting belt is expected to grow faster than before, at least until 2031, based on official Irish projections. This gives us further indication that the FUA will continue to experience sprawl.

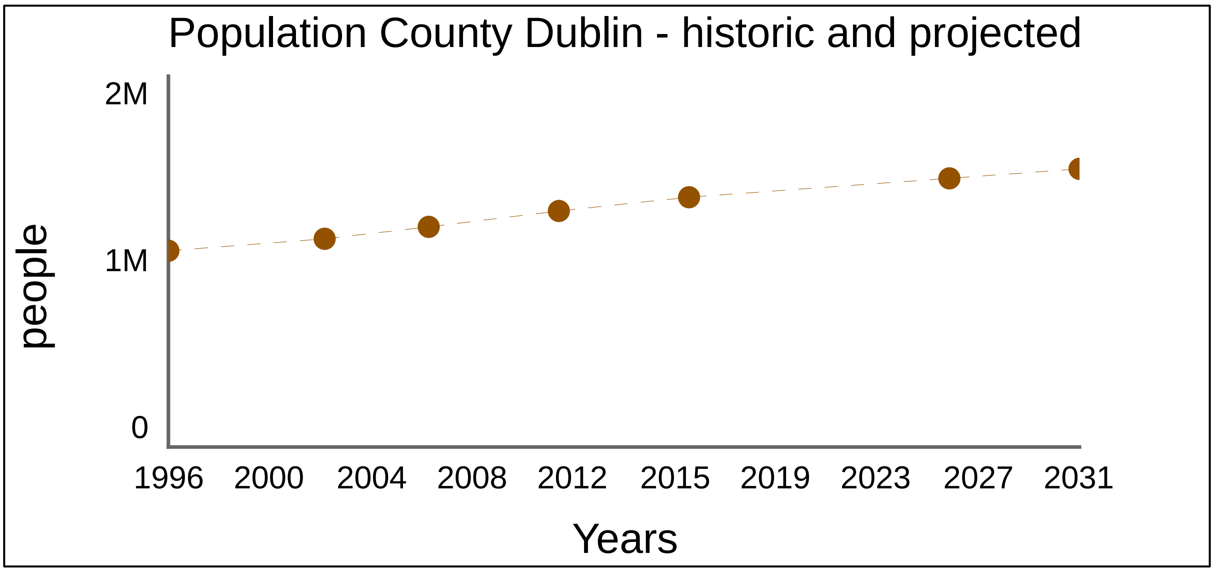


Figure 6 – reference mode: Population County Dublin (raw and interpolated) (CSO, 1996, 2016d, 2016e)

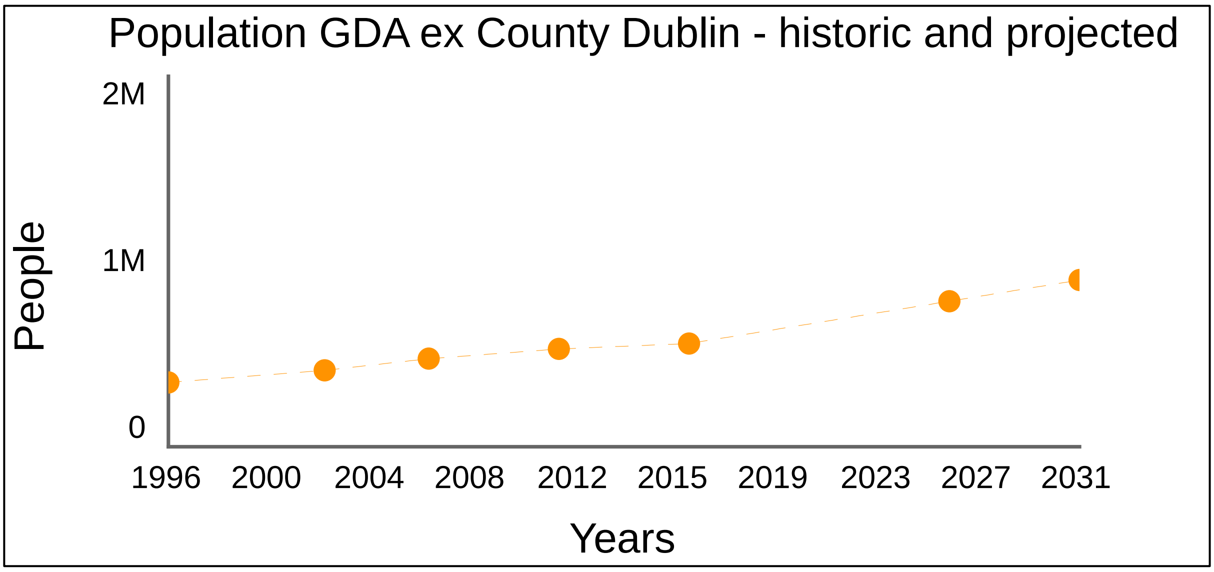


Figure 7 – reference mode: Population GDA ex County Dublin (raw and interpolated) (CSO, 2016d, 2016e)

In line with the sprawl observation, there is also data indicating that workers traveling from outside the city has increased in the same period (Figure 8). The number of commercial buildings in Dublin City has also increased (Figure 9). This variable serves as proxy for economic opportunity, so when it increases that means there are more job opportunities which is what draws people to the inner city and its surrounding areas. The number of people who choose to commute by car in the country (direct data on the GDA were not available, so country statistics will function as a proxy – the differences inside the country are not especially large (CSO, 2016a)) has also increased in the same period as the region has sprawled (Figure 10) – not surprisingly given the close link between sprawl and car use discussed at length in the literature review above.

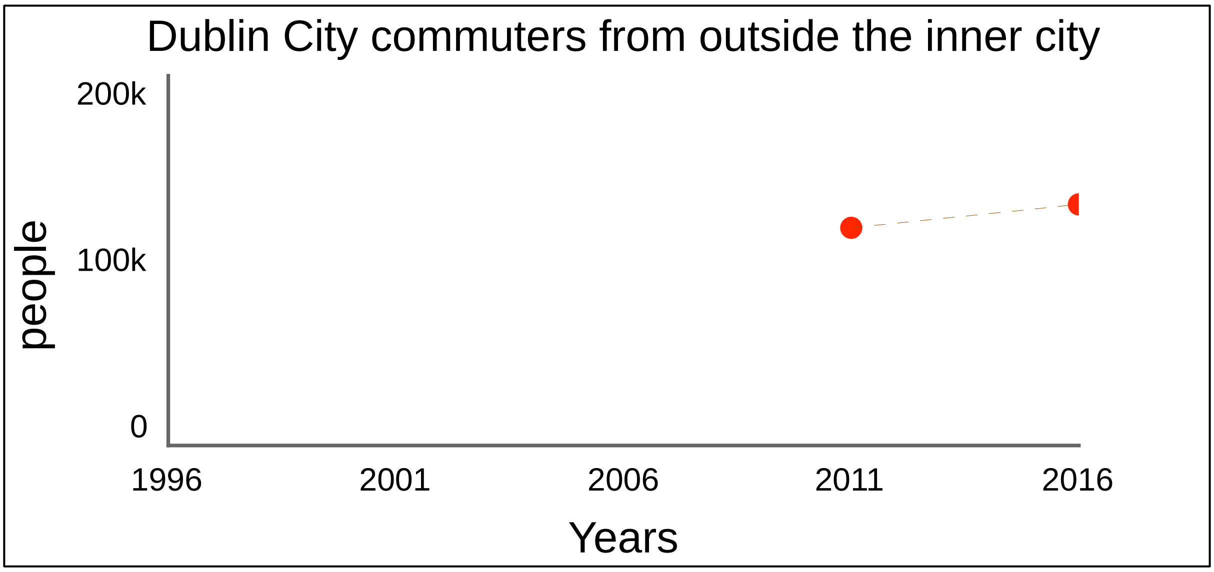


Figure 8 – reference mode: Dublin City commuters from outside the inner city(raw and interpolated)(CSO, 2016a)

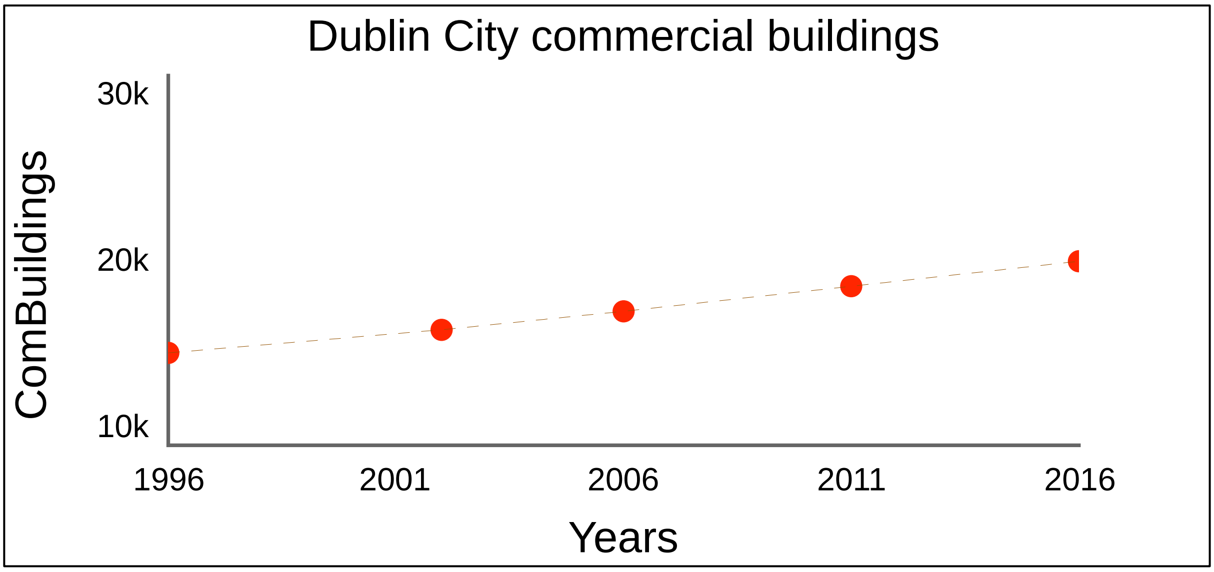


Figure 9 – reference mode: Dublin City commercial buildings (raw and interpolated) (CSO, 2019)

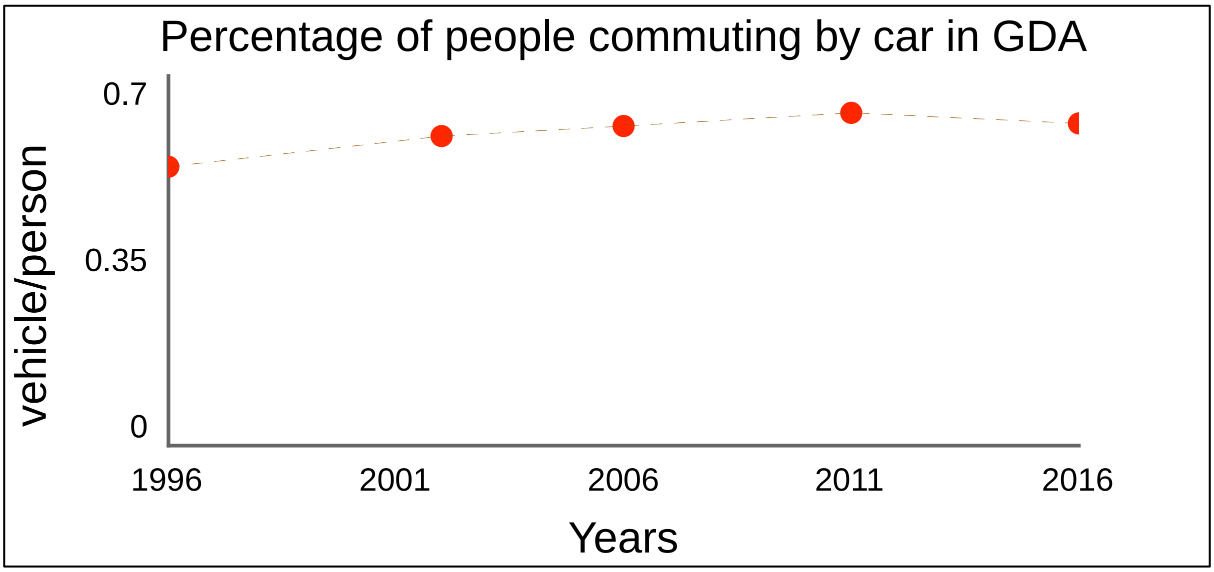


Figure 10 – reference mode: Percentage of people commuting by car in GDA (raw and interpolated) (CSO, 2016a)

1.5 Research questions and objective

Given that the dynamic of urban sprawl likely contributes to unsustainable emissions from the residential sector, policymakers need tools for curtailing it. For those tools to be effective however, there needs to be a common understanding of what the system looks like. The primary research question is therefore:

- (RQ1) *“What are the endogenous drivers of observed urban sprawl?”*

Answering this question is also intended to shed light on the systemic effects of a policy that is already in place and has had the most “momentum”, namely building roads as the main response to rising congestion and travel times by car. To address this momentum policy, and support the primary research question, a secondary research is posed:

- (RQ2) “*What is, and has been, the effects of building roads on urban sprawl?”*

Thesis structure – how the research questions are answered

The thesis is divided into three chapters: “Chapter 1: Introduction”; “Chapter 2: Structural hypothesis and methodology”; and “Chapter 3: Model analysis and discussion” following the system dynamics method (see section “2.1 Methodology and process”) will in part allow for the research questions to be answered. The structural hypothesis and its validation (see sections “2.2 Structural hypothesis – why cities sprawl”, and “3.2 Model validation” respectively), but particularly the loop dominance analysis (see section “3.2.3 Loop dominance analysis and behaviour replication”), will answer RQ1. RQ2 will be addresses in these same sections as well but will be given special consideration in the section “3.3 Policy scenarios – effects of road construction and reallocation”. It should be noted however that policy implementation modelling and extensive policy recommendations is outside the scope of this project.

Each of the research questions will also be addressed directly under their own headings in the section “3.3 Results and discussion”. There the findings will be put into more context and explained.

Chapter 2: Structural hypothesis and methodology

2.1 Methodology and process

A simulating system dynamics model was developed for exploring the research questions. System dynamics is the study of complex dynamic systems and their behaviour. Cities in all their facets are highly complex systems, and as such they are ideally suited study objects from a system dynamics perspective. This is not surprising, considering the renown and longstanding relevance of Forester's *Urban Dynamics* (1969). Dynamic complexity arise from systems that are (among other things) governed by feedback, exhibit nonlinear relationships between elements, are adaptive, ever changing, resistant to policy and often counterintuitive (see Meadows, 2008; Sterman, 2000, p. 22). These characteristics are all present in the system under study for this project.

The structure of this thesis, and the modelling process, follows the steps outlined by Sterman (2000, pp. 83-105). Having identified the problem of urban sprawl, the research questions were formulated, and datasets were collected as reference modes that the eventual model would attempt to replicate. The research questions and the reference modes gave direction to the structural hypothesis and defined the boundaries of the model. Unlike so called "black box" modelling methodologies where the goal is to produce algorithms that predict outputs given some input (see: Townsend et al., 2018), system dynamics requires that relationships between variables to be made explicit such that behaviour over time can be explained with reference to the structure of the system. Those relationships were made explicit as a structural hypothesis that took the form a causal loop diagram (CLD). The simulating model in turn, was based on the CLD.

Inside the boundaries set by the research questions and reference modes, the CLD construction was informed by the literature laid out in the above research review, and then vetted on two occasions by experienced policy makers and experts in related fields (Eskinasi, 2022; Jaber et al., 2022). Based on the CLD a simulating quantitative model able to replicate the reference modes was built. The modelling process was iterative in nature, as the simulating model revealed inaccuracies in the assumptions of the initial CLD which prompted corrections to it. All numerical data was collected from the Irish Central Statistics Office, and available publicly (https://www.cso.ie/en/index.html). The data gathered benefitted the project greatly as it served as reference modes that the model was calibrated to.

The field of system dynamics has largely been concerned with the formulation and testing of policies, but as Gkini (2020) has remarked upon, “it […] has and will continue to be successfully used for the development and testing of theoretical insights” (p. 11). This project will have elements of both. The ultimate purpose is to understand how to limit or reverse urban sprawl with targeted polices. However, the process will also explore the theoretical potential of generic system archetypes (Wolstenholme, 2004) as a policy analysis and identification tool – an approach that remains experimental (Eskinasi et al., 2022).

2.2 Structural hypothesis – why cities sprawl

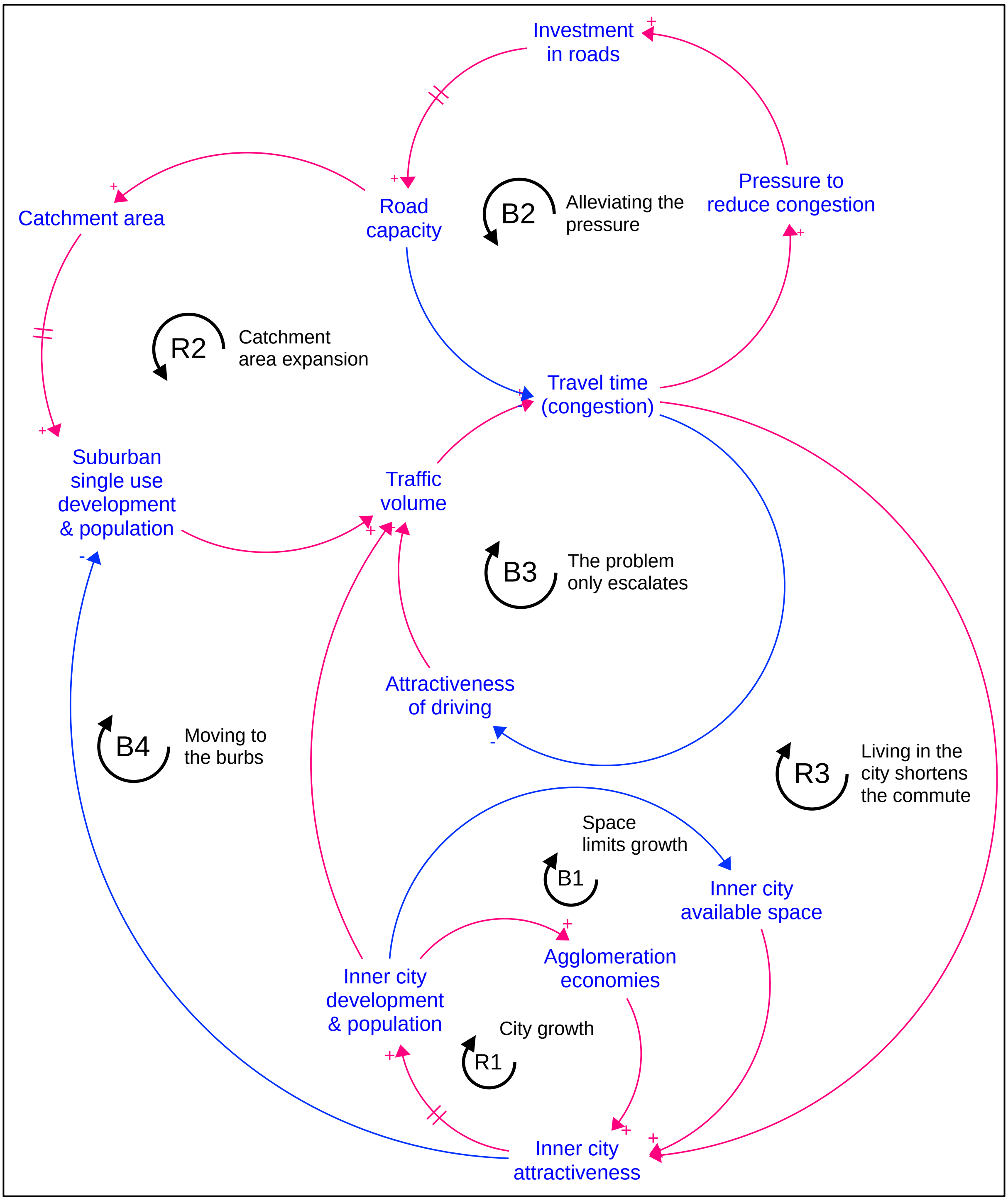


Figure 11– Structural hypothesis CLD: why cities sprawl

The below description is an attempt at telling the story of how cities sprawl. The text will reference the CLD in Figure 11 which captures the whole system. The text and the CLD is the hypothesis on which the thesis rests and it attempts to do two things: (1) piece together the information laid out in the above research review into a systemic representation capable of explaining the modes of reference; and (2) give a digestible visual and narrative explanation of the simulating model's logic. On the second point, it's very important to stress that the model is a lot more complex and disaggregated than the CLD. The CLD is not a perfect representation of the simulation model, but it is as accurate as it could be made while at the same time keeping it simple and readable. However, the full model documentation is available in "Appendix III: model documentation" and the model's stock and flow structure is shown and explained in the section 3.1 Model structure description.

City growth and its limits – R1, B1

Agglomeration economies will make cities attractive, and it makes them grow (R1: City growth). Nothing can grow forever though, and that holds for cities as well. As more and more residential and commercial buildings are erected land becomes scarcer and construction slows down (B1: Space limits growth). With scarcity comes higher housing prices, making the inner city become prohibitively expensive for many. In other words, gentrification will take place as lower income groups are kept out by an increasing cost of living. In addition, the population density can only be so high before the volume of people and cars reduces the perceived environmental quality of the city.

Reducing congestion – B2 and B3

To relieve the congestion of a growing city roads are built (B2: Alleviating the pressure). With increased road capacity, congestion and people's travel times are reduced. However, outside the mental model (or the "system boundary") of well-intentioned policy makers is the increased attractiveness of driving that comes from the reduction in congestion. As more roads are built it will attract more cars to the road, and as a result congestion will not be reduced nearly as much as intended, or not at all, which in turn will increase the pressure to build yet more roads (Hymel et al., 2010; OECD, 2021) - this is captured by "B3: The problem only escalates". This process by which the construction of roads creates more, rather than less, congestion is referred to as induced demand. In archetypical terms, this is a "relative control problem" (Wolstenholme, 2004, p. 13). It's an escalatory problem "in the sense that an increasing traffic volume will increase the road capacity, which in turn increases the traffic again – and on it goes" (Eskinasi et al., 2022).

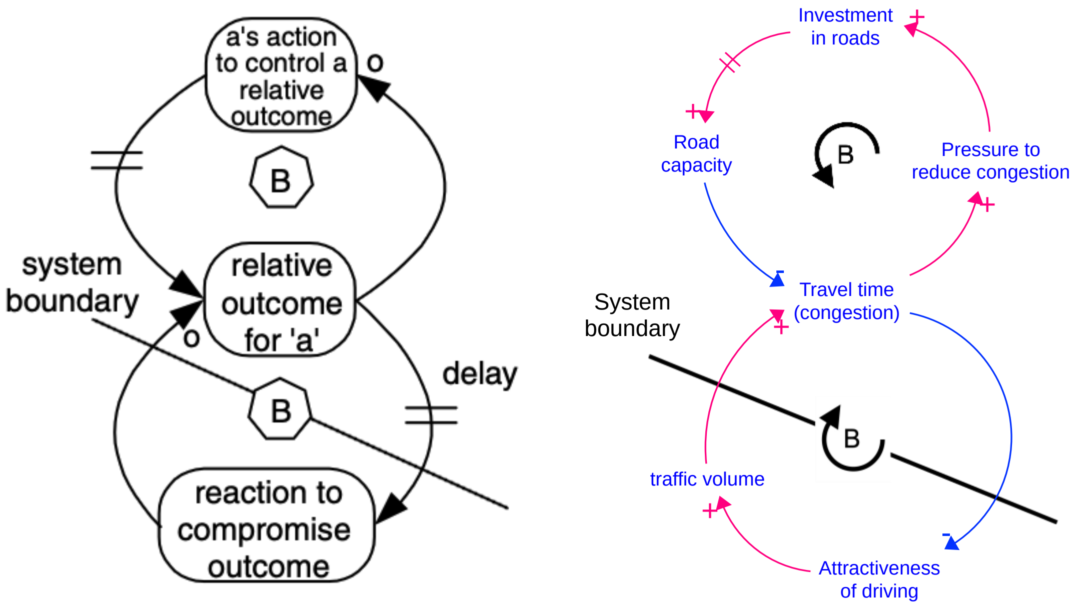


Figure 12 – relative control archetype (Wolstenholme, 2004, p. 13)

Urban sprawl – R2, R3 and R4

A second unintended systemic reaction to increased road capacity is the expansion of the catchment area (R2: catchment area expansion). Initially, inner city areas are more attractive relative to peripheral areas because of the shorter commuting times (R3: Living in the city shortens the commute), but as the size of the area within an acceptable travel time increases it will not take long for developers, and families tired (or unable to pay for) city life, to realise that the areas surrounding the newly built roads can be turned into suburbs. The result is urban sprawl. With urban sprawl comes a second archetypical problem, the "out of control" archetype (Wolstenholme, 2004, p. 13), or alternatively the less generic, but similarly structured, "shifting the burden" archetype (Wolstenholme, 2004, p. 17).

Comparing the two CLDs in Figure 13 we see that the intended fix (building roads) alleviates the symptom (congestion), without solving the fundamental problem (urban sprawl). And as so often happens when the root cause of an issue is left unaddressed, it comes back with a vengeance; when the suburban houses are built, and people have moved in, there will be more cars, and the congestion will be back. Additionally, the lower the density of the suburban development is, the less effective public transport can be, which further increases the attractiveness of driving.

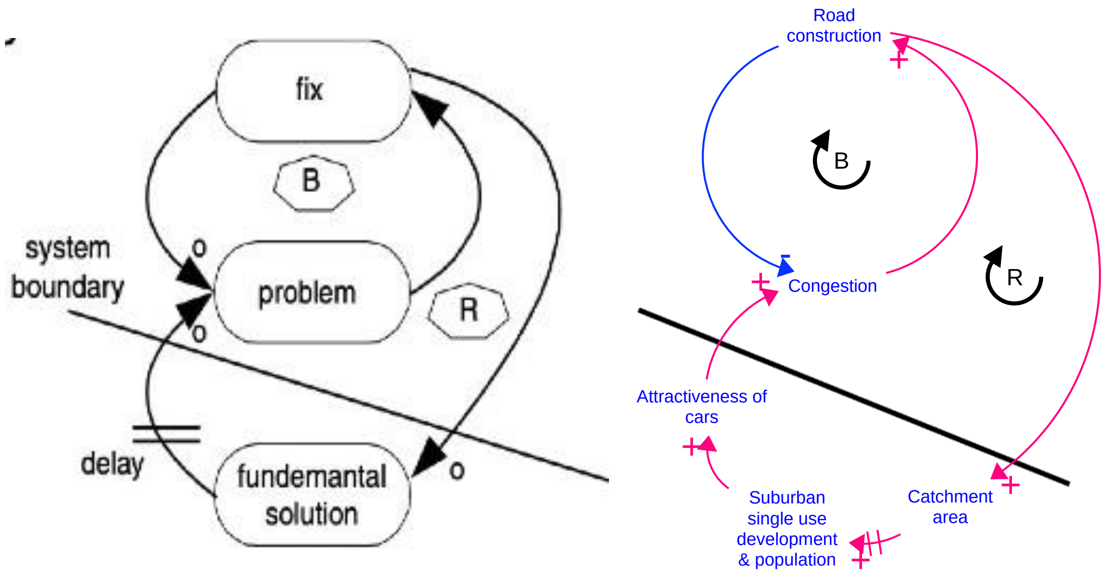


Figure 13 – Shifting the burden archetype (Wolstenholme, 2004, p. 13)

Suburban expansion – B4

The sprawl will perpetuate itself as the effect of “R2” continues to increase the congestion that “B2” will try to relieve by building more roads. With housing prices soaring and more traffic volume in and around the city, there are more roads built, the cities will be less and less pleasant to be in, their attractiveness will fall, pushing even more people out of the inner city through “B4”. As the existing suburbs grow and new ones are developed, those living in them will demand infrastructure improvements to support them in relation to the discrepancy between the actual and desired travel times they experience.

The explanation for the sprawl dynamic can be summed up as follows: A city that approaches its limits in terms of affordability and perceived environmental quality, space and privacy will push families into the suburbs. The size of that suburb will depend on the infrastructure supporting it – which has historically been expanded to cater for an ever-increasing number of cars.

Chapter 3: Model analysis and discussion

3.1 Model structure description

The model is composed of three interlinked sectors: a "transport sector"; a "land use sector"; and a "population sector". Together they make up the quantitative model of the structural hypothesis. There is one array dimension in the model, "region", and it has three elements. Those are the three levels of a FUA: inner city; metropolitan area; and commuting zone. Since section "2.2 Structural hypothesis – why cities sprawl" goes through the story of why cities sprawl, this section will only summarise and explain the model's logic. "Appendix III: model documentation" contains all equations, parameter values and explanations in further detail.

3.1.1 Transport model sector

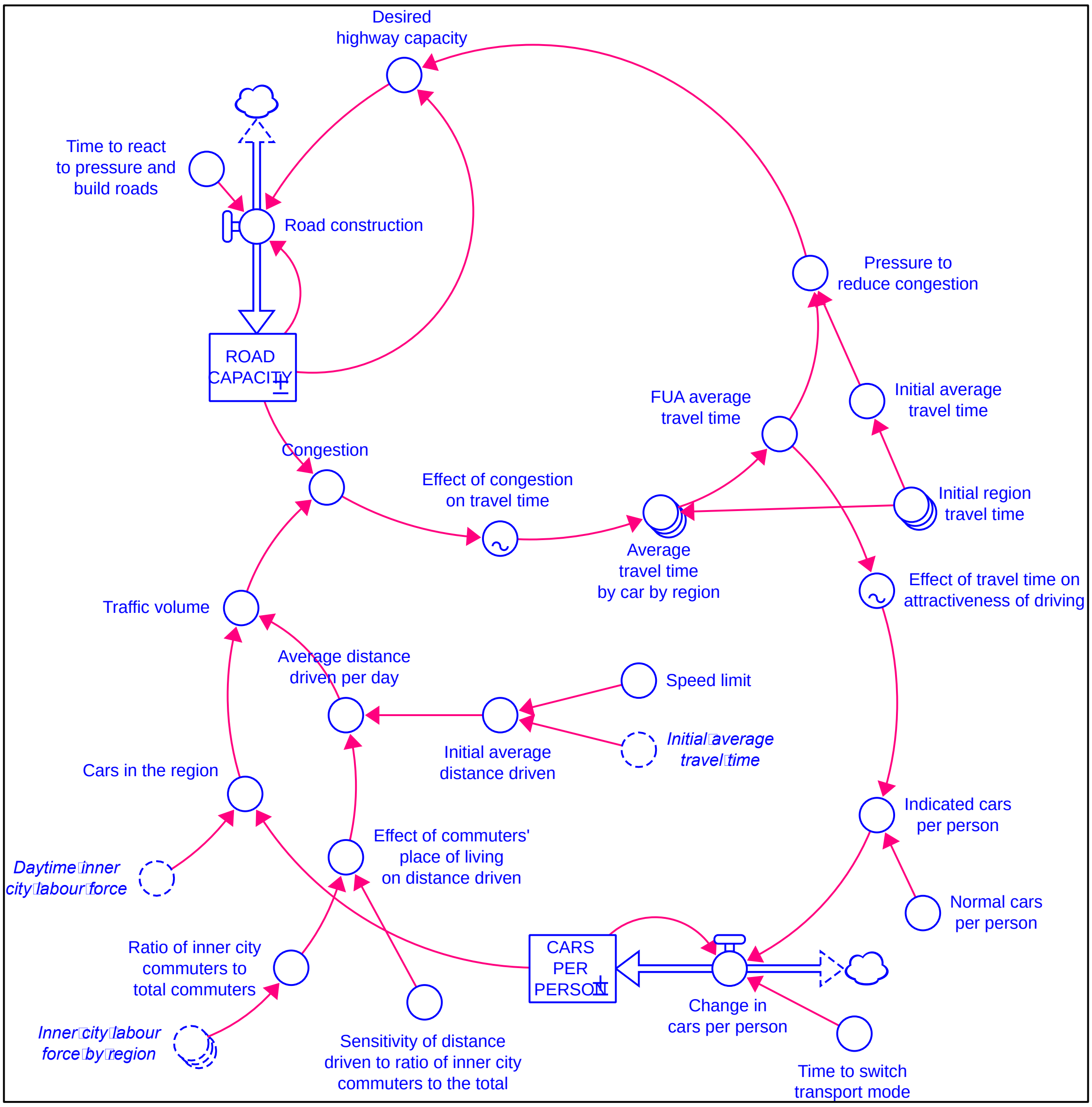


Figure 14 – Model sector: transport

The transport model sector (Figure 14) represents the two balancing loops causing induced demand, the process by which building roads to alleviate congestion can lead to more traffic rather than less. This is the escalatory “relative control problem” already discussed. The size of the “daytime inner city labour force” is the dynamical input to this model sector calculated elsewhere in the model and it represents the number of potential motorists using the roads.

The stock “cars per person” is updated by a first order information delay; it has as its goal the “indicated cars per person” which the stock reaches over the adjustment time represented by “time to switch transport mode”. A first order information delay structure was chosen because people do not react to changes in their environment immediately. It takes time to perceive that traffic has changed from what it was, to make the decision to change one’s mode of transport, and to buy or sell a car.

Continuing backwards the “indicated cars per person” is the product of “normal cars per person” and the “effect of travel time on the attractiveness of driving”. It is assumed that on average people chose to buy and drive a car based on its convenience (i.e., how quickly it gets people where they are going), and as such the effect of travel time on car buying is reverse s-shaped. The “FUA average travel time” is in turn the result of “congestion” which is the ratio of “traffic volume” to “road capacity”. The “traffic volume” is naturally determined by the “average distance driven per day” and the “cars in the region” that are in use. “Cars in the region” is determined by “daytime inner city labour force” (potential motorists) and “cars per person” which closes the first of two loops in this sector.

The other stock in Figure 14, “road capacity”, is also updated by a first order information delay. It takes time to plan and build roads which is why a first order information delay was chosen for this structure as well. It is assumed that there are sufficient resources to build the desired road capacity and maintain it, so this structure was deemed sufficient. The “road capacity” stock reaches its goal the “desired road capacity” over the adjustment time (“time to react to pressure and build roads”). The “desired highway capacity” is the product of “road capacity” and “pressure to reduce congestion”. The pressure in turn is based on deviations of the “FUA average travel time” from the initial travel time – if “congestion” grows, and the commute becomes lengthier, then the pressure to reduce that congestion also grows. And again, “congestion” is the ratio of traffic volume and road capacity and thus this second loop too is closed.

3.1.2 Land use model sector

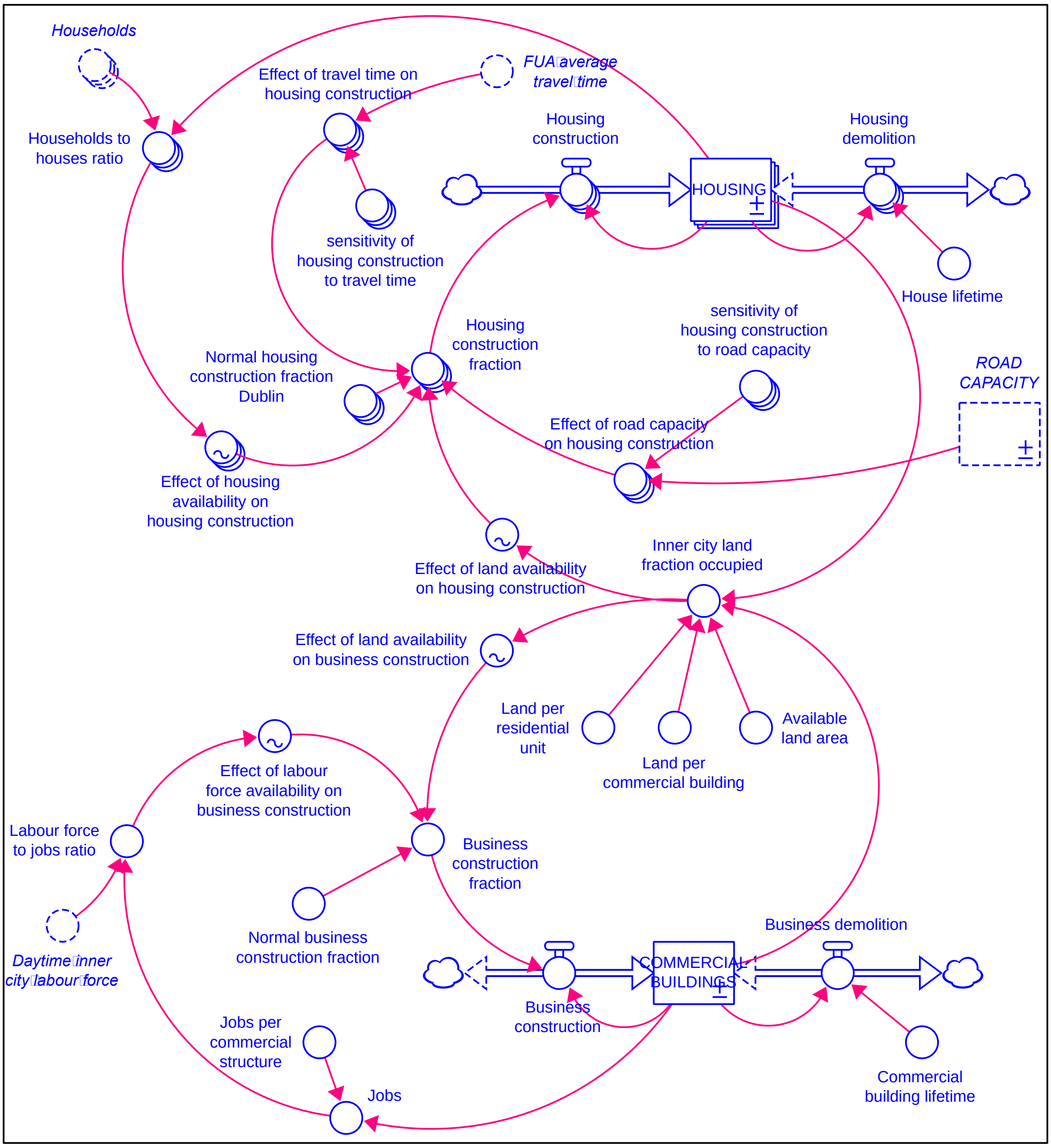


Figure 15 – Model sector: land use

The land use model sector represents the buildings that make up the urban form. Since only "commercial buildings" in the inner city are considered by this model, that stock is not arrayed by region like the "housing" stock is. The stock of "commercial buildings" increases by the "business construction fraction" which is affected by two things, the "effect of land availability on business construction" and the "effect of labour force availability on business construction". The general structure is largely based on *Urban Dynamics* (Forrester, 1969) and *Urban1* (Alfeld & Graham, 1976).

Moving backwards to explain how the number of "commercial buildings" is calculated, the "effect of labour force availability on business construction" is determined by the ratio of "daytime inner city labour force" and "jobs" passed through a s-shaped function for purpose of determining the effect of job availability on the "business construction fraction". The number of "jobs" available is a proxy for the number of commercial buildings and is based on an assumption of "Jobs per commercial structure". This process is a balancing loop that matches jobs with labourers over time. If there are more jobs than labourers, then that will slow down "business construction" and vice-versa.

The second set of key stocks calculated in this sector of the model is "housing". To calculate "housing", we start with the "effect of land availability on business construction" which is determined by how much of the inner city land is developed, the "inner city land fraction occupied". How much land is developed is partially dependent on how many commercial buildings are erected, which closes yet another loop. This loop is one that cannot be ascribed one polarity or another. Its polarity depends on how much of the land is developed. When more and more of a region gets developed it gets more and more popular, but it will reach a point where it is crowded and therefore too expensive to continue to develop – the relationship is parabolic.

The same parabolic relationship applies to the "housing construction" loop right above the one just described. The "inner city land fraction occupied" is also dependent on "housing" in the inner city. As a region becomes more developed, it becomes more attractive and therefore there is more development until the natural "carrying" capacity of the land is met. This process is represented by the loop that moves through the stock "housing" and the variables "housing construction fraction", "effect of land availability of housing construction", "inner city land fraction occupied" and back to "housing".

There is a second minor loop acting on the "housing construction fraction", whose purpose is to match "housing" to the number of households in need of housing. If there are too few houses, there is a shortage and more will be built and vice-versa. Moving backwards from "housing construction fraction" this loop goes through the "effect of housing availability on housing construction", "households to housing ratio", "housing" and back "housing construction fraction" where the loop is closed. This is a balancing loop.

The last two effects on the "housing construction fraction" is the "effect of road capacity on housing construction" and the "effect of travel time on housing construction" which both are outputs of the transport model sector. With more road capacity places further out from the inner city will become more accessible by car and it can therefore support more homes.

Regions further out from the inner city is more sensitive to increases in road capacity than the inner city which is not affected since places of interest are closer at hand. A similar logic holds for the "effect of travel time on housing construction". When congestion decreases, and travel times shorten, places further out become more attractive settlements. Housing construction in the two outer regions is therefore more sensitive to travel time than inner city areas.

3.1.3 Population model sector

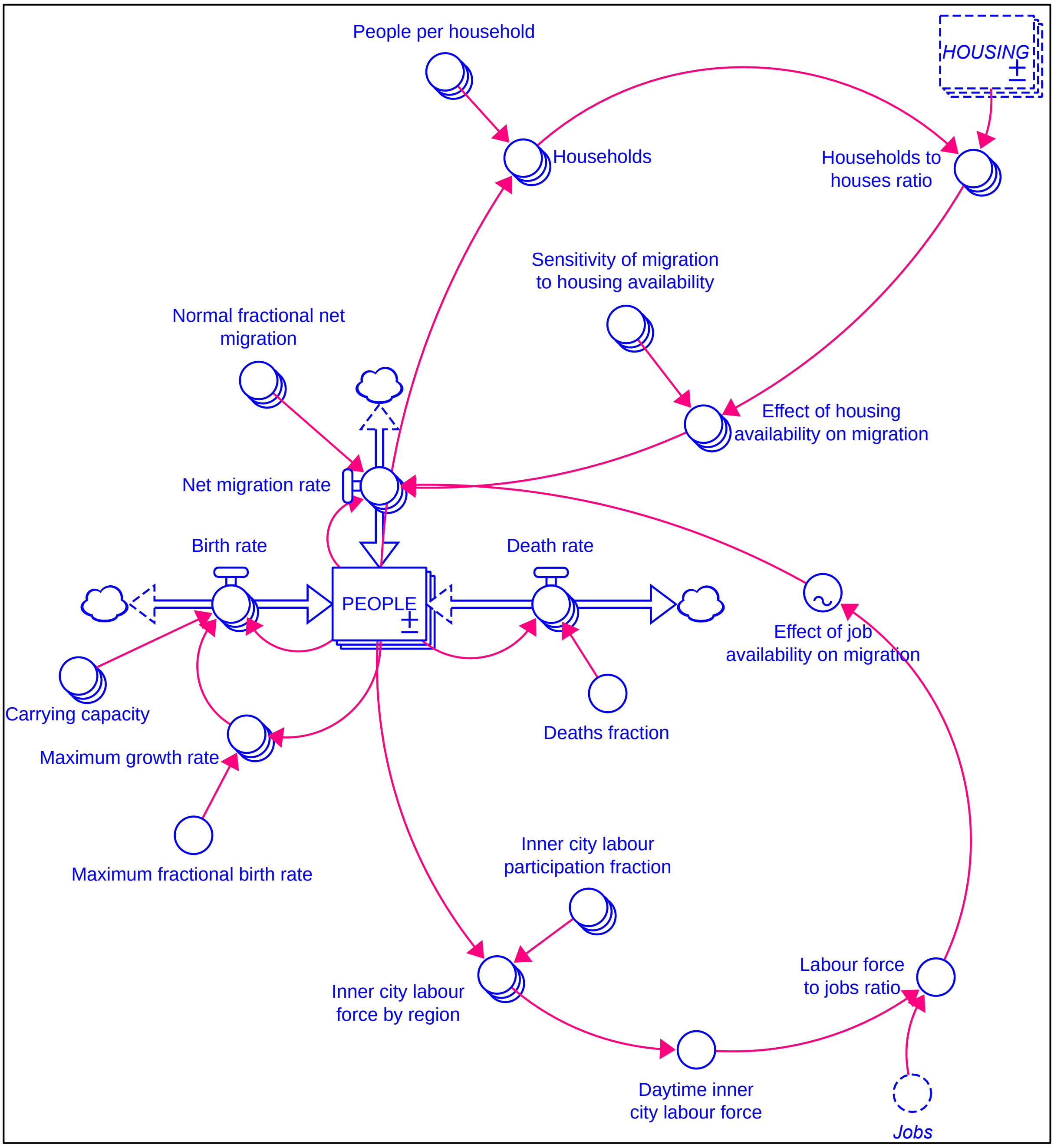


Figure 16 – Model sector: population

The population model sector represents the demographics in and around the city. The stock of "people" is arrayed into three regions. The "birth rate(s)" follows a surplus growth curve where all else equal the "people" stocks will grow in an s-shaped manner towards the carrying capacity of each region which is based on population projections from the Irish Central Statistics Office (see "Appendix III: model documentation" for further details).

The net migration rate connects this model sector to the others. Beginning with the first of two loops influencing "net migration rate" and moving backwards, there is the "effect of job availability on migration". That effect is based on the "labour force to jobs ratio" which grows with the population if "jobs" stays equal. With more people than jobs there is a job shortage, and fewer people will migrate to the area. With more job opportunity, more people will migrate to the area. Therefore, this is a balancing loop. Continuing backwards there is the "daytime inner city labour force" which is made up of inner city workers from all the regions which of course is based on the "people" stocks from all of the city regions.

The second loop influencing "net migration rate" to each of the regions, going backwards, goes through is the "effect of "housing availability on migration", "households to housing ratio", "households", "people" and back to "net migration rate". Its logic is like the previous loop, where the ratio of "households" to "housing" affects the "net migration rate" for each of the regions. If are too few houses relative to households and there is a housing shortage, then housing will be expensive or not available thus fewer people will move there. If houses are widely available, they will be more affordable and more people will move in.

3.2 Model validation

System dynamics models are *by definition* a simplification of the real world. In that sense, it does not make sense to ask whether a model is *true* or not. Instead, what we do is run our models through a battery of tests that build our confidence in them and their ability to produce the right behaviour for the right reasons. Like so many before me I'll quote Barlas and Carpenter who wrote "models cannot be proved valid, but can be judged to be so" (1990, p. 148). Validation of this project's model follows the framework detailed by Barlas (1996). It includes three types of tests that build on each other: structure confirmation tests; structure-oriented behaviour tests; and behaviour pattern tests. The tests used, their logic, and how they are relevant to this project will be detailed in the following sections.

3.2.1 Direct Structure tests

Structure, parameter, and dimensional consistency confirmation

The purpose of the structure confirmation tests is to make sure the "model structure does not contradict knowledge about the real-world system" (Kopainsky, 2020). The tests involve justifying the equations and logical relationships in the model against the real world while also ensuring dimensional consistency across variables and parameters. Oftentimes the knowledge that the equations and relationships are based on are highly qualitative in nature. Therefore, the structure and parameter confirmation tests are somewhat informal as there is no quantification or formalised algorithms for/in carrying it out (Barlas, 1996, p. 190). Those tests were a gradual and iterative process that was carried out throughout the project as the model took shape based on the literature in the research review above, and dialogue with experts (Jaber et al., 2022) informed the modelling process.

All units are dimensionally consistent, and no inconsistencies are reported by the modelling software, nor have any undue "unit-fixing" parameters been used to this end. The highest quality sources in the hierarchy of scientific knowledge were prioritised, but sometimes the author's own reasoning abilities had to be depended on. When assumptions were made, they were acknowledged as such. Equations, relationships and parameter values are all documented and explained with references (where relevant) following Rahmandad and Sterman's (2012) *reporting guidelines for simulation-based research in social sciences*, specifically the "preferred model reporting requirements" (PMRR) (p. 6). PMRR includes: units of measure for all variables and parameters; sources of data (qualitative or quantitative) for different equations and algorithmic rules; definition of all the variables used in the model and the logic behind their formulation; and source code in the original implementation platform. The documentation, with references, can be found in "Appendix III: model documentation"

Direct extreme-conditions

Out of the direct structure tests, the direct extreme-condition test is a more formal one. Its purpose is to test the equations and logical relationships in the model under extreme conditions to see if they still produce logical outputs that would be considered reasonable given the input. If they do, the model equations can be judged robust. The values determined to be "extreme" inputs are not likely conditions that would occur in the real world, but rather the most extreme values that are physically possible – if the equations produce plausible outputs our confidence in them can be higher. All equations have been subjected to extreme conditions and produce plausible outputs with one inconsequential exception; the table function “effect of job availability on migration does not produce negative effects if the labour force greatly exceeds the jobs available – which it likely would in the real world. It is exceedingly unlikely that there will be an extreme job shortage in Ireland over the next ten years however, so this is not a problem for this application of the model.

3.2.2 Structure-oriented behaviour tests

Indirect extreme conditions

Like with the direct extreme conditions test, extreme values will be given to select variables to assess outcomes. However, for the *direct* extreme conditions test we look at the model equation by equation and judge their outputs, while for the *indirect* extreme conditions test, we look at the behaviour of the whole model (or large chunks of it). If the model responds plausibly when subjected to extreme policies, shocks, and parameters we can have more confidence in the model. The below table describes the tests that were ran. For the stocks (capitalised), inflows were added for the purposes of testing (unless stated otherwise), and the values are those given to them. For the parameters multipliers were added to the calibrated base run values. All variables were given extreme high and low values and results were compared to a base simulation run calibrated to the data.

Variable	Value	Expected behaviour	Simulated behaviour	Takeaway
Land per residential building	0.155*1.4	Fewer total commercial buildings, housing units and smaller population in the inner city	As expected	-
	0.155*0.6	More total commercial buildings, housing units and higher population in the inner city	Smaller impact than expected, but directionally as predicted	
(Inflow to) PEOPLE[commuting zone]	IF Region = Region.Commuting_Zone AND TIME = 2000 THEN PEOPLE * 2 ELSE 0	Sharp increase in HOUSING[Commuting Zone] and ROAD CAPACITY built after year 2000	Directionally as predicted, but ROAD CAPACITY changed less than expected	The ROAD CAPACITY had enough buffer relative traffic volume such that it could swallow the additional cars when increased. For the same reason it did not change much in the negative direction either.
	IF Region = Region.Commuting_Zone AND TIME = 2000 THEN PEOPLE - PEOPLE*2 ELSE 0	Less HOUSING[Commuting Zone] units and ROAD CAPACITY built after year 2000	Directionally as predicted, but ROAD CAPACITY changed less than expected	
(Inflow to) Housing[inner city]	IF Region = Region.Inner_city AND TIME = 2000 THEN HOUSING * 2 ELSE 0	Lack of inner city land leading to slower housing construction and business construction, higher migration to the inner city, small population decreases in other regions and somewhat less road capacity built	Directionally as predicted, but smaller reduction in business construction than expected. Population in other regions decreased very little.	Enough land available such that it did not affect construction much in either direction, the change in housing construction came mostly from the supply and demand dynamics. The relative over- or undersupply of house was the primary driver of change.
	IF Region = Region.Inner_city AND TIME = 2000 THEN HOUSING – HOUSING * 2 ELSE 0	Liberated space leading to faster housing construction and business construction, but less migration to the inner city	Directionally as predicted for all variables, but the liberated space made little difference. The	

			demand for houses made the difference in housing construction.	
(Inflow from) ROAD CAPACITY	IF TIME = 2000 THEN ROAD_CAPACITY*2 ELSE 0	More sprawl, i.e., the HOUSING[Metropolitan Area] and Housing[Commuting Zone] stocks will be higher and so will CARS PER PERSON will be higher	As expected	-
	IF TIME > 2000 THEN -Road_construction ELSE 0 (i.e., no road construction from 2000 onwards)	Less sprawl, i.e., the HOUSING[Metropolitan Area] and Housing[Commuting Zone] stocks will be lower and so will CARS PER PERSON	As expected	
Normal business construction fraction	0.05*1.4	Higher Net migration rate[*] and less available land available and therefore a smaller HOUSING[Inner City] stock	Directionally as predicted, but housing went down less than expected	Again, there is enough land available such that such that even a large change in construction does not slow down further construction much
	0.05*0.6	Lower Net migration rate[*] and more available land available and therefore a higher HOUSING[Inner City] stock	Directionally as predicted, but a smaller increase in in housing than expected	
CARS PER PERSON	Inflows disconnected and the stock initialised at 1 (i.e., everyone drives)	More ROAD CAPACITY and HOUSING[Metropolitan Area, Commuting Zone] built (i.e., more urban sprawl)	As expected	
	Inflows disconnected and the stock initialised at 0 (i.e., no-one drives)	More ROAD CAPACITY and HOUSING[Metropolitan Area, Commuting Zone] built (i.e., more urban sprawl)	As expected	

Figure 17 – Table: indirect extreme conditions tests and takeaways

Sensitivity analysis

The behaviour sensitivity test has as its objective to assess the model's sensitivity to its parameters and if that sensitivity is plausible (Barlas, 1996, p. 191). Over 100000 runs, with Sobol Sequence sampling, the 35 parameters of the model were given randomly selected values along a uniform probability distribution. The minimum and maximum values for the distributions for each parameter were set to 10% below and 10% above base run values[1]. In Figure 18 below the mean behaviour over time (from the 100000 runs) of the main metrics – the housing stock for each of the three regions in the Dublin FUA – are displayed above the base run behaviours. As the charts in Figure 18 shows, the mean over time does not deviate from the base run behaviour in any meaningful way, which gives us confidence that the model is fairly robust to reasonable changes to parameter values – there are no qualitative changes to the behaviour modes compared to the base run. The mean and the median over time along with the confidence intervals are shown in figures Figure 19, Figure 20 and Figure 21. A list of the parameters, their base run values, and units can be found in "Appendix I: sensitivity analysis parameter values and units".

[1] Except for the parameter "available land area" where the precise number is known. It was only *reduced* by 10% to test for the possibility that some of the land area may not be suitable for construction.

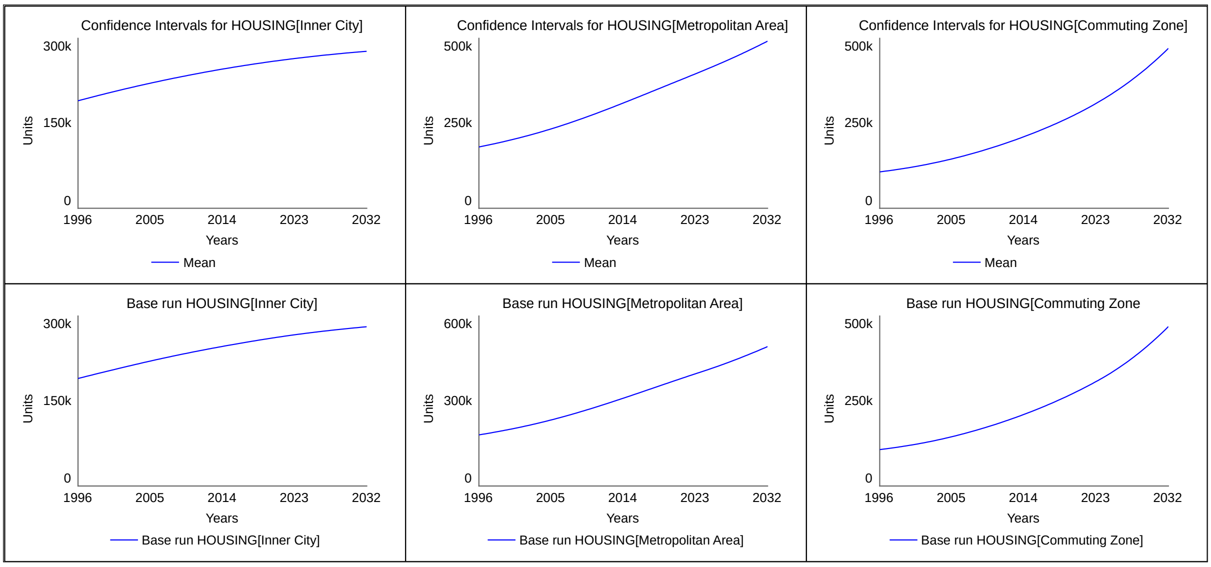
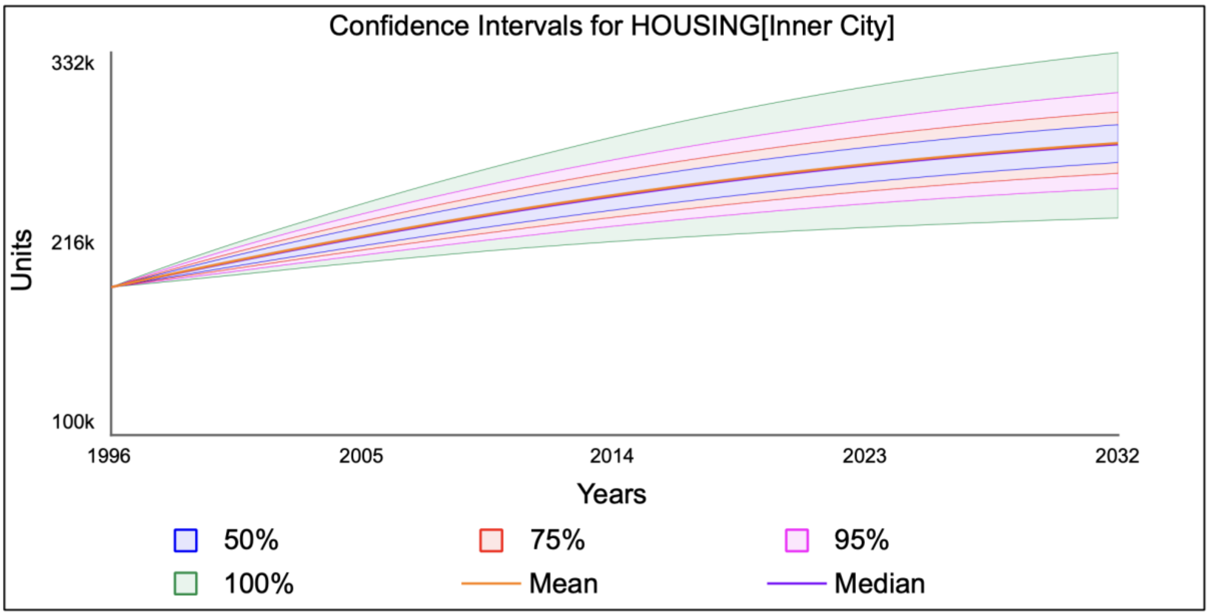
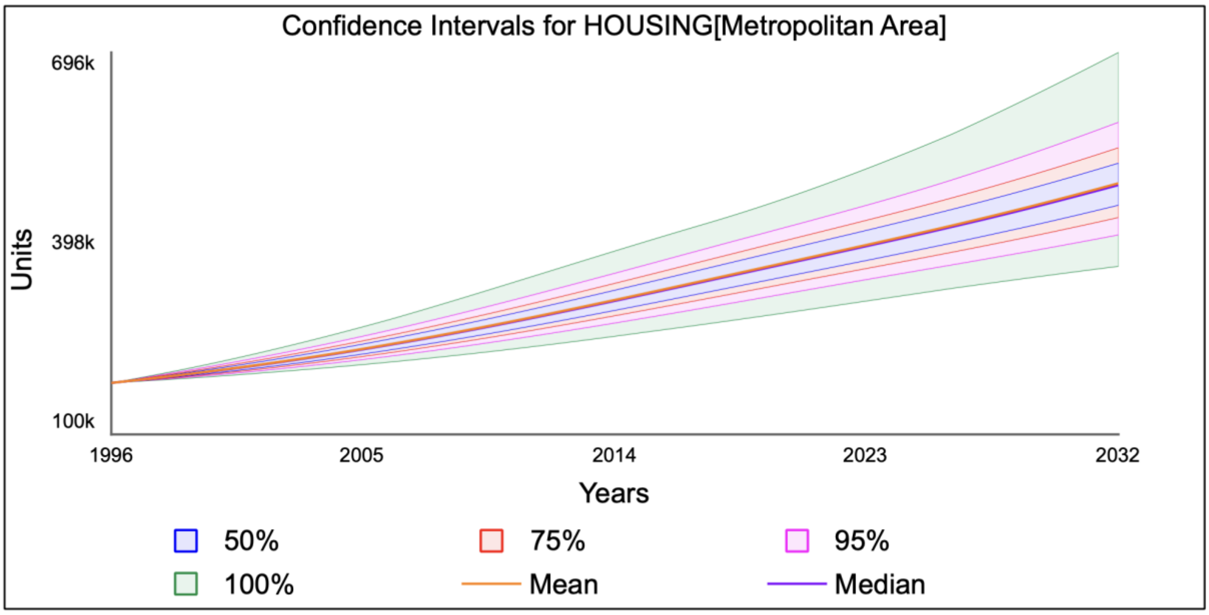


Figure 18 – Sensitivity analysis: 100000 run mean & base run



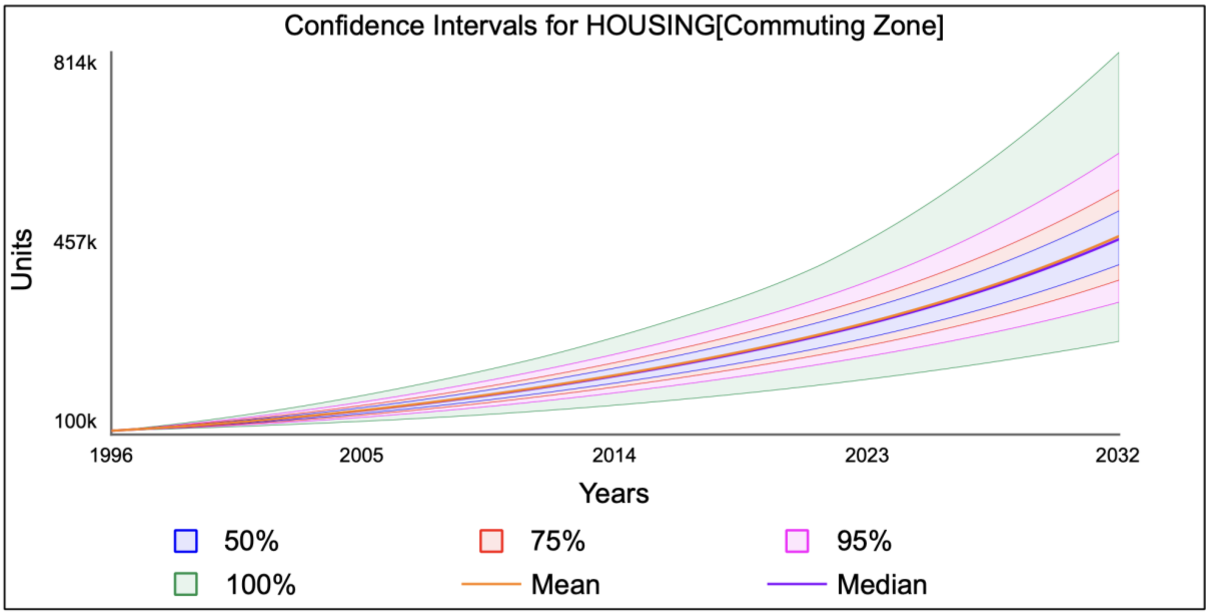
Confidence intervals for HOUSING[Inner City] values in year 2032		
Confidence interval	Minimum	Maximum
50%	265000	288000
75%	259000	296000
95%	250000	308000
100%	232000	332000

Figure 19 – Sensitivity analysis: confidence intervals for HOUSING[Inner City] (chart and table)



Confidence intervals for HOUSING[Metropolitan Area] values in year 2032		
Confidence interval	Minimum	Maximum
50%	457000	523000
75%	438000	547000
95%	411000	587000
100%	362000	696000

Figure 20 – Sensitivity analysis: confidence intervals for HOUSING[Metropolitan Area] (chart and table)



Confidence intervals for HOUSING[Commuting Zone] values in year 2032		
Confidence interval	Minimum	Maximum
50%	417000	518000
75%	388000	557000
95%	347000	625000
100%	274000	814000

Figure 21 – Sensitivity analysis: confidence intervals for HOUSING[Commuting Zone] (chart and table)

3.2.3 Loop dominance analysis and behaviour replication

The first research question, *"What are the endogenous drivers of observed urban sprawl?"* makes the loop dominance analysis and the behaviour replication especially central to this thesis. The reference modes already presented in figures Figure 2, Figure 3 and Figure 4 showcase the problem of sprawl in Dublin. In this section it will be demonstrated that the model structure can replicate that problem behaviour when simulated. Then, a loop dominance analysis will be conducted so to "understand how that structure works to produce that problem" (Schoenberg et al., 2020).

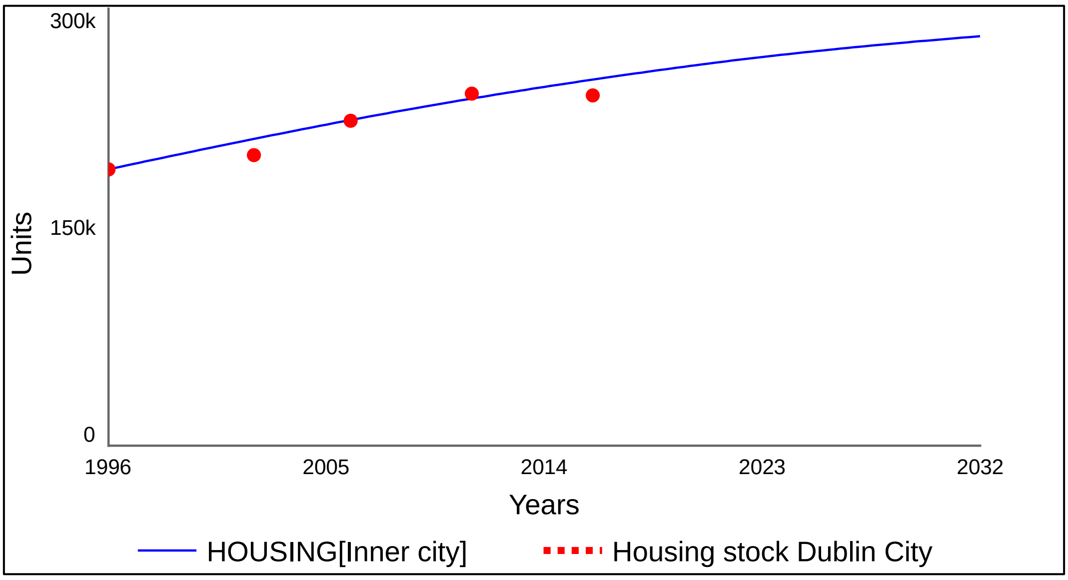


Figure 22 – Behaviour replication: inner city housing

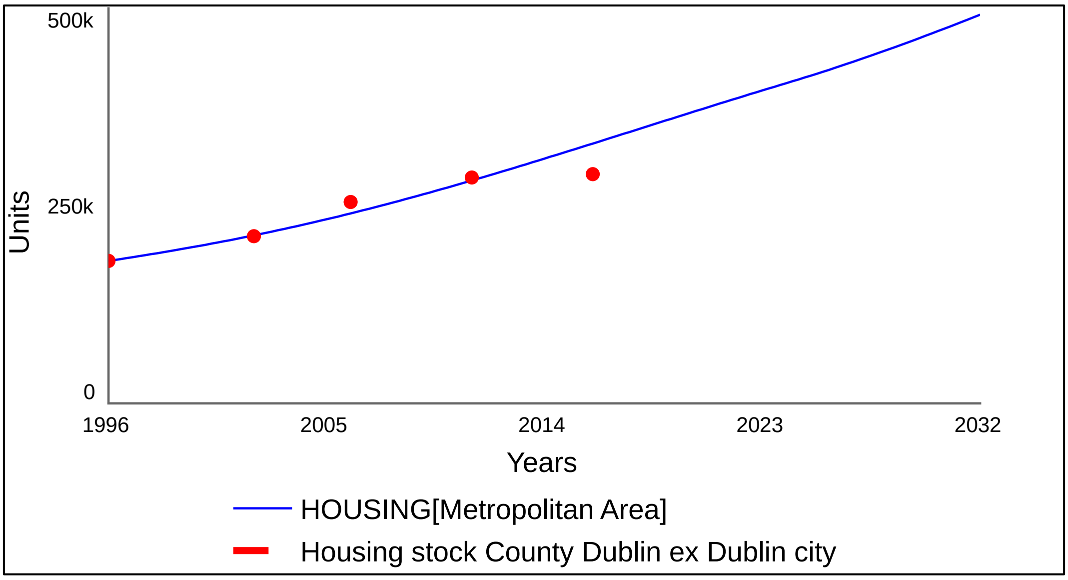


Figure 23 – Behaviour replication: metropolitan area housing

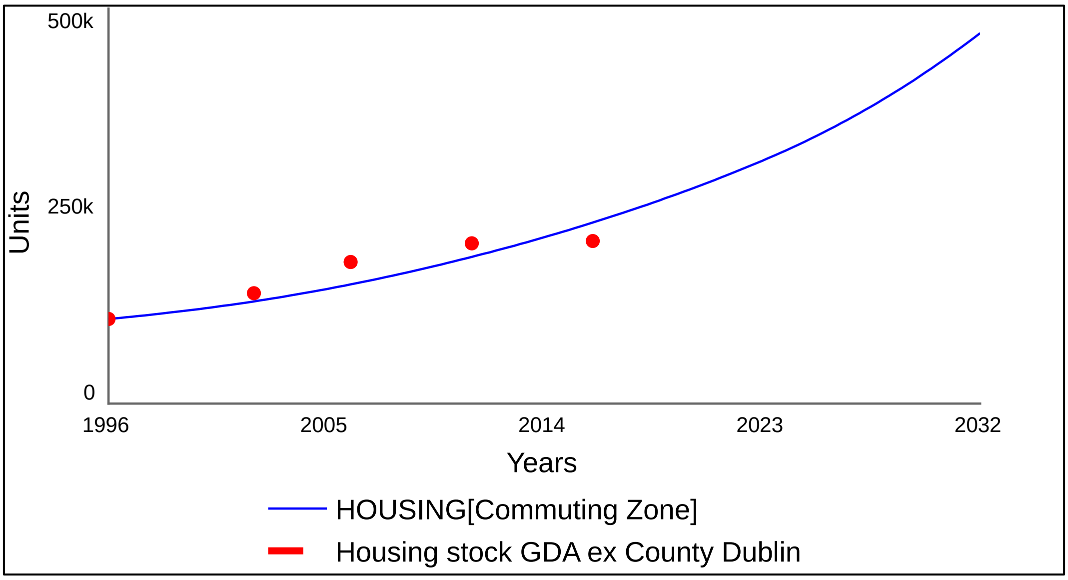


Figure 24 – Behaviour replication: commuting zone housing

In figures Figure 22,Figure 23 and Figure 24 the blue line is the model produced behaviour, while the red dots are the raw data from the Irish Central Statistics Office (CSO, 2016b). Seeing from the graphs, the model produces behaviour linking the data points and it follows their trajectory. For model behaviour plotted over all the collected data see "Appendix II: historic behaviour replication". The housing stock of the inner city displays a goal seeking behaviour that increases decreasingly, while the metropolitan area and the commuting zone both have housing stocks that the model predicts will grows approximately exponentially. Worryingly if one wants to avoid urban sprawl, the commuting zone (the outmost residential region) grows the fastest over the simulation time horizon.

The next step is to understand why it is that the model is producing these behaviour modes. That will be done through a loop dominance analysis using Loops That Matter (LTM) (Schoenberg et al., 2020). A "loop dominance profile" can be made using this method which gives insight into which feedback loops are responsible for what behaviours, over time. Looking at the behaviour replication figures above, we know that the model produces the *right behaviour*, but the loop dominance analysis will reveal if it is doing so for the *right reasons (Schoenberg & Swartz, 2021)* – If the sequence of contributions from the various loops matches what is known about the real system as laid out in the research review and the structural hypothesis sections.

The model has 103 loops in it. The stacked area graph below (Figure 25) shows all their explanatory power over time. In this figure it is too difficult to make out the contribution of a single loop, but it does show that the model is largely driven by balancing feedback (the blue areas) over the simulation run. The exception is the time period between approximately 2015 and 2018 where reinforcing feedback (the red areas) dominated.

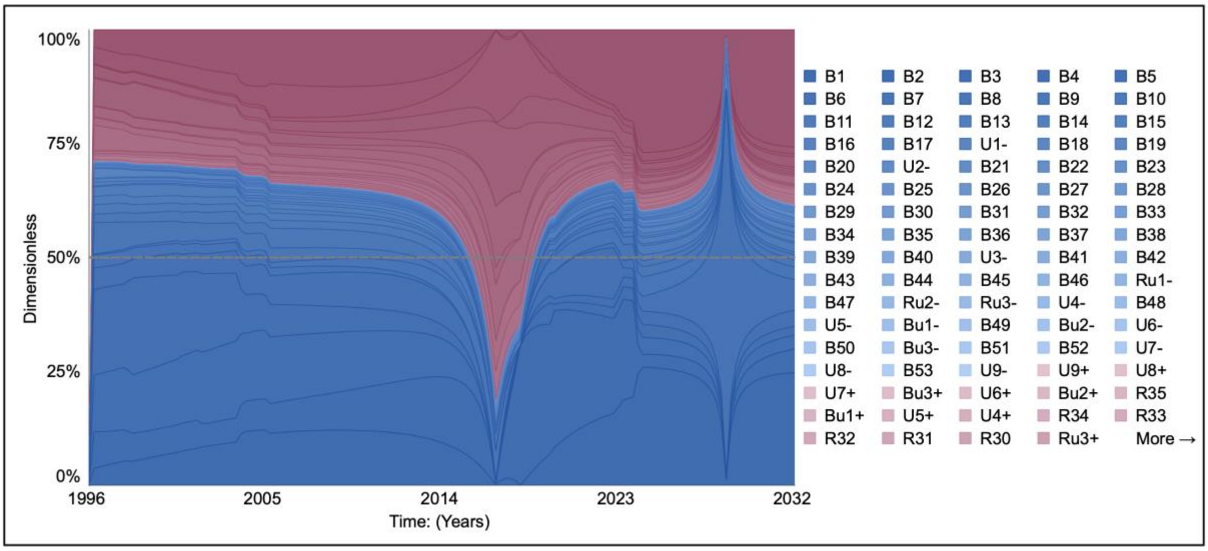


Figure 25 – Model loop dominance profile (total)

To develop a cogent and coherent story about what the model is doing I let the modelling software Stella combine feedback loops into "feedback concepts" that include multiple loops. The loops combined into a single concept are of the same polarity and at least 99% similar in their contribution to the overall behaviour (see Schoenberg and Eberlein (2022) for further details). It is the corelation between relative (as opposed to absolute) loop scores that are chosen to determine inclusion into a single concept.

The list of loop concepts turns out to include 46 of them – a considerably more manageable list than the 103 individual loops. To further simplify, and to get a clearer picture, the loop concepts explaining 70% of the model behaviour were singled out. Those make up 8 loop concepts and each of those explains 5% of the model behaviour or more. Figure 26 below is a new stacked area graph showcasing their relative contributions alone. The graph clearly displays the same behaviour and phases as Figure 25 since the contributions of the 8 loop concepts explains the bulk of the model's overall behaviour.

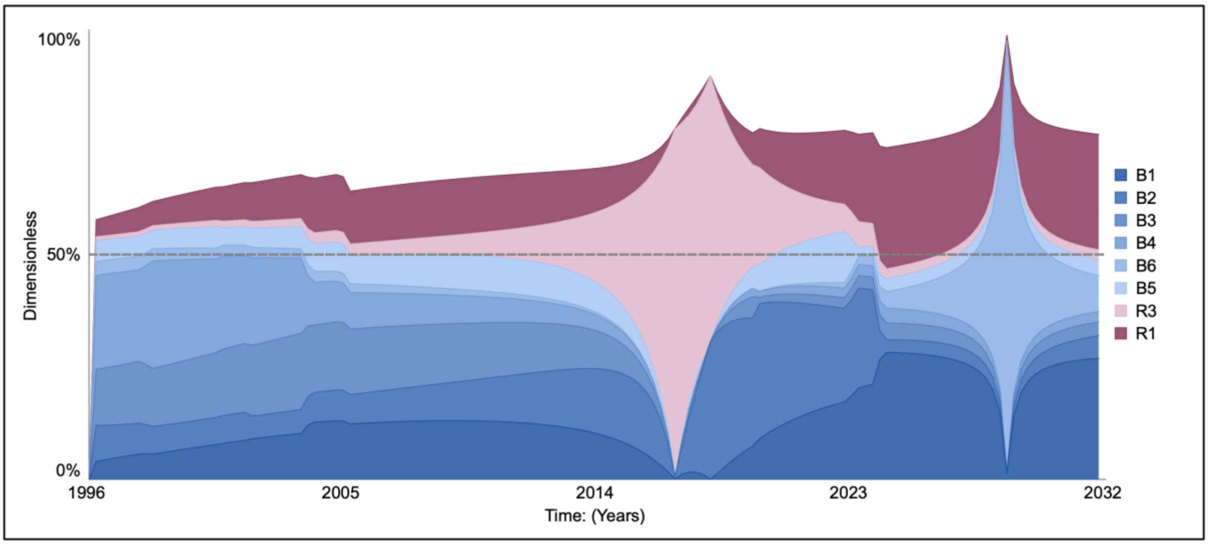


Figure 26 – Model loop dominance profile (loop concepts explaining 70% of model behaviour)

Figure 27 below shows the 8 loop concepts plotted into a CLD with labels corresponding to Figure 26. The smaller structures not connected to the larger one, are connected in the actual model. However, the loops that connect them to the rest of the model are not important enough (they are among the 30% least explanatory loops) to be included in the simplified CLD.

Often, changes in the loop dominance profile are interesting because it can help explain changes in model behaviour over a simulation run – what loop(s) in the model turn exponential growth into goal seeking behaviour, say. As the stocks in this model do not change their modes of behaviour to any significant degree, using LTM to explore phase changes is not interesting in this case. Instead, the most explanatory loops (the 8 loop concepts in Figure 27) over the entire simulation will be explained. The purpose is to assess if the relative contribution of the various feedback mechanisms in the model correspond to the literature review and the structural hypothesis of this project.

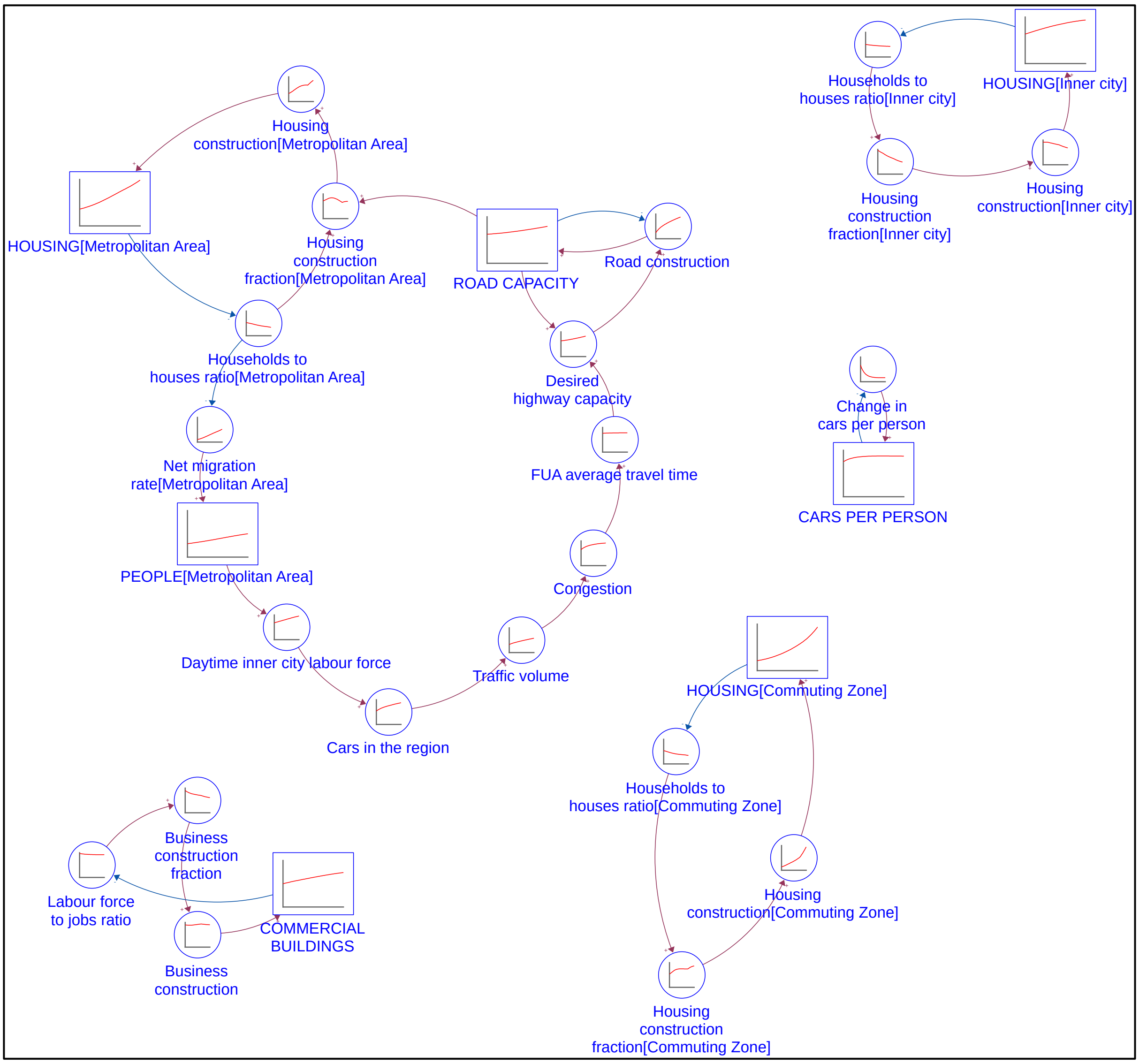


Figure 27 – CLD: 11 loop concepts explaining 70% of the model behaviour

Loop concepts B1 & R1: road construction

Figures Figure 28 and Figure 29 shows the two loop concepts whose changes contributes the most to the rest of the model behaviour. They are B1 and R1 respectively and are highlighted in each of their figures. B1, in Figure 28, represents the balancing processes by which “road capacity” tries to reach the goal of “desired highway capacity”. “Road construction” slows down as the “road capacity” nears its goal of “desired highway capacity” and is thereby a balancing loop. “desired highway capacity” increases over the simulation run however, so the balancing loop B1 produces growth in the “road capacity” stock. The increasing “congestion” is what makes the “desired highway capacity grow” to try and make traffic freer flowing.

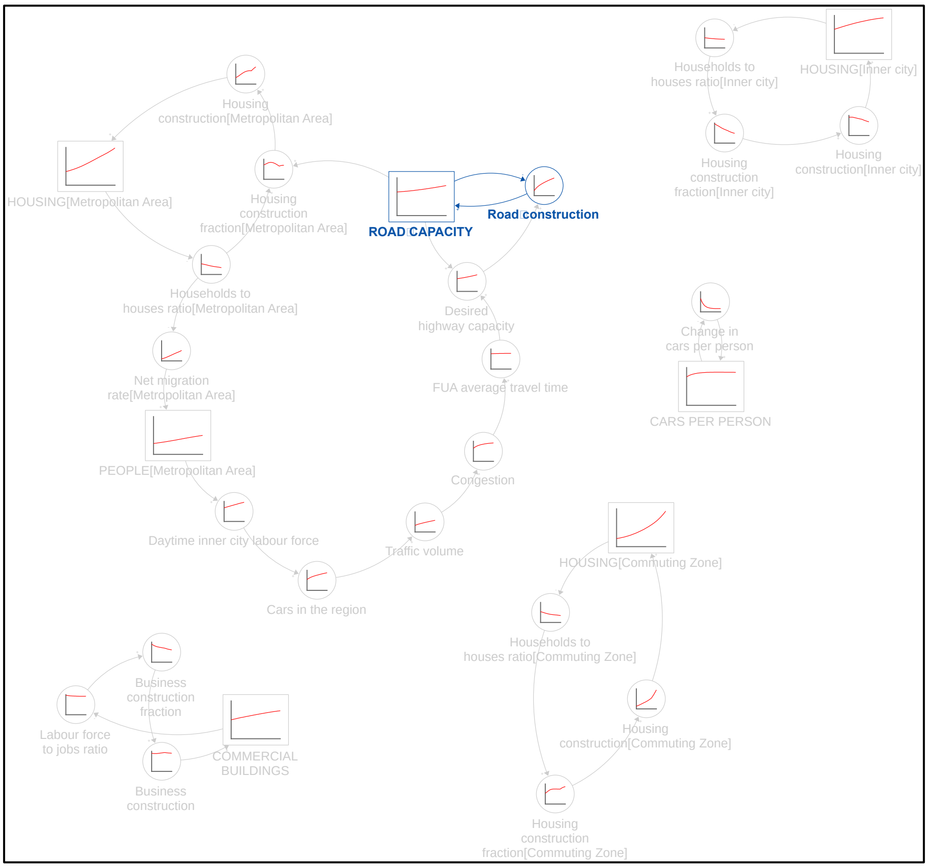


Figure 28 – CLD: LTM loop concept B1 (-13.12% of total behaviour)

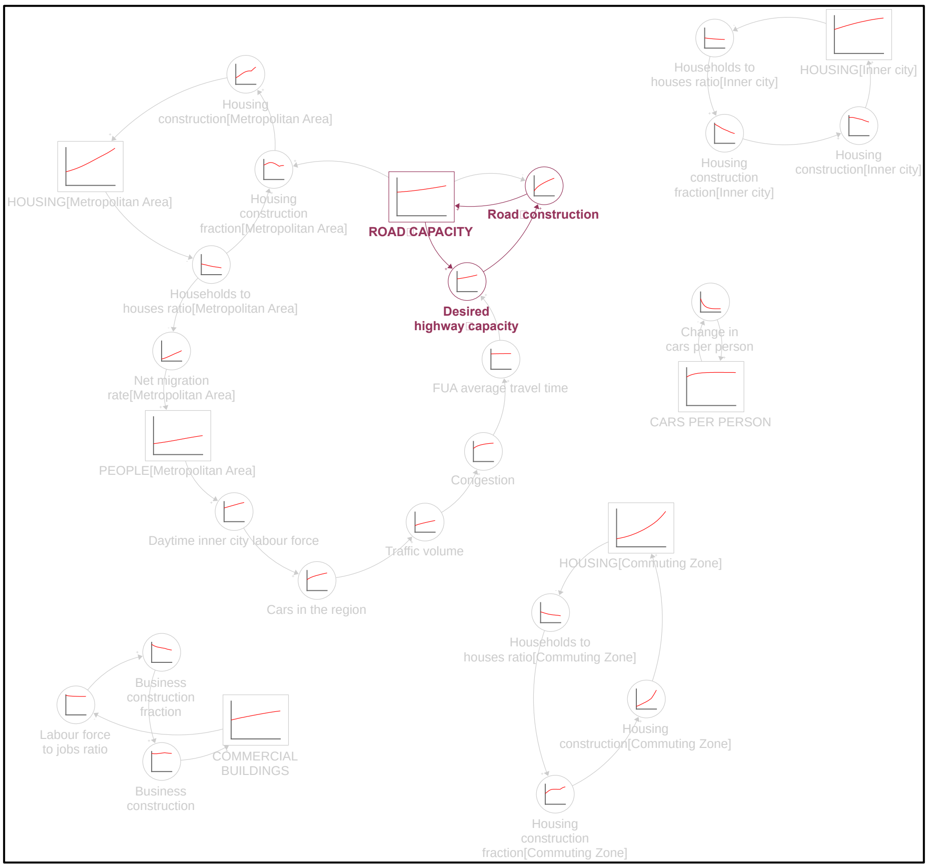


Figure 29 – CLD: LTM loop concept R1 (12.52% of total behaviour)

The loop concept R1 in Figure 29 is reinforcing since desired highway capacity in the model is given by the equation

*Desired highway capacity = highway capacity * pressure to reduce congestion*[2]

which means that with a higher road capacity and all else equal the desired highway capacity increases too which speeds up road construction[3]. Road construction has been touted as the most fundamental driver of urban sprawl in this thesis. So, B1 and R1 being the two most powerful drivers of the model behaviour strongly supports this.

Loop concepts B2 and R3: Housing in the metropolitan area and road construction

The loop concept B2 in Figure 30 is the concept which contributes the third most to the overall model behaviour. As no other individual loops are 99% similar to it or more, it includes only the single balancing loop. This balancing loop is the process by which new houses are built in the metropolitan area (excluding the inner city) based on whether there is a housing shortage or the opposite. When the "households to houses ratio[metropolitan area]" is high, there is more "housing construction[metropolitan area]" which accumulates the "housing[metropolitan area]" stock. As the stock grows, the "households to houses ratio[metropolitan area]" declines.

The "housing construction[metropolitan area]" is influenced by more than just the housing availability in the area which brings us to the loop concept R2 in Figure 31. With increasing road capacity more and more areas outside the inner city will be suitable for development and that is substantiated by the relative contribution of this loop concept. This loop concept is almost as influential as the abovementioned (it explains ~10% of model behaviour versus ~10% for B2 and ~13% for R1 and B1). With more "road capacity", there is more "housing construction[metropolitan area]" which accumulates the "housing[metropolitan area]" stock. With more houses available in that region, "net migration[metropolitan area] increases. With the resulting increase in "people[metropolitan area]" there are more "cars in the region" and "congestion" which puts pressure on policy makers to continue "road construction". The "road capacity" that follows opens up yet more areas for housing development which continues the perpetuation of sprawl and road construction. The relatively strong contribution of this loop gives further indication that the model produces the right behaviour for the right reasons.

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[2] Pressure to reduce congestion is not shown in the CLD's in this section, see "Appendix III: model documentation" for more details on the equations

[3] All else will not be equal however because "road construction" is a downward driver of "pressure to reduce congestion" (see "Appendix III: model documentation" for further details)

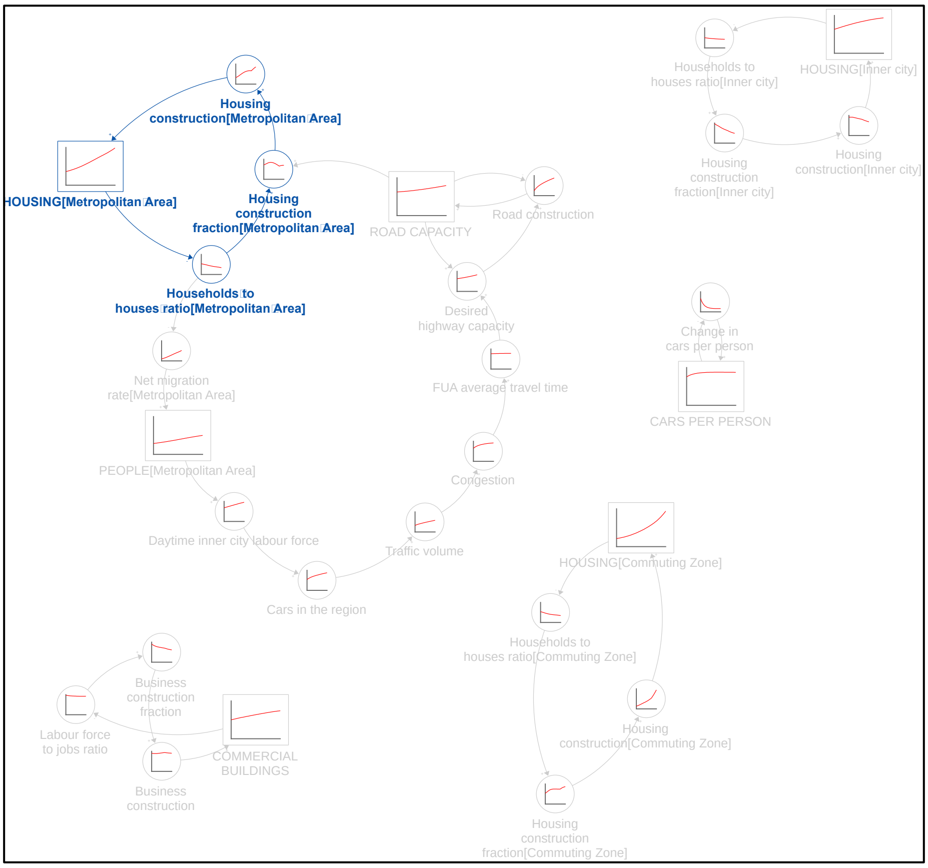

Figure 30 – CLD: LTM loop concept B2 (10.49% of total behaviour)

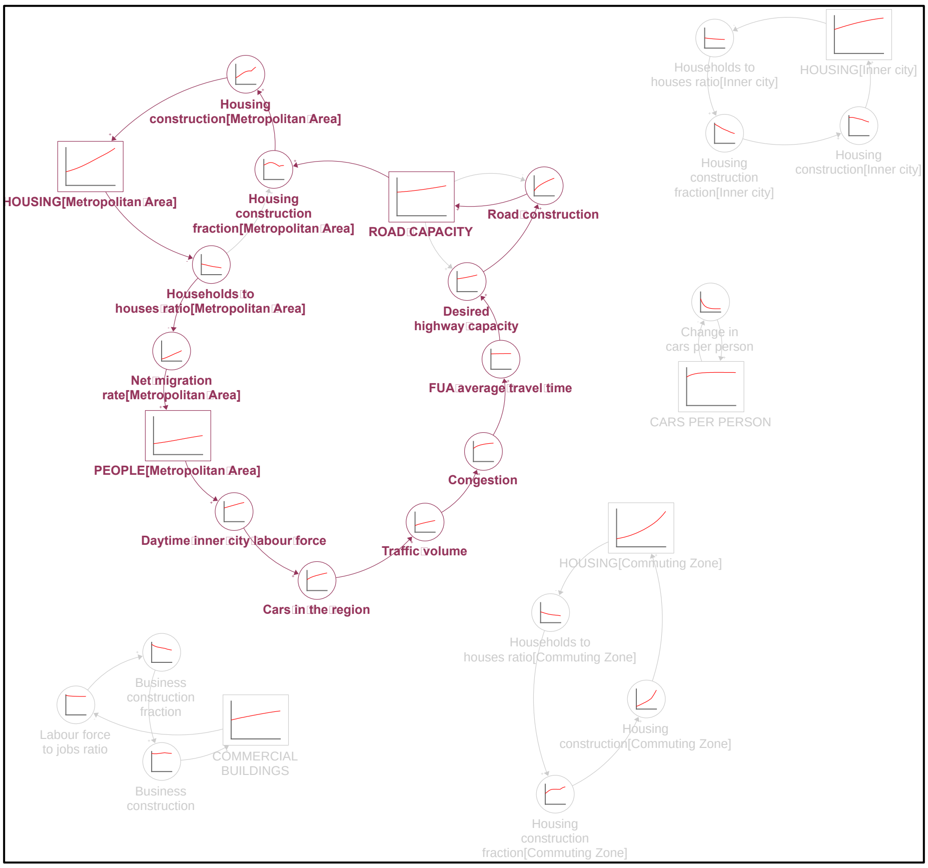

Figure 31 – CLD: LTM loop concept R2 (10.17% of total behaviour)

Loop concepts B3 and B4

The balancing loop concept B3 highlighted in Figure 32 consists only of one loop. It explains -8.17% of total behaviour. B3 explains the process by which the stock “commercial buildings” changes. With more “commercial buildings” there are more jobs available. With more jobs available relative to the labour force the “labour force to jobs ratio” decreases. As the demand for jobs is satisfied “business construction fraction” decreases which slows down growth in the “commercial buildings” stock. This loop concept is not connected to the larger structure in the CLD because the loops that connect them explain less than 30% of the overall model behaviour – it is thereby below the inclusion threshold for this loop dominance analysis. However, as the “commercial buildings” stock grows, more of the land inside the inner city is used up, which forces developers to start building outside it. This process – while included in the model structure – was not strong enough for the simulation analysed to be important.

The loops connecting B4 in Figure 33 to the larger structure is also below the inclusion threshold and explains -7.19% of total model behaviour. It explains how the stock “housing[inner city]” changes. When “housing[inner city]” grows it eventually meets the demand for housing in the region as the “households to houses ratio” declines. With less demand “housing construction[inner city]” slows down, and so does the stock “housing[inner city]”. That this loop concept is separate from the larger structure where “road capacity” is involved makes sense; road infrastructure is less relevant to inner city development because the denser development allows places of interest (jobs, shops, etc.) to be accessed without cars.

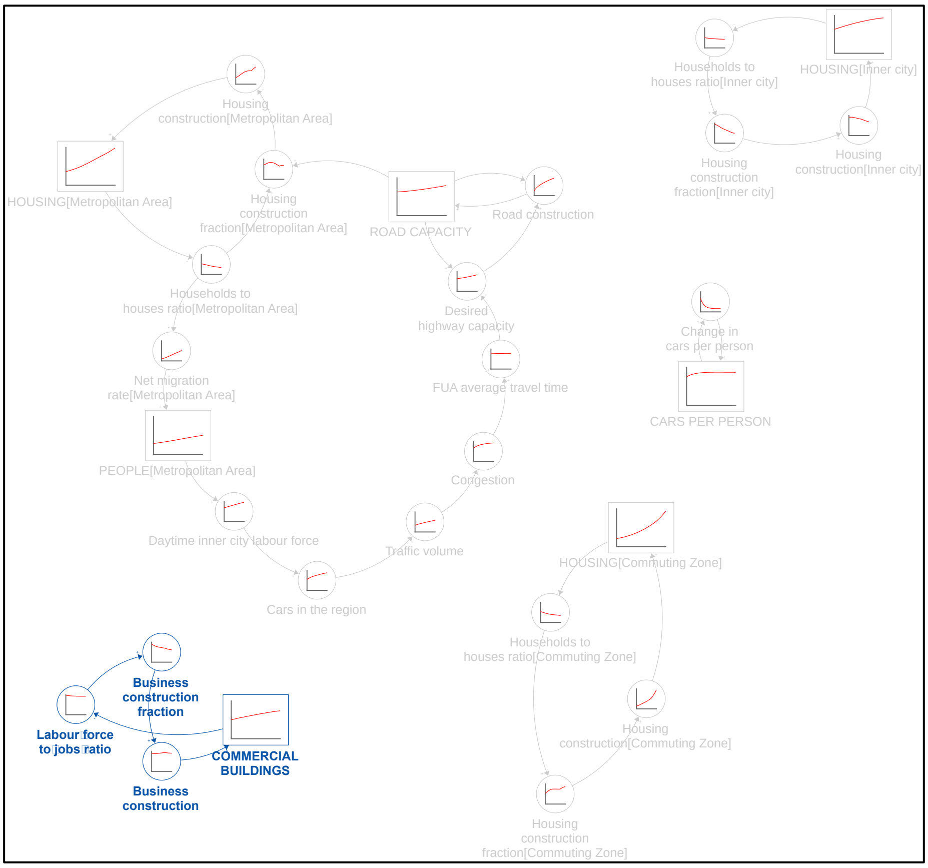

Figure 32 – CLD: LTM loop concept B3 (-8.17% of total behaviour)

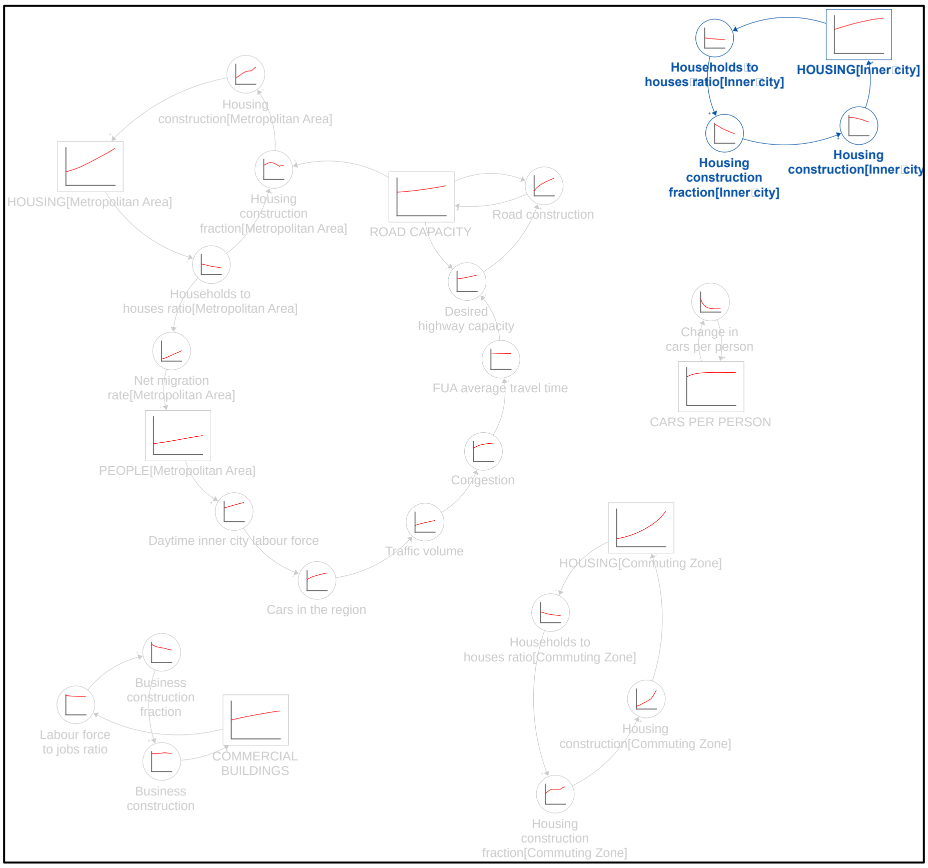

Figure 33 – CLD: LTM loop concept B4 (-7.19% of total behaviour)

The loop concepts B5 and B6 highlighted in figure Figure 34 and Figure 35 respectively are the last two concepts under consideration. They too have loops connecting them to the larger structure in the CLD in the actual model, but they are below the inclusion threshold. B5 shows the balancing process of people adopting cars as their mode of transport. By a first order information delay the stock "cars per person" approaches the goal of the "indicated cars per person (attractiveness of cars)" (not shown in the Figure 34 CLD, see "Appendix III: model documentation" for details) the growth in the stock slows down towards that goal.

That the loops connecting B6 to the larger structure are missing is interesting. It means that road construction in the base case is less impactful on housing construction in the commuting zone, than it was for the metropolitan area in this simulation. B6 explains the how housing in the outermost belt from the inner city changes. As "housing[commuting zone]" grows "households to houses ratio[commuting zone]" declines because demand for housing in that region is met. The result is less "housing construction[commuting zone]" which slows down growth in the "housing[commuting zone]". Road construction does positively impact housing construction in that region in the model, but it seems it is of much less importance than the supply and demand dynamics of housing availability.

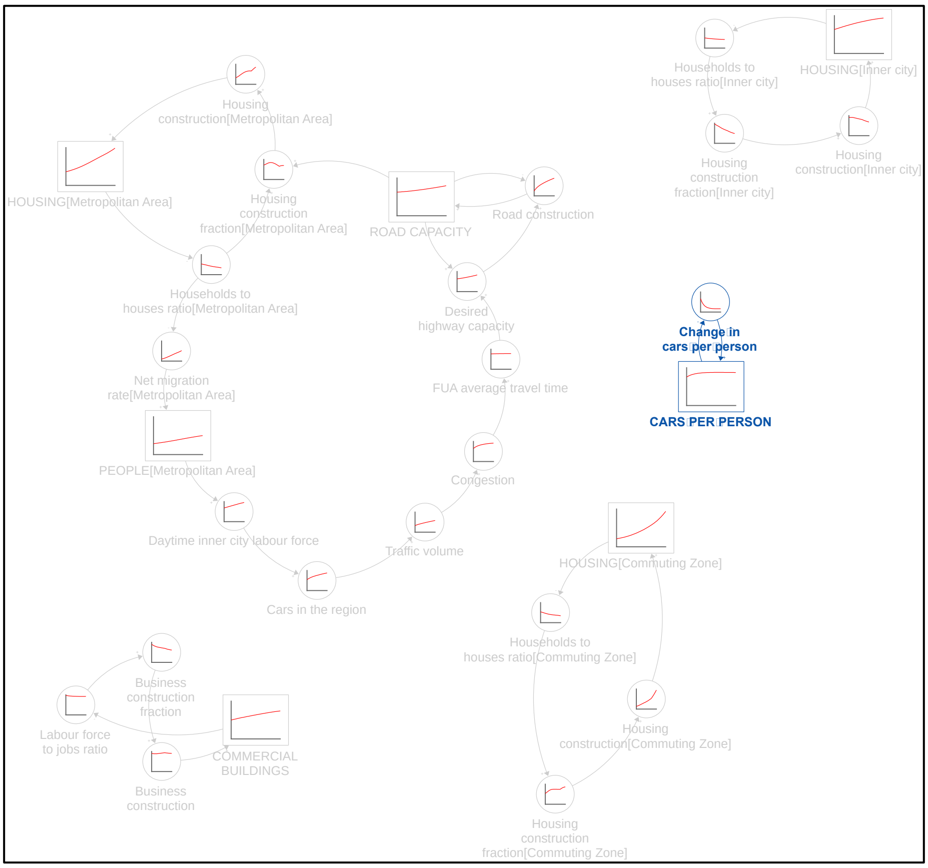

Figure 34 – CLD: LTM loop concept B5 (-5.07% of total behaviour)

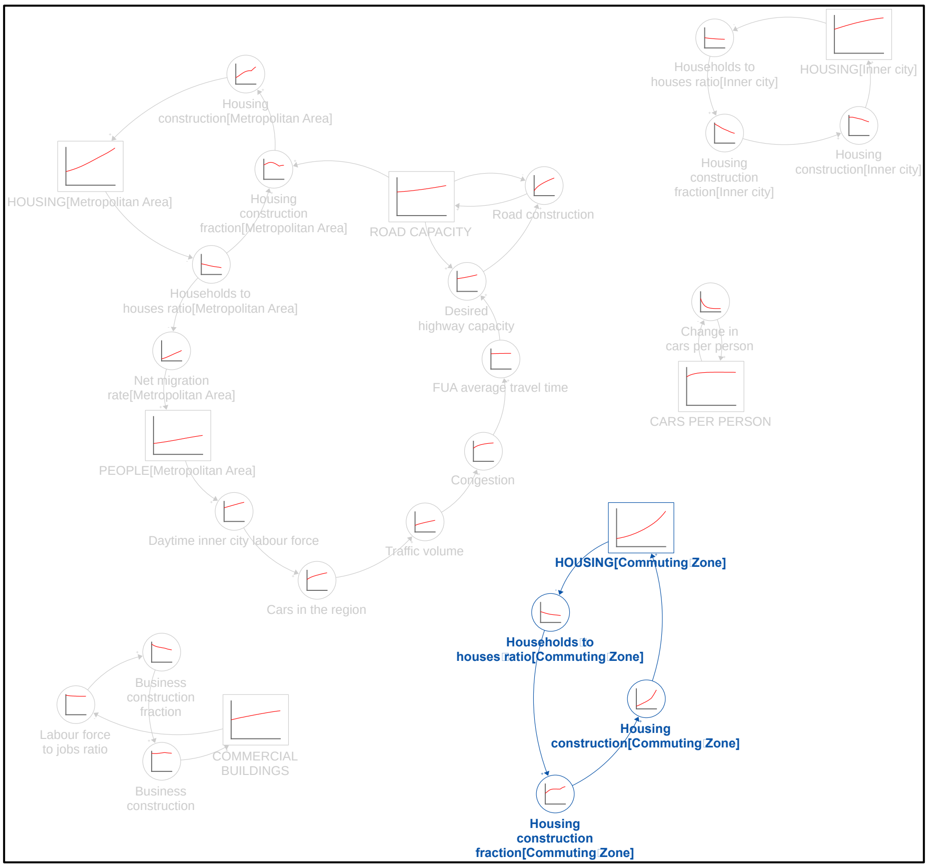

Figure 35 – CLD: LTM loop concept B6 (-5.04% of total behaviour)

3.3 Policy scenarios – effects of road construction and reallocation

Road construction is fundamental to the behaviour of the system. The loop dominance analysis in the previous section made that clear and began answering research question 2, "*What is, and has been, the effects of building roads on urban sprawl?"*. It is pertinent then, to manipulate the "road capacity" stock to gain further insight into how development patterns might evolve.

Three interventions have been tested and compared to the base run calibrated to Dublin. They are the following:

1. Not yielding to the pressure to build roads from 1996 onwards such that no new roads are built beyond the initial conditions;
2. Ceasing road construction from 2022 to the end of the simulation period in 2032; and
3. Removing 2% of the road capacity from 2022 to the end of the simulation period in 2032.

This section is under the heading "policy" because the action of road reallocation – i.e., removing road space and using it for things other than driving – is a known policy tool (Combs & Pardo, 2021; Forum, 2022; OECD, 2021). However, extensive policy implementation modelling and firm policy recommendations is outside the scope of this project.

Policy 1: No road construction from 1996-2032

The first policy scenario is derived from the experimental process of archetype analysis. Induced demand – the process by which road construction can produce more rather than less congestion – was identified in section "Reducing congestion – B2 and B3" as an archetypical "relative control problem". And as such there is a generic solution: setting an "absolute target" (rightmost CLD in Figure 36). Instead of yielding to the "pressure to reduce congestion" and "investing in roads", that link (in the leftmost CLD in Figure 36) is ignored in favour of an unchanging absolute target.

Policy 1 is a "what if" scenario where the absolute target is the level of road capacity of 1996. For this policy the link between desired road capacity and road construction is severed; no additional roads will be built beyond those already in place by the beginning of the simulation in 1996. In the policy literature, this intervention has been called "planned congestion" (Eskinasi et al., 2022). The experiment makes explicit that urban sprawl and reliance on cars is not an inevitable consequence of growth, but the result of policy decisions – i.e., constructing roads.

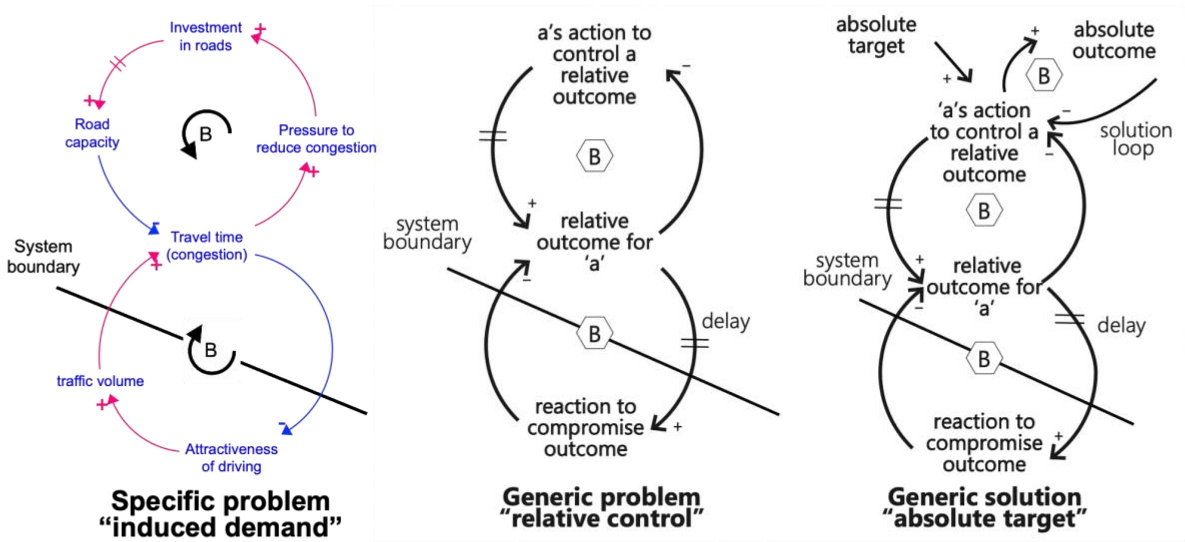

Figure 36 – Relative control archetype, problem and solution (Wolstenholme, 2004)

The result is the flat line in the graph on the right of Figure 37. With fewer roads, the land in surrounding areas become less accessible. Looking at Figure 39, the difference in sprawl is stark for policy 1 relative to the base run. The inner-city housing development is unchanged for policy 1, but the metropolitan area and the commuting zone belts surrounding it sees much slower growth. This hypothetical scenario sees the FUA become more compact and less sprawled. The "cars per person" stock also sees a change under policy 1, but curiously it does not deviate from the base run until approximately 2024 when it starts to decline. The reason is the time frame of the population growth. The FUA population still grows, but it takes until 2024 for the roads to be congested enough for people to choose other modes of transport. It should be noted here that other modes of transport are not explicitly modelled. It is instead assumed that there is enough capacity in public transport and other models for people to no longer use their cars if they so choose. Otherwise, the decline in "cars per person" is unlikely.

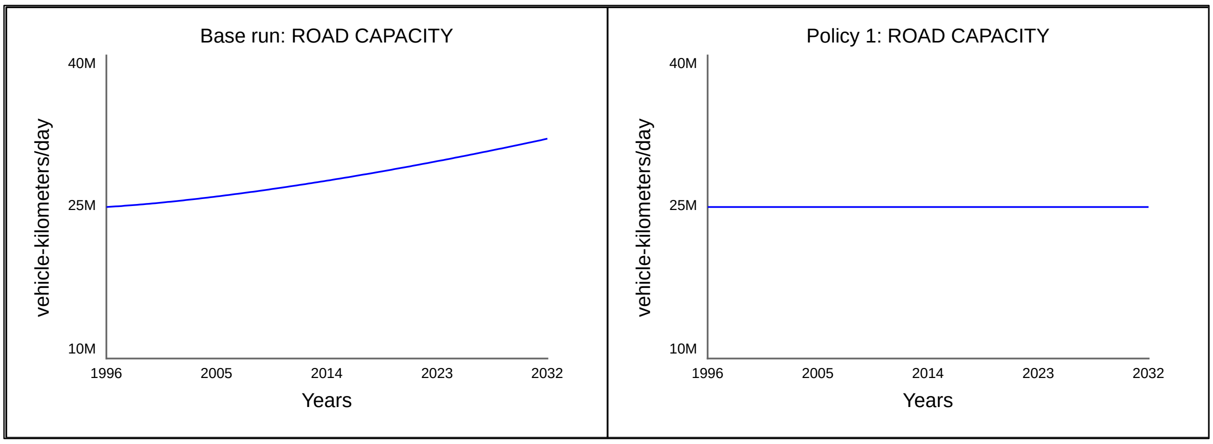

Figure 37 – Base run vs. policy 1: road capacity

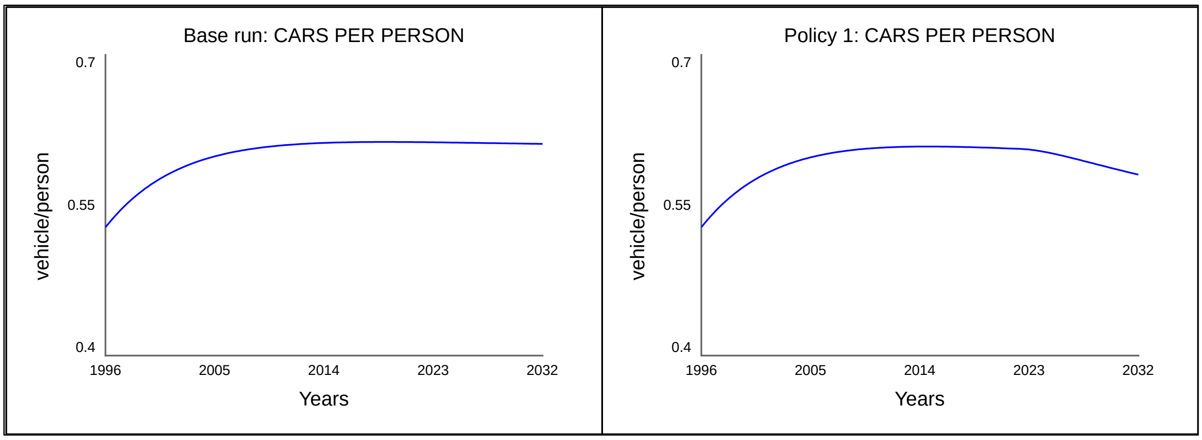

Figure 38 – Base run vs. policy 1: cars per person

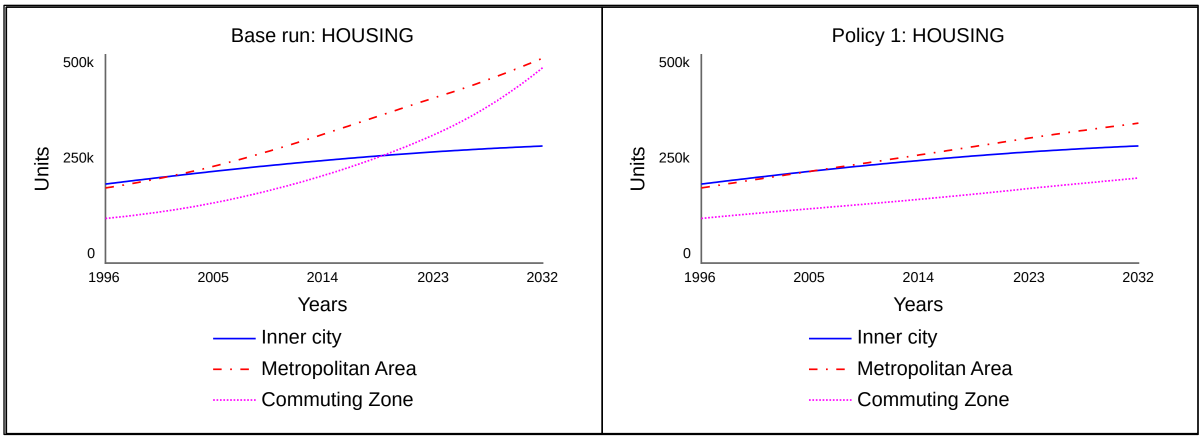

Figure 39 – Base run vs. policy 1: housing

Policy 2: No road construction from 2022-2032

Policy 2 answers the question of what would happen if no more roads were built over the next ten years. Thus, it is another example of the "absolute target solution". Regarding car usage, there is a very slight decline in "car per person" from about 2023 onwards relative to the base run. This gives a good indication of the timeframes involved; ten years of not increasing road capacity has only a negligible effect. However, over many more decades there will likely be an appreciable effect on how many people rely on cars as indicated by testing policy 1.

The situation is the same regarding sprawl. The metropolitan area sees the least development relative to the base run. The loop dominance analysis revealed that the metropolitan area is most sensitive to road construction, so this is expected. Still, both the metropolitan area and the commuting zone see their respective curves become less steep. Like “cars per person”, the development going forward will likely not accelerate and grow as much as the “business-as-usual” base run.

Anderson et al. (1996, p. 13) explains how policies targeted at sprawl may not have any great effect because the infrastructure is already in place – sprawl is built into the “hardware” of the system and therefore difficult to reverse. Policy 2 would be an example of this; ten years of not adding to the road network, and very little happens. But what if one were restructure the “hardware”? Road reallocation is an option which policy 3 gets at.

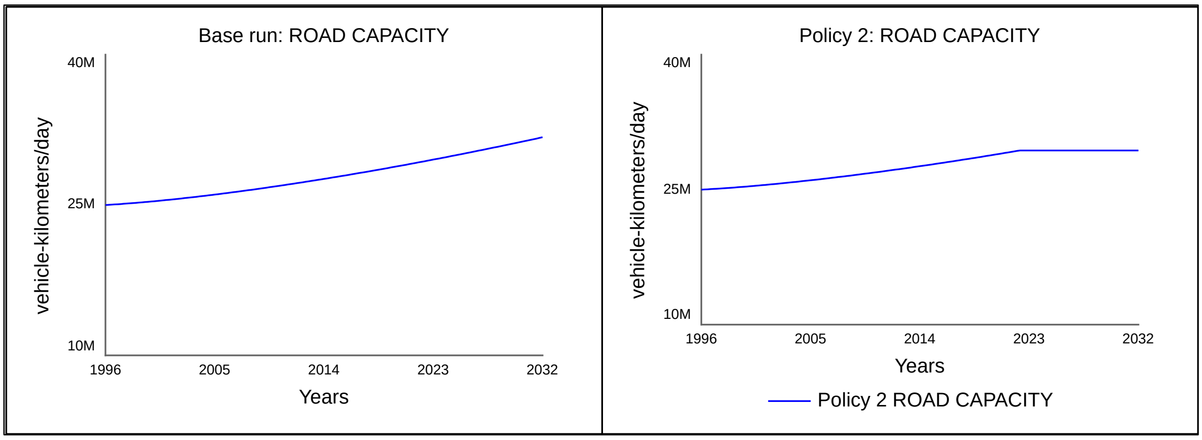

Figure 40 Base run vs. policy 2: road capacity

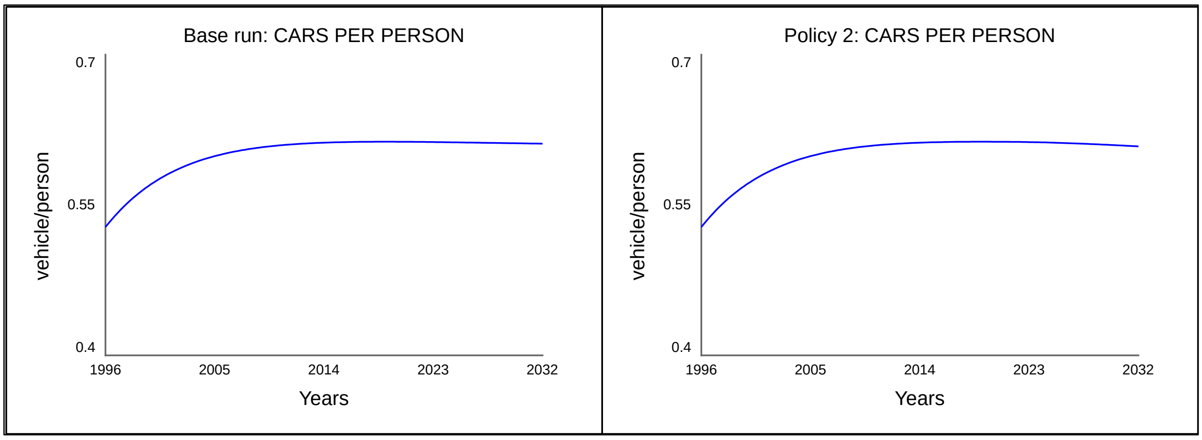

Figure 41 – Base run vs. policy 2: cars per person

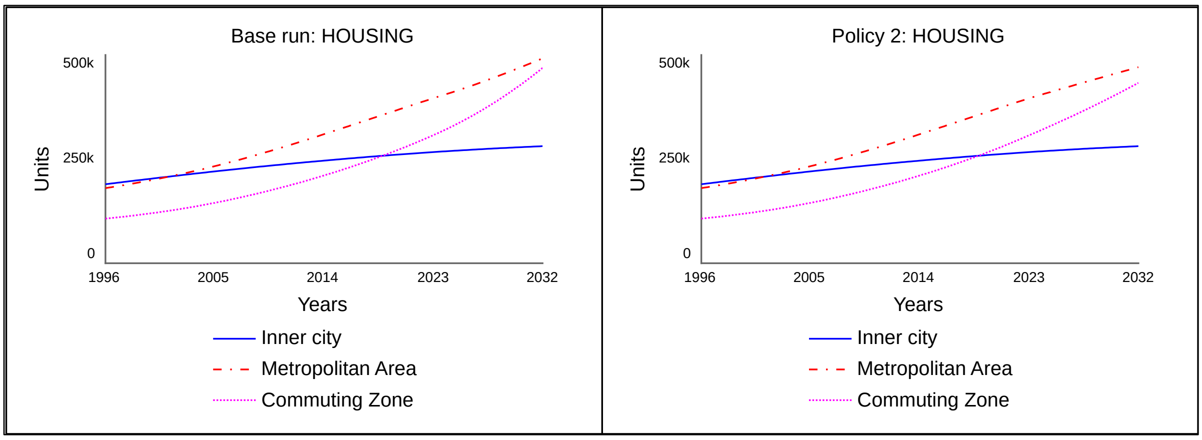

Figure 42 – Base run vs. policy 2: housing

Policy 3: Reallocating 2% of roads space from 2022-2032

Policy 3, instead of ceasing road construction, policy 3 reduces road capacity from 2022 onwards by 2% each year. Urban sprawl is radically reduced under this scenario. Looking at Figure 45, housing in areas surrounding the inner-city goes slightly down after 2022 instead of the exponential growth shown in the "business-as-usual" base run.

One might expect extreme levels of congestion when removing roads, but this is not so. As roads are taken away, travel times by car increase. Under this scenario, if there are other alternatives (public transport, bike lanes, etc.), people will likely choose not to drive. That is why in Figure 44, the "cars per person" sharply declines from 2022 onwards. This here is an example of a systemic intervention with high leverage potential. It gets at the most fundamental driver of sprawl as identified by this work, namely road construction.

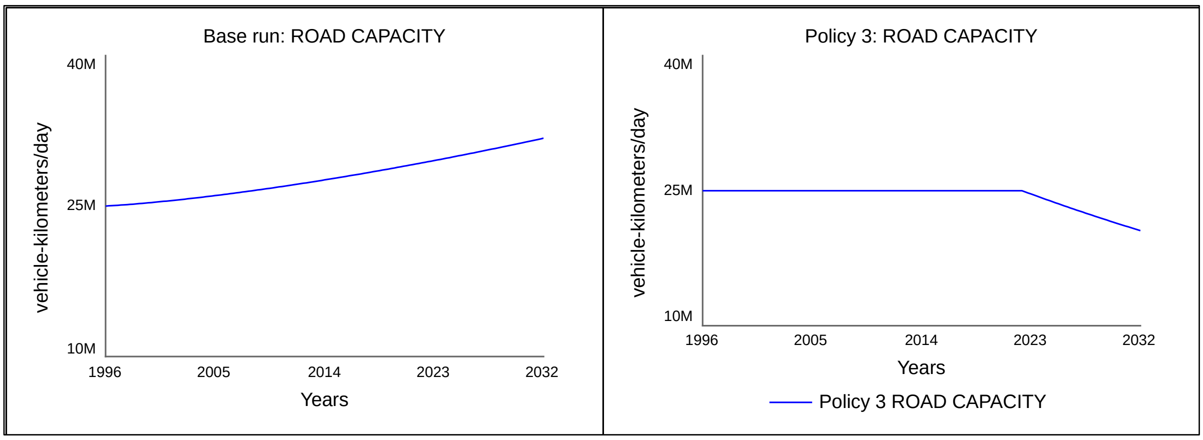

Figure 43 – Base run vs. policy 3: road capacity

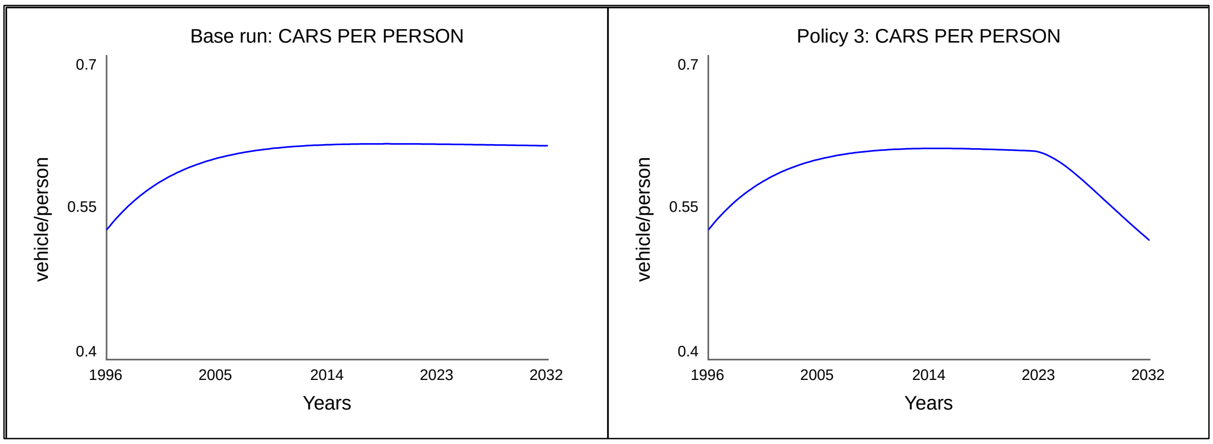

Figure 44 – Base run vs. policy 3: cars per person

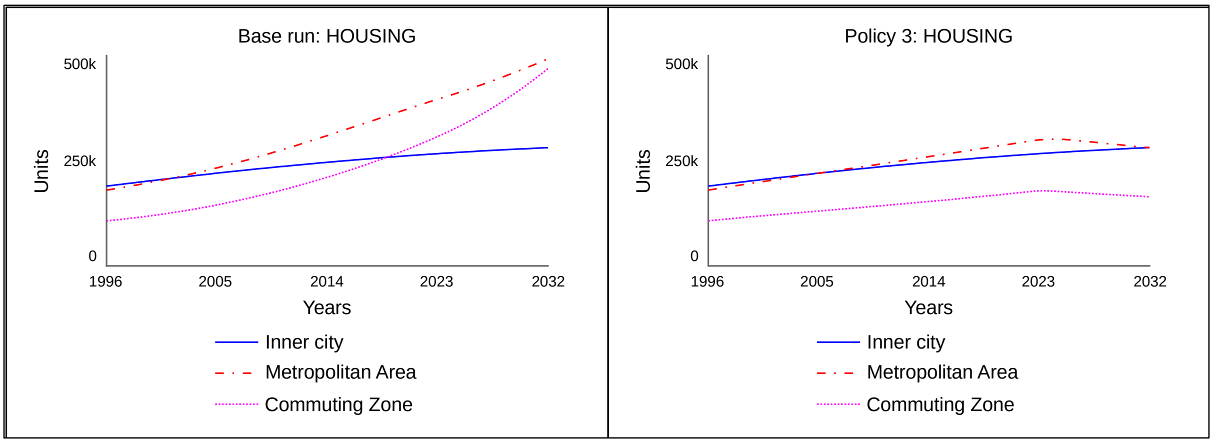

Figure 45 – base run vs. policy 3: housing

3.3 Results and discussion

This thesis addresses two research questions: *"What are the endogenous drivers of observed urban sprawl?"*; and "*What is, and has been, the effects of building roads on urban sprawl?"*. Both questions have been addressed by following the system dynamics method (see section "2.1 Methodology and process"). The following paragraphs will provide a short summary of the findings and a discussion on them – see the relevant sections for more detail.

3.3.1 RQ1: What are the endogenous drivers of observed urban sprawl?

Every step of the thesis has been concerned with the main research question, *"What are the endogenous drivers of observed urban sprawl?"*, from "1.2 Research review" through "3.3 Policy scenarios – effects of road construction and reallocation". The "2.2 Structural hypothesis – why cities sprawl" lays out the nature of the system driving sprawl. In a nutshell: processes of agglomeration make inner cities grow; surrounding areas get developed provided there is sufficient road infrastructure for convenient access to the inner city. With more people driving, more roads are built, and more surrounding areas get developed and thus cities sprawl.

3.3.2 RQ2: What is, and has been, the effects of building roads on urban sprawl?

The literature on sprawl makes it clear that road construction has special significance, and therefore it was pertinent to ask the second research question "*What is, and has been, the effects of building roads on urban sprawl?"*. During modelling it became clear that the model structures of models such as *Urban Dynamics* (Forrester, 1969) and *Urban1* (Alfeld & Graham, 1976) were insufficient in explaining the outward expansion of cities, but with the inclusion of the personal transport sector the reference modes could be replicated.

Replicating the reference modes – with transport considered – gave the first indication of road construction's significance from an endogenous systems perspective. The following 3.2.3 Loop dominance analysis and behaviour replication made it all but certain (for this case). Out of the 8 loop concepts with the most explanatory power with respect to the model behaviour, three out of the top four were directly linked with road construction.

The "3.3 Policy scenarios – effects of road construction and reallocation" gave further evidence of road construction's effects on sprawl: building fewer of them halted development in peripheral areas and ensured higher densities. It also made explicit that sprawl is not an inevitability, but instead the effect of conscious policy choices. In the case of Dublin, where this process has gone on for decades, merely stopping road construction will make little difference in the medium term. Road reallocation however could be a viable strategy for incentivising compactness of the urban form – given sufficient alternatives to driving.

3.3.3 Discussion

The model has been calibrated to a single city and its surrounding area. It convincingly replicates data from that region, the Greater Dublin Area, and as such serves as a successful first attempt at including the spatial dimension to city growth with a system dynamics approach. However, it cannot be claimed that this model is generally applicable until more cities, over different time horizons have been replicated.

The attempt has been to avoid any claims to the normative status of urban sprawl beyond what the literature reflects. And very specific policy recommendations were never the ambition of this project. However, if sprawl is to be avoided it seems a new perspective is warranted on how roads are used, and our relationship to cars. That is a central finding of this project, and it reflects the wider literature.

That said, it would be a shame if personal cars went away completely. They remain a brilliant invention, and a cherished recreation for many. Webber (1994) made the observation that like telephones, cars "permit a direct connection from everywhere to everywhere" (p. 28). Public transport does not. The objective is to balance the negative externalities of urban sprawl, as they are, with a sustainable relationship to transportation and living needs, such that collective well-being is ensured to the highest degree.

3.4 Limitations

By the models very nature there are several limitations to it; the intention behind it was to create as generalisable a model as possible. The scope of this thesis project did not allow the model to be tested on cities and regions other than the Greater Dublin Area, but the long-term ambition is to do so. Since the model is intended to capture any city and its surrounding regions regardless of its level of development, there are particularities about the Irish context that are not explicitly included. In this sense, this limitation is there by design such that the model can be applied to many different contexts while changing as little as possible to its structure.

Still, there are aspects of every city that could have been included – if nothing else, then for ruling them out as inconsequential for sprawl. The economic incentive for developers is one; it is generally more profitable to develop untouched greenfield sites than it is to redevelop previously developed brownfield sites which likely influences the urban form. These incentives structures would have been an interesting inclusion, especially for policy testing purposes.

Perceived environmental quality and health concerns are also potential drivers of sprawl that could be included in the model. Air, water, and noise pollution and any other form of pollution resulting from high "loading" of human activity onto the land probably drive people out of dense areas and towards the suburbs. Measure of gentrification and crime too could have independent effects on the where people choose (or are forced) to live.

The most glaring omissions however are public transport and economic development outside of the inner city, and their effects on the system. High quality public transport likely has compacting effect on the urban form, and sprawl likely erodes that quality – so there are almost certainly important feedbacks there. Also, it's a truism that "jobs follow people", and the economic development that will pop up outside of the inner city will necessarily have an independent draw on people – and therein lies even more feedback. As of now, some of these elements are partly baked into the effect variables between the sectors of the model, but it would benefit from the inclusion of these elements as well (especially if longer time horizons are to be explored).

3.5 Future research

As this project is an early attempt at modelling urban sprawl endogenously, there is much work to be done. The most interesting are the following. First, the model needs to be applied to more cities to confirm and strengthen its generalisability. Second, there are aspects of all cities that the model does not capture. It would be fruitful to try and include the effects of public transport for example to see how it interacts with sprawl. Third, the economic incentives for developers, as defined by policy or otherwise, is likely an interesting inclusion.

A last consideration for future research is adapting this model, or creating a new one, that can capture a multinucleated or polycentric city. The multinucleated or polycentric urban form is one in which a FUA has not one urban centre, but several "nodes" or "nuclei" all providing services and economic opportunity for those in its vicinity. This project's model construes the city as monocentric and expanding concentrically outward (if it sprawls). However, sprawl can also be understood as a matter of degree (Ewing, 2008, p. 520). Scattered development is the typical manifestation of sprawl, but scattered development is one end of a spectrum that has multinucleated, or polycentric development on the other end. "At what number of centres polycentrism ceases and sprawl begins is not clear" states Gordon and Wong (1985, p. 662).

Scattered development is considered inefficient as far as infrastructure, public service provision, etc. is concerned. Well-planned multinucleation on the other hand, can be more efficient even than very compact centralised urban forms when the single centre and its metropolitan area has grown beyond a certain size and population threshold (Anderson et al., 1996; Haines, 1986; Tayyaran & Khan, 1994). Since sprawl tends to produce scattered development and scattered development exists on the same spectrum as multinucleation, harnessing sprawl to steer the urban form towards a multinucleated one is a very exciting prospect if that is indeed desirable. This idea was put forth by Anderson et al. (1996, p. 19). Unfortunately, the current model created for this project can only capture concentrically expanding FUAs from a single node so to explore what it is that drives the single metropolitan area to expand its borders.

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Appendices

Appendix I: sensitivity analysis parameter values and units

Parameters	Values	Units
Available_land_area	11700	ha
Carrying_capacity[Inner_city]	700000	People
Carrying_capacity[Metropolitan_Area]	1100000	People
Carrying_capacity[Commuting_Zone]	1400000	People
Commercial_building_lifetime	55	Years
House_lifetime	100	Years
Initial_region_travel_time[Inner_city]	15	minutes/day
Initial_region_travel_time[Metropolitan_Area]	30	minutes/day
Initial_region_travel_time[Commuting_Zone]	45	minutes/day
Inner_city_labour_participation_fraction[Inner_city]	0.65	People/People
Inner_city_labour_participation_fraction[Metropolitan_Area]	0.14	People/People
Inner_city_labour_participation_fraction[Commuting_Zone]	0.04	People/People
Jobs_per_commercial_structure	35	jobs/ComBuildings
Land_per_commercial_building	0.155	ha/ComBuildings
Land_per_residential_unit	0.015	ha/Units
Maximum_fractional_birth_rate	0.019	people/people/year
Normal_business_construction_fraction	0.05	ComBuildings/ComBuildings/year
Normal_cars_per_person	1	vehicle/person
Normal_housing_construction_fraction_Dublin[Inner_city]	0.015	Units/Units/year
Normal_housing_construction_fraction_Dublin[Metropolitan_Area]	0.03	Units/Units/year
Normal_housing_construction_fraction_Dublin[Commuting_Zone]	0.03	Units/Units/year
People_per_household[Inner_city]	2.5	people/households
People_per_household[Metropolitan_Area]	3.01	people/households
People_per_household[Commuting_Zone]	3.01	people/households
Sensitivity_of_distance_driven_to_ratio_of_inner_city_commuters_to_the_total	-1	dmnl
sensitivity_of_housing_construction_to_road_capacity[Metropolitan_Area]	15	dmnl
sensitivity_of_housing_construction_to_road_capacity[Commuting_Zone]	30	dmnl
sensitivity_of_housing_construction_to_travel_time[Metropolitan_Area]	-2	dmnl
sensitivity_of_housing_construction_to_travel_time[Commuting_Zone]	-4	dmnl
Sensitivity_of_migration_to_housing_availability[Inner_city]	-1	dmnl
Sensitivity_of_migration_to_housing_availability[Metropolitan_Area]	-5	dmnl
Sensitivity_of_migration_to_housing_availability[Commuting_Zone]	-17.5	dmnl
Speed_limit	1	km/minute
Time_to_react_to_pressure_and_build_roads	5	Years
Time_to_switch_transport_mode	7	year

Figure 46 – Base run parameters, their values, and units

Appendix II: historic behaviour replication

The following graphs shows model behaviour plotted over the all the raw data collected for the key variables in the model.

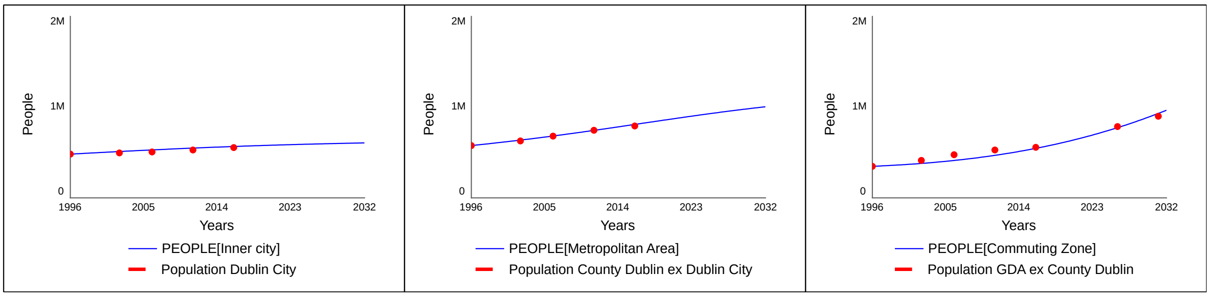

Figure 47 – Calibration data: population (inner city, metropolitan area, commuting zone) (CSO, 1996, 2016d, 2016e)

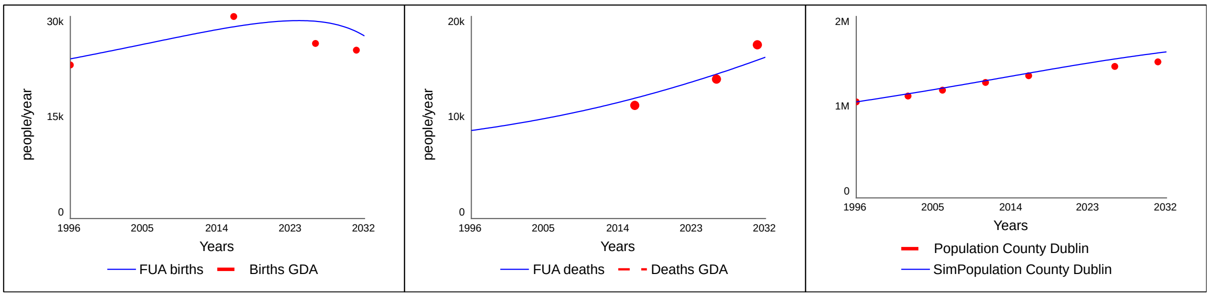

Figure 48 – Calibration data: population change (CSO, 2016c) (every region) and population County Dublin (CSO, 2016d)

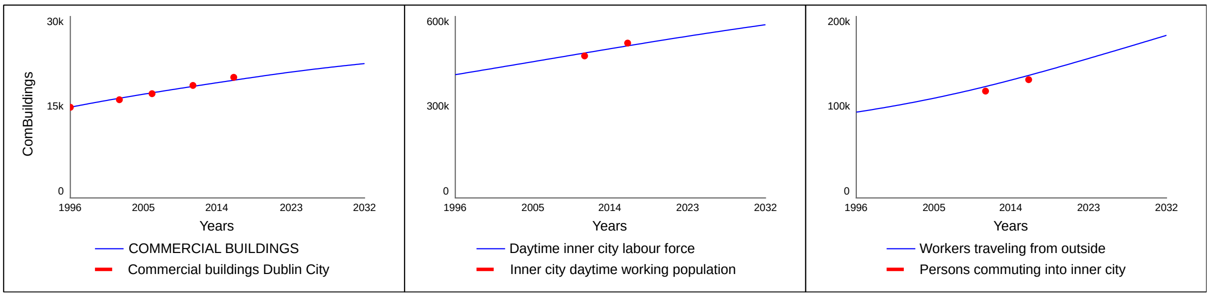

Figure 49 – Calibration data: commercial buildings (Group, 2015), commuting (CSO, 2016a), and work force (CSO, 2016a)

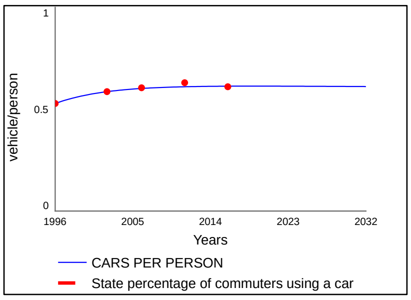

Figure 50 – Calibration data: Cars per person (CSO, 2016a)

Appendix III: model documentation

The following is the complete documentation for the Sprawl Dynamics model as initialised for the Greater Dublin Area.

{ The model has 99 (151) variables (array expansion in parens).

In root model and 0 additional modules with 4 sectors.

Stocks: 5 (9) Flows: 9 (19) Converters: 85 (123)

Constants: 45 (63) Equations: 49 (79) Graphicals: 7 (9) }

Top-Level Model:

CARS_PER_PERSON(t) = CARS_PER_PERSON(t - dt) + (Change_in_cars_per_person) * dt

INIT CARS_PER_PERSON = State_percentage_of_commuters_using_a_car

UNITS: vehicle/person

DOCUMENT: The stock CARS PER PERSON is a measure of the proportion of people who drive a car for their work commute. It accumulates its inflow change in cars per person. The stock is initialised with data from the Irish Central Statistics office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/)

COMMERCIAL_BUILDINGS(t) = COMMERCIAL_BUILDINGS(t - dt) + (Business_construction - Business_demolition) * dt

INIT COMMERCIAL_BUILDINGS = 15000

UNITS: ComBuildings

DOCUMENT: The stock COMMERCIAL BUILDINGS is the measure of all commercial buildings in the Inner City. It accumulates its inflow business construction and is depleted by its outflow business demolition. The initial value is based on business demography data from the Irish Central Statistics Office (CSO, 2019, https://data.cso.ie/table/BRA18) and assumptions on the average number of businesses per building.

HOUSING[Inner_city](t) = HOUSING[Inner_city](t - dt) + (Housing_construction[Inner_city] - Housing_demolition[Inner_city]) * dt

INIT HOUSING[Inner_city] = Housing_stock_Dublin_City

UNITS: Units

DOCUMENT: The stock HOUSING is arrayed by region. It accumulates the inflow housing construction and is depleted by its outflow housing demolition. The initial values for each array are based on data from the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

HOUSING[Metropolitan_Area](t) = HOUSING[Metropolitan_Area](t - dt) + (Housing_construction[Metropolitan_Area] - Housing_demolition[Metropolitan_Area]) * dt

INIT HOUSING[Metropolitan_Area] = Housing_stock_County_Dublin_ex_Dublin_city

UNITS: Units

DOCUMENT: The stock HOUSING is arrayed by region. It accumulates the inflow housing construction and is depleted by its outflow housing demolition. The initial values for each array are based on data from the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

HOUSING[Commuting_Zone](t) = HOUSING[Commuting_Zone](t - dt) + (Housing_construction[Commuting_Zone] - Housing_demolition[Commuting_Zone]) * dt

INIT HOUSING[Commuting_Zone] = Housing_stock_GDA_ex_County_Dublin

UNITS: Units

DOCUMENT: The stock HOUSING is arrayed by region. It accumulates the inflow housing construction and is depleted by its outflow housing demolition. The initial values for each array are based on data from the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

PEOPLE[Inner_city](t) = PEOPLE[Inner_city](t - dt) + (Birth_rate[Inner_city] + Net_migration_rate[Inner_city] - Death_rate[Inner_city]) * dt

INIT PEOPLE[Inner_city] = Population_Dublin_City

UNITS: People

DOCUMENT: The stocks of PEOPLE are arrayed by region. It accumulates its inflows birth rate and net migration rate. It declines as people die by way of the stocks' death rate outflows. The initial values for each regions stock of people where collected from the Irish Central Statistics Office (CSO, 2016a, https://data.cso.ie/table/E2001, 1996, https://data.cso.ie/table/A0101).

PEOPLE[Metropolitan_Area](t) = PEOPLE[Metropolitan_Area](t - dt) + (Birth_rate[Metropolitan_Area] + Net_migration_rate[Metropolitan_Area] - Death_rate[Metropolitan_Area]) * dt

INIT PEOPLE[Metropolitan_Area] = Population_County_Dublin_ex_Dublin_City

UNITS: People

DOCUMENT: The stocks of PEOPLE are arrayed by region. It accumulates its inflows birth rate and net migration rate. It declines as people die by way of the stocks' death rate outflows. The initial values for each regions stock of people where collected from the Irish Central Statistics Office (CSO, 2016a, https://data.cso.ie/table/E2001, 1996, https://data.cso.ie/table/A0101).

PEOPLE[Commuting_Zone](t) = PEOPLE[Commuting_Zone](t - dt) + (Birth_rate[Commuting_Zone] + Net_migration_rate[Commuting_Zone] - Death_rate[Commuting_Zone]) * dt

INIT PEOPLE[Commuting_Zone] = Population_GDA_ex_County_Dublin

UNITS: People

DOCUMENT: The stocks of PEOPLE are arrayed by region. It accumulates its inflows birth rate and net migration rate. It declines as people die by way of the stocks' death rate outflows. The initial values for each regions stock of people where collected from the Irish Central Statistics Office (CSO, 2016a, https://data.cso.ie/table/E2001, 1996, https://data.cso.ie/table/A0101).

ROAD_CAPACITY(t) = ROAD_CAPACITY(t - dt) + (Road_construction) * dt

INIT ROAD_CAPACITY = 25000000

UNITS: vehicle-kilometers/day

DOCUMENT: The stock ROAD CAPACITY is a representation of the road capacity in the whole FUA. It accumulates its inflow road construction.

Birth_rate[Region] = Maximum_growth_rate*(PEOPLE/Carrying_capacity)*(1-PEOPLE/Carrying_capacity)*4

UNITS: People/Years

DOCUMENT: The birth rate is arrayed by region. It is the rate at which infants are born. The birth rate for each region corresponds to the population in the region. The relationship between population and birth rate is non-linear and follows the logic of a surplus growth curve dependent on the maximum growth rate and the carrying capacity for each region.

Business_construction =
COMMERCIAL_BUILDINGS*Business_construction_fraction

UNITS: ComBuildings/Years

DOCUMENT: The business construction is the rate at which commercial buildings are erected. It is the product of COMMERCIAL BUILDINGS and the business construction fraction.

Business_demolition = COMMERCIAL_BUILDINGS/Commercial_building_lifetime

UNITS: ComBuildings/Years

DOCUMENT: Business demolition is the rate at which COMMERCIAL BUILDINGS depreciate and are demolished. It is the quotient of COMMERCIAL BUILDINGS divided by commercial building lifetime.

Change_in_cars_per_person =
("Indicated_cars_per_person_(attractiveness_of_cars)"-
CARS_PER_PERSON)/Time_to_switch_transport_mode

UNITS: vehicle/person/Years

DOCUMENT: The change in cars per person is a first order information delay that updates the stock CARS PER PERSON to the indicated cars per person with a delay given by the parameter time to switch transport mode.

Death_rate[Region] = PEOPLE*Deaths_fraction

UNITS: People/year

DOCUMENT: The death rate is arrayed by region and is the rate at which people die in each region. The death rates for each region depletes the PEOPLE stocks for the corresponding region. The death rates are proportional and linearly dependent on the size of the relevant stock of PEOPLE and the Deaths fraction.

Housing_construction[Region] = HOUSING*Housing_construction_fraction
{UNIFLOW}

UNITS: Units/Years

DOCUMENT: The housing construction is the rate at which housing is constructed and it is arrayed by region. It is the product of the stock HOUSING and the housing construction fraction for each of the regions.

Housing_demolition[Region] = HOUSING/House_lifetime

UNITS: Units/Years

DOCUMENT: Housing demilition is arrayed by region and is the rate at which houses are demolished. It is the product of the stock HOUSING and parameter house lifetime.

Net_migration_rate[Inner_city] = PEOPLE[Inner_city]*Normal_fractional_net_migration*Effect_of_housing_availability_on_migration[Inner_city]*Effect_of_job_availability_on_migration

UNITS: People/Years

DOCUMENT: The net migration rate is arrayed by region and is the rate at which people migrate into and out of any of the three regions. For each region it is the product of the normal fractional net migration, the stock of PEOPLE, the effect of housing availability on migration and the effect of job availability on migration. It is assumed that each regions net migration rate increases by the normal fractional net migration proportionally to the relevant stock of PEOPLE for the region, but with effects of housing availability and effects of job availability influencing the rate. It's assumed to be a purely multiplicative relationship because if there are no jobs available, or there are no houses available there is no reason to move to the region.

Net_migration_rate[Metropolitan_Area] = PEOPLE[Metropolitan_Area]*Normal_fractional_net_migration*Effect_of_housing_availability_on_migration[Metropolitan_Area]*Effect_of_job_availability_on_migration

UNITS: People/Years

DOCUMENT: The net migration rate is arrayed by region and is the rate at which people migrate into and out of any of the three regions. For each region it is the product of the normal fractional net migration, the stock of PEOPLE, the effect of housing availability on migration and the effect of job availability on migration. It is assumed that each regions net migration rate increases by the normal fractional net migration proportionally to the relevant stock of PEOPLE for the region, but with effects of housing availability and effects of job availability influencing the rate. It's assumed to be a purely multiplicative relationship because if there are no jobs available, or there are no houses available there is no reason to move to the region.

Net_migration_rate[Commuting_Zone] = PEOPLE[Commuting_Zone]*Normal_fractional_net_migration*Effect_of_housing_availability_on_migration[Commuting_Zone]*Effect_of_job_availability_on_migration

UNITS: People/Years

DOCUMENT: The net migration rate is arrayed by region and is the rate at which people migrate into and out of any of the three regions. For each region it is the product of the normal fractional net migration, the stock of PEOPLE, the effect of housing availability on migration and the effect of job availability on migration. It is assumed that each regions net migration rate increases by the normal fractional net migration proportionally to the relevant stock of PEOPLE for the region, but with effects of housing availability and effects of job availability influencing the rate. It's assumed to be a purely multiplicative relationship because if there are no jobs available, or there are no houses available there is no reason to move to the region.

Road_construction = (Desired_highway_capacity-ROAD_CAPACITY)/Time_to_react_to_pressure_and_build_roads

UNITS: vehicle-kilometers/day/Years

DOCUMENT: The road construction is the rate at which new roads are built in the whole FUA. It is a first order information delay in which updates the stock ROAD CAPACITY so to reach the Desired highway capacity with a adjustment time given by the time to react to pressure and build roads.

"TEMP.Population_Dublin_County_ex_Dublin_City" = 576410

UNITS: People

"TEMP.Population_GDA_ex_County_Dublin" = 347407

UNITS: People

Available_land_area = 11700

UNITS: ha

DOCUMENT: The parameter available land area is just that, the size of Dublin City (Dublin City Council, n.d.)

Average_distance_driven_per_day = Initial_average_distance_driven*Effect_of_commuters'_place_of_living_on_distance_driven

UNITS: km/day

DOCUMENT: The average distance driven is the average distance driven per day in the region. It is the product of initial average distance driven and effect of commuters' place of licing on distance driven

Average_travel_time_by_car_by_region[Region] = Initial_region_travel_time*Effect_of_congestion_on_travel_time

UNITS: minutes/day

DOCUMENT: The variable average travel time by car by region is arrayed by region. It is for each respective region the average travel time as the names suggests. It is the product of initial region travel time and the effect of congestion on travel time.

Births_Dublin_City = NAN

UNITS: People/year

DOCUMENT: These data make very little sense, there are four times as many births every year than there are people under 1 years old - so we'll forget this for a while

Births_GDA = NAN

UNITS: people/year

Births_GDA_ex_County_Dublin = NAN

UNITS: people/year

Business_construction_fraction = (Normal_business_construction_fraction*Effect_of_labour_force_availability_on_business_construction*Effect_of_land_availability_on_business_construction)

UNITS: ComBuildings/ComBuildings/year

DOCUMENT: The business construction fraction is the product of the normal business construction fraction, the effect of labour force availability on business construction and the effect of land availability on business construction. The relationship between the effect are considered multiplicative because no labour force or no land availability will seize all or almost all construction of commercial buildings.

Businesses_Dublin_City = NAN

UNITS: Bussinesses

Businesses_per_building_Dublin_City = 4

UNITS: Bussinesses/ComBuildings

Carrying_capacity[Inner_city] = 700000

UNITS: People

DOCUMENT: The parameter Carrying capacity is arrayed by region and represents the maximum number of people a given region can hold. It is calibrated to population statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections)

Carrying_capacity[Metropolitan_Area] = 1100000

UNITS: People

DOCUMENT: The parameter Carrying capacity is arrayed by region and represents the maximum number of people a given region can hold. It is calibrated to population statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections)

Carrying_capacity[Commuting_Zone] = 1400000

UNITS: People

DOCUMENT: The parameter Carrying capacity is arrayed by region and represents the maximum number of people a given region can hold. It is calibrated to population statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections)

Cars_in_the_region = Daytime_inner_city_labour_force*CARS_PER_PERSON

UNITS: vehicle

DOCUMENT: The variable cars in the region is just that, it is the cars in the region used by work commuters. It is the product of daytime inner city labour force and the stock CARS PER PERSON.

Commercial_building_lifetime = 55

UNITS: Years

DOCUMENT: The parameter commercial building lifetime is the length of time that commercial buildings are in use before they are demolished. The value is based on statements by a commercial building construction company (Shingobee, 2021).

Commercial_buildings_Dublin_City = Businesses_Dublin_City/Businesses_per_building_Dublin_City

UNITS: ComBuildings

Congestion = Traffic_volume/ROAD_CAPACITY

UNITS: dmnl

DOCUMENT: The congestion is the the measure of how much of the road capacity is used per day. It is the quotient of traffic volume divided by ROAD CAPACITY.

Daytime_inner_city_labour_force = Inner_city_labour_force_by_region[Inner_city]+Inner_city_labour_force_by_region[Metropolitan_Area]+Inner_city_labour_force_by_region[Commuting_Zone]

UNITS: People

DOCUMENT: The variable daytime inner city labour force is the total daytime workforce of the inner city including those who travel into the inner city from the other regions.

Deaths_Dublin_City = NAN

UNITS: People/year

Deaths_fraction = 0.0062

UNITS: people/people/year

DOCUMENT: The deaths fraction is the probability of any given person dying every year. It is based on regional and state statistics from the Irish Central Statistics Office (CSO, 2021, https://data.cso.ie/table/VSA03, 2019, https://data.cso.ie/table/VSA38)

Deaths_GDA = NAN

UNITS: people/year

Desired_highway_capacity = ROAD_CAPACITY*Pressure_to_reduce_congestion

UNITS: vehicle-kilometers/day

DOCUMENT: The desire highway capacity is the product of ROAD CAPACITY and pressure to reduce congestion. As pressure to reduce congestion rise the desired highway capacity rises. It is the goal for the stock ROAD CAPACITY.

Effect_of_commuters'_place_of_living_on_distance_driven = 1+Sensitivity_of_distance_driven_to_ratio_of_inner_city_commuters_to_the_total*((Ratio_of_inner_city_commuters_to_total_commuters/INIT(Ratio_of_inner_city_commuters_to_total_commuters))-1)

UNITS: dmnl

DOCUMENT: The effect of commuters place of living is a linear effect variable influencing the average distance driven per day. The effect produces an output given any change in the variable ratio of inner city commuters to total commuters. The size of the effect is determined by the sensitivity of of distance driven to commuters' place of living. The fewer people who live and work in the inner city relative to every one who works in the inner city the longer the average distance driven - the more people who live further away, the longer the commute is.

Effect_of_congestion_on_travel_time = GRAPH(Congestion)

Points: (0.000, 1.00), (0.100, 1.00), (0.200, 1.00), (0.300, 1.025), (0.400, 1.05), (0.500, 1.41), (0.600, 2.22), (0.700, 3.44), (0.800, 4.87), (0.900, 6.81), (1.000, 9.12), (1.100, 11.90), (1.200, 15.48), (1.300, 19.53), (1.400, 24.00) {GF EXTRAPOLATED}

UNITS: dmnl

DOCUMENT: The effect of congestion on average travel time is a table function producing a nonlinear effect of congestion on average travel time by car by region. The relationship assumed to be exponential - as the roads become more congested the travel time rises faster and faster.

Effect_of_housing_availability_on_housing_construction[Inner_city] = GRAPH(Households_to_houses_ratio)

Points: (0.000, 0.000), (0.250, 0.050), (0.500, 0.100), (0.750, 0.300), (1.000, 1.000), (1.250, 1.800), (1.500, 2.400), (1.750, 2.800), (2.000, 3.000)

UNITS: dmnl

DOCUMENT: The effect of housing availability on housing construction is a table function producing a nonlinear effect of the households to houses ratio on the housing construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969). The relationship is likely s-shaped in that when there are very few families, but an overabundance of houses there is will be less construction going on. As there are more and more families relative to the supply of houses the demand will be higher and more and more houses will be built. The effect levels off at a point where the construction capacity of the region is presumably maxed out.

Effect_of_housing_availability_on_housing_construction[Metropolitan_Area] = GRAPH(Households_to_houses_ratio)

Points: (0.000, 0.000), (0.250, 0.050), (0.500, 0.100), (0.750, 0.300), (1.000, 1.000), (1.250, 1.800), (1.500, 2.400), (1.750, 2.800), (2.000, 3.000)

UNITS: dmnl

DOCUMENT: The effect of housing availability on housing construction is a table function producing a nonlinear effect of the households to houses ratio on the housing construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969). The relationship is likely s-shaped in that when there are very few families, but an overabundance of houses there is will be less construction going on. As there are more and more families relative to the supply of houses the demand will be higher and more and more houses will be built. The effect levels off at a point where the construction capacity of the region is presumably maxed out.

Effect_of_housing_availability_on_housing_construction[Commuting_Zone] = GRAPH(Households_to_houses_ratio)

Points: (0.000, 0.000), (0.250, 0.050), (0.500, 0.100), (0.750, 0.300), (1.000, 1.000), (1.250, 1.800), (1.500, 2.400), (1.750, 2.800), (2.000, 3.000)

UNITS: dmnl

DOCUMENT: The effect of housing availability on housing construction is a table function producing a nonlinear effect of the households to houses ratio on the housing construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969). The relationship is likely s-shaped in that when there are very few families, but an overabundance of houses there is will be less construction going on. As there are more and more families relative to the supply of houses the demand will be higher and more and more houses will be built. The effect levels off at a point where the construction capacity of the region is presumably maxed out.

Effect_of_housing_availability_on_migration[Region] = 1+Sensitivity_of_migration_to_housing_availability*(Households_to_houses_ratio /INIT(Households_to_houses_ratio)-1)

UNITS: dmnl

DOCUMENT: The effect of housing availability on migration is arrayed by region. It is a linear effect variable influencing the net migration rate. The effect produces an output given any change in the input variable household to houses ratio. The size of the effect is determined by the sensitivity of migration to housing availability.

Effect_of_job_availability_on_migration = GRAPH(Labour_force_to_jobs_ratio)

Points: (0.000, 2.600), (0.250, 2.600), (0.500, 2.400), (0.750, 1.800), (1.000, 1.000), (1.250, 0.400), (1.500, 0.200), (1.750, 0.100), (2.000, 0.050)

UNITS: dmnl

DOCUMENT: The effect of job availability on migration is a table function producing a nonlinear effect of the labour force to jobs ratio on the net migration rate. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969). Job opportunity influences a regions attractiveness, and the relationship is likely z-shaped; when there are a lot of jobs available the area is attractive, and there is more immigration, and as vacancies are filled and there are fewer, or no jobs available migration is reduced. The table function has a similar effects on migration in each of the three regions, but it only considers the jobs and the labourforce in the inner city, and not job opportunities elsewhere (a limitation of the model).

Effect_of_labour_force_availability_on_business_construction = GRAPH(Labour_force_to_jobs_ratio)

Points: (0.000, 0.01339), (0.250, 0.04595), (0.500, 0.1517), (0.750, 0.4454), (1.000, 1.000), (1.250, 1.555), (1.500, 1.848), (1.750, 1.954), (2.000, 1.987) {GF EXTRAPOLATED}

UNITS: dmnl

DOCUMENT: The effect of labour force availability on business construction is a table function producing a nonlinear effect of the labour force to jobs ratio to houses ratio on the housing construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969) and is similar to the table function Effect of housing availability on construction. The relationship is likely s-shaped in that when the labour force is small, but there is an overabundance of houses there will be less construction going on. As the labour force grows relative to the number of job available more commercial buildings will get built. The effect levels off at a point where the construction capacity of the region is presumably maxed out.

Effect_of_land_availability_on_business_construction = GRAPH(Inner_city_land_fraction_occupied)

Points: (0.000, 1.000), (0.100, 1.150), (0.200, 1.300), (0.300, 1.400), (0.400, 1.450), (0.500, 1.400), (0.600, 1.300), (0.700, 1.000), (0.800, 0.700), (0.900, 0.400), (1.000, 0.000)

UNITS: dmnl

DOCUMENT: The effect of land availability on business construction is a table function producing a nonlinear effect of the inner city land fraction occupied on the business construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969) and is similar to the table function effect of land availability on housing construction. When first there are some people who settle in an area and there is some economic activity going on it will become increasingly attractive as it produces agglomeration economies and community. As the land area becomes increasingly occupied there will be fewer sites that can be developed until there are none left and area has reached its capacity.

Effect_of_land_availability_on_housing_construction = GRAPH(Inner_city_land_fraction_occupied)

Points: (0.000, 0.400), (0.100, 0.900), (0.200, 1.300), (0.300, 1.600), (0.400, 1.800), (0.500, 1.900), (0.600, 1.800), (0.700, 1.400), (0.800, 0.700), (0.900, 0.200), (1.000, 0.000)

UNITS: dmnl

DOCUMENT: The effect of land availability on housing construction is a table function producing a nonlinear effect of the inner city land fraction occupied on the housing construction fraction. It's logic is based on similar model structure from Forrester's Urban Dynamics (1969). When first there are some people who settle in an area and there is some economic activity going on it will become increasingly attractive as it produces agglomeration economies and community. As the land area becomes increasingly occupied there will be fewer sites that can be developed until there are none left and area has reached its capacity.

Effect_of_road_capacity_on_housing_construction[Region] = 1+sensitivity_of_housing_construction_to_road_capacity*((ROAD_CAPACITY/INIT(ROAD_CAPACITY))-1)

UNITS: dmnl

DOCUMENT: The effect of road capacity on housing construction is arrayed by region. It is a linear effect variable influencing the housing construction fraction. The effect produces an output given any change in the stock ROAD CAPACITY. The size of the effect is determined by the sensitivity of housing construction to road capacity which is different for the different regions, and non-existent for the inner city. The logic is that as the highway capacity increase and more roads are built, more and more areas peripheral to the inner city can be developed.

Effect_of_travel_time_on_attractiveness_of_driving = GRAPH(FUA_average_travel_time)

Points: (15.00, 0.7893), (18.75, 0.7784), (22.50, 0.7569), (26.25, 0.7165), (30.00, 0.6459), (33.75, 0.5375), (37.50, 0.4000), (41.25, 0.2625), (45.00, 0.1541), (48.75, 0.08346), (52.50, 0.04306), (56.25, 0.02163), (60.00, 0.01071)

UNITS: dmnl

DOCUMENT: The effect of travel time on attractiveness of driving is a table function producing a nonlinear effect of FUA average travel time on indicated cars per person. The relationship is z-shaped. With very low travel times by car to one's place of work, driving them is very attractive, and as travel time rises it drops faster and faster. As travel times by car to one's place of work approaches an hour it the drop in the effect slows as there will continue to be those who continue to appreciate driving despite long travel times, or cannot use alternative modes for whatever reason. The size of the effect is calibrated to data from the Irish Central Statistics Office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/).

Effect_of_travel_time_on_housing_construction[Region] = 1+sensitivity_of_housing_construction_to_travel_time*(FUA_average_travel_time /INIT(FUA_average_travel_time)-1)

UNITS: dmnl

DOCUMENT: The effect of travel time on housing construction is arrayed by region. It is a linear effect variable influencing the housing construction fraction. The effect produces an output given any change in the variable FUA average travel time. FUA is short for functional urban area as defined in section 1.4 reference modes and the Irish context. The size of the effect is determined by the sensitivity of housing construction to travel time which is different for the different regions, and non-existent for the inner city. The logic is that as travel times in the region decreases the size of the area within an acceptable travel time from the inner city increases and more house are built further out.

FUA_average_travel_time = MEAN(Average_travel_time_by_car_by_region)

UNITS: minutes/day

DOCUMENT: The FUA travel time is the actual average travel time by car in the whole FUA.

FUA_births = SUM(Birth_rate)

UNITS: people/year

FUA_deaths = SUM(Death_rate)

UNITS: people/year

House_lifetime = 100

UNITS: Years

DOCUMENT: House lifetime is a parameter representing the average lifetime of residential buildings in all the regions the model represents. A precise number could not be procured, so 100 years was landed on as an imprecise assumption that makes the housing stock behave reasonably.

Households[Inner_city] = PEOPLE[Inner_city]/People_per_household[Inner_city]

UNITS: Households

DOCUMENT: Households is arrayed by region and is the product of the stock PEOPLE and People per household. It is the measure of the number of households.

Households[Metropolitan_Area] = PEOPLE[Metropolitan_Area]/People_per_household[Metropolitan_Area]

UNITS: Households

DOCUMENT: Households is arrayed by region and is the product of the stock PEOPLE and People per household. It is the measure of the number of households.

Households[Commuting_Zone] = PEOPLE[Commuting_Zone]/People_per_household[Commuting_Zone]

UNITS: Households

DOCUMENT: Households is arrayed by region and is the product of the stock PEOPLE and People per household. It is the measure of the number of households.

Households_to_houses_ratio[Inner_city] = Households[Inner_city]/HOUSING[Inner_city]

UNITS: Households/Units

DOCUMENT: Households to houses ratio is arrayed by region. It is the quotient of households divided by housing units in each region. It is a measure of housing availability.

Households_to_houses_ratio[Metropolitan_Area] = Households[Metropolitan_Area]/HOUSING[Metropolitan_Area]

UNITS: Households/Units

DOCUMENT: Households to houses ratio is arrayed by region. It is the quotient of households divided by housing units in each region. It is a measure of housing availability.

Households_to_houses_ratio[Commuting_Zone] = Households[Commuting_Zone]/HOUSING[Commuting_Zone]

UNITS: Households/Units

DOCUMENT: Households to houses ratio is arrayed by region. It is the quotient of households divided by housing units in each region. It is a measure of housing availability.

Housing_construction_fraction[Inner_city] = Normal_housing_construction_fraction_Dublin*Effect_of_housing_availability_on_housing_construction*Effect_of_land_availability_on_housing_construction*Effect_of_road_capacity_on_housing_construction*Effect_of_travel_time_on_housing_construction

UNITS: Units/Units/year

DOCUMENT: The housing construction fraction is arrayed and is the product of normal housing construction, the effect of travel time on housing construction, the effect of highway capacity of housing construction and the effect of housing availability. highway capacity and travel time (to ones place of work) does only effect the commuting belts metropolitan area, and the commuting zone, and not the inner city since the travel times are considered negligible once one lives in the inner city where the jobs are. The relationship between the effect are considered multiplicative because a lack of roads, extremely long travel times and an over supply of houses will all stop construction in the area.

Housing_construction_fraction[Metropolitan_Area] = Normal_housing_construction_fraction_Dublin*Effect_of_housing_availability_on_ housing_construction*Effect_of_road_capacity_on_housing_construction*Effect_of_travel_time_on_housing_construction

UNITS: Units/Units/year

DOCUMENT: The housing construction fraction is arrayed and is the product of normal housing construction, the effect of travel time on housing construction, the effect of highway capacity of housing construction and the effect of housing availability. highway capacity and travel time (to ones place of work) does only effect the commuting belts metropolitan area, and the commuting zone, and not the inner city since the travel times are considered negligible once one lives in the inner city where the jobs are. The relationship between the effect are considered multiplicative because a lack of roads, extremely long travel times and an over supply of houses will all stop construction in the area.

Housing_construction_fraction[Commuting_Zone] = Normal_housing_construction_fraction_Dublin*Effect_of_housing_availability_on_housing_construction*Effect_of_road_capacity_on_housing_construction*Effect_of_travel_time_on_housing_construction

UNITS: Units/Units/year

DOCUMENT: The housing construction fraction is arrayed and is the product of normal housing construction, the effect of travel time on housing construction, the effect of highway capacity of housing construction and the effect of housing availability. highway capacity and travel time (to ones place of work) does only effect the commuting belts metropolitan area, and the commuting zone, and not the inner city since the travel times are considered negligible once one lives in the inner city where the jobs are. The relationship between the effect are considered multiplicative because a lack of roads, extremely long travel times and an over supply of houses will all stop construction in the area.

Housing_stock_County_Dublin_ex_Dublin_city = NAN

UNITS: Units

Housing_stock_Dublin_City = NAN

UNITS: Units

Housing_stock_GDA_ex_County_Dublin = NAN

UNITS: Units

"Indicated_cars_per_person_(attractiveness_of_cars)" = Normal_cars_per_person*Effect_of_travel_time_on_attractiveness_of_driving

UNITS: vehicle/person

DOCUMENT: The indicated cars per person (attractiveness of cars) is the goal values for the stock CARS PER PERSON. it is the product of normal cars per person multiplied by the effect of travel time on attractiveness of driving. It is assumed that it is mainly the travel time (i.e., the convenience of driving) that affects the choice to drive or not in Ireland.

Initial_average_distance_driven = Initial_average_travel_time*Speed_limit

UNITS: km/day

DOCUMENT: The initial average distance driven is the initial value that is adjusted by the effect of commuters' place of living to get the average distance driven per day. It is the product of initial average travel time and the speed limit.

Initial_average_travel_time = MEAN(Initial_region_travel_time)

UNITS: minutes/day

DOCUMENT: The initial average travel time is the initial travel time for the whole FUA.

Initial_region_travel_time[Inner_city] = 15

UNITS: minutes/day

DOCUMENT: The initial region travel time is arrayed by region. It is the assumed average travel time at the simulation start time for each region. It is based on transport data from the Irish Central Statistics Office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6td/) and values for each of the regions are distributed around the approximate average.

Initial_region_travel_time[Metropolitan_Area] = 30

UNITS: minutes/day

DOCUMENT: The initial region travel time is arrayed by region. It is the assumed average travel time at the simulation start time for each region. It is based on transport data from the Irish Central Statistics Office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6td/) and values for each of the regions are distributed around the approximate average.

Initial_region_travel_time[Commuting_Zone] = 45

UNITS: minutes/day

DOCUMENT: The initial region travel time is arrayed by region. It is the assumed average travel time at the simulation start time for each region. It is based on transport data from the Irish Central Statistics Office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6td/) and values for each of the regions are distributed around the approximate average.

Inner_city_daytime_working_population = NAN

UNITS: people

Inner_city_labour_force_by_region[Inner_city] = PEOPLE[Inner_city]*Inner_city_labour_participation_fraction[Inner_city]

UNITS: People

DOCUMENT: Inner city labour force by region is arrayed by region. It is product of stock of PEOPLE and inner city labour participation fraction for each of the regions. It is a measure of how many people in a particular region who works in the inner city.

Inner_city_labour_force_by_region[Metropolitan_Area] = PEOPLE[Metropolitan_Area]*Inner_city_labour_participation_fraction[Metropolitan_Area]

UNITS: People

DOCUMENT: Inner city labour force by region is arrayed by region. It is product of stock of PEOPLE and inner city labour participation fraction for each of the regions. It is a measure of how many people in a particular region who works in the inner city.

Inner_city_labour_force_by_region[Commuting_Zone] = PEOPLE[Commuting_Zone]*Inner_city_labour_participation_fraction[Commuting_Zone]

UNITS: People

DOCUMENT: Inner city labour force by region is arrayed by region. It is product of stock of PEOPLE and inner city labour participation fraction for each of the regions. It is a measure of how many people in a particular region who works in the inner city.

Inner_city_labour_participation_fraction[Inner_city] = 0.65

UNITS: People/People

DOCUMENT: The inner city labour participation fraction is arrayed by region and represents the proportion of people working in the inner city in each of the regions. It is based on labour participation data for people over 15 years of age as only those numbers where available and then calibrated to match data on Dublin City labour force (CSO, 2022, https://data.cso.ie/table/QLF02, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/)

Inner_city_labour_participation_fraction[Metropolitan_Area] = 0.14

UNITS: People/People

DOCUMENT: The inner city labour participation fraction is arrayed by region and represents the proportion of people working in the inner city in each of the regions. It is based on labour participation data for people over 15 years of age as only those numbers where available and then calibrated to match data on Dublin City labour force (CSO, 2022, https://data.cso.ie/table/QLF02, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/)

Inner_city_labour_participation_fraction[Commuting_Zone] = 0.04

UNITS: People/People

DOCUMENT: The inner city labour participation fraction is arrayed by region and represents the proportion of people working in the inner city in each of the regions. It is based on labour participation data for people over 15 years of age as only those numbers where available and then calibrated to match data on Dublin City labour force (CSO, 2022, https://data.cso.ie/table/QLF02, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/)

Inner_city_land_fraction_occupied = (HOUSING[Inner_city]*Land_per_residential_unit+COMMERCIAL_BUILDINGS*Land_per_commercial_building)/Available_land_area

UNITS: dmnl

DOCUMENT: The inner city land fraction occupied is the product of HOUSING (for the inner city), COMMERCIAL BUILDINGS (in the inner city), land per residential unit, land per commercial building divided by the available land are in the inner city. It is a measure of the available land area in the inner city at any give time.

Jobs = COMMERCIAL_BUILDINGS*Jobs_per_commercial_structure

UNITS: jobs

DOCUMENT: the variable jobs in the the number of jobs in the inner city. It is the product of COMMERCIAL BUILDINGS and jobs per commercial structure.

Jobs_per_commercial_structure = 35

UNITS: jobs/ComBuildings

DOCUMENT: Jobs per commercial structure is an assumption based on business demographics data from the Irish Central Statistics Office (CSO, 2019, https://data.cso.ie/table/BRA18) and the single report on commercial buildings that could be sourced (SEAI Energy Modelling Group, 2015).

Labour_force_to_jobs_ratio = Daytime_inner_city_labour_force/Jobs

UNITS: people/jobs

DOCUMENT: Households to houses ratio It is the quotient of daytime inner city labour force divided by jobs. It is a measure of housing economic opportunity. The variable considers the daytime labour force in the inner city, including those who travel in from elsewhere, and only the jobs available in the inner city.

Land_per_commercial_building = 0.155

UNITS: ha/ComBuildings

DOCUMENT: The parameter land per commercial building is based on a SEAI Energy Modelling Group report (2015, p. 48)

Land_per_residential_unit = 0.015

UNITS: ha/Units

DOCUMENT: The parameter land per residential unit is based on the assumptions used in the Dublin City residential plan (Dublin City Council, 2022, https://dublincitydevelopmentplan.ie/downloads/Written%20Statement%20Volume%201.pdf)

Maximum_fractional_birth_rate = 0.019

UNITS: people/people/year

DOCUMENT: The maximum fractional birth rate is the maximum probability of any given person giving birth per year. It is calibrated to population statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections)

Maximum_growth_rate[Region] = PEOPLE*Maximum_fractional_birth_rate

UNITS: people/year

DOCUMENT: The maximum growth rate is arrayed by region. For each region it is the product of PEOPLE and Maximum fractional birth rate, and it represents the maximum number of people who can be born in each region per year.

Net_births_Dublin_City = NAN

UNITS: People/year

Net_migration_Dublin_City = NAN

UNITS: People/year

Normal_business_construction_fraction = 0.05

UNITS: ComBuildings/ComBuildings/year

DOCUMENT: The normal business construction fraction is based on the approximate rate of commercial building construction for the simulation start time based on business demographics data from the Irish Central Statistics Office and assumptions about the number of businesses per building (CSO, 2019, https://data.cso.ie/table/BRA18)

Normal_cars_per_person = 1

UNITS: vehicle/person

DOCUMENT: The normal cars per person is a parameter given the value 1 and is the value that is adjusted to get the indicated cars per person by the effect of travel time on attractiveness of driving.

Normal_fractional_net_migration[Inner_city] = 0.0001

UNITS: people/people/year

DOCUMENT: The parameter normal fractional net migration is arrayed by region. the values are informed by regional statistics from the 1996 (the simulation start time) and then adjusted to fit the historical time series data from the Irish Central Statistics office (CSO, 2002, https://data.cso.ie/table/B0402, 2006, https://data.cso.ie/table/C0402, 2011b, https://data.cso.ie/table/CD123).

Normal_fractional_net_migration[Metropolitan_Area] = 0.002

UNITS: people/people/year

DOCUMENT: The parameter normal fractional net migration is arrayed by region. the values are informed by regional statistics from the 1996 (the simulation start time) and then adjusted to fit the historical time series data from the Irish Central Statistics office (CSO, 2002, https://data.cso.ie/table/B0402, 2006, https://data.cso.ie/table/C0402, 2011b, https://data.cso.ie/table/CD123).

Normal_fractional_net_migration[Commuting_Zone] = 0.002

UNITS: people/people/year

DOCUMENT: The parameter normal fractional net migration is arrayed by region. the values are informed by regional statistics from the 1996 (the simulation start time) and then adjusted to fit the historical time series data from the Irish Central Statistics office (CSO, 2002, https://data.cso.ie/table/B0402, 2006, https://data.cso.ie/table/C0402, 2011b, https://data.cso.ie/table/CD123).

Normal_housing_construction_fraction_Dublin[Inner_city] = 0.015

UNITS: Units/Units/year

DOCUMENT: The parameter normal housing construction fraction Dublin is based on on the average number of houses built per year in each of the regions (CSO, 2011, https://data.cso.ie/table/CD464)

Normal_housing_construction_fraction_Dublin[Metropolitan_Area] = 0.03

UNITS: Units/Units/year

DOCUMENT: The parameter normal housing construction fraction Dublin is based on on the average number of houses built per year in each of the regions (CSO, 2011, https://data.cso.ie/table/CD464)

Normal_housing_construction_fraction_Dublin[Commuting_Zone] = 0.03

UNITS: Units/Units/year

DOCUMENT: The parameter normal housing construction fraction Dublin is based on on the average number of houses built per year in each of the regions (CSO, 2011, https://data.cso.ie/table/CD464)

People_per_household[Inner_city] = 2.5

UNITS: people/households

DOCUMENT: The parameter people per household is arrayed by region and is as the name suggests the number of people per household on average per region. it is based on population statistics by the Irish Central Statistics Office (CSO, 2011a, https://data.cso.ie/table/CD532).

People_per_household[Metropolitan_Area] = 3.01

UNITS: people/households

DOCUMENT: The parameter people per household is arrayed by region and is as the name suggests the number of people per household on average per region. it is based on population statistics by the Irish Central Statistics Office (CSO, 2011a, https://data.cso.ie/table/CD532).

People_per_household[Commuting_Zone] = 3.01

UNITS: people/households

DOCUMENT: The parameter people per household is arrayed by region and is as the name suggests the number of people per household on average per region. it is based on population statistics by the Irish Central Statistics Office (CSO, 2011a, https://data.cso.ie/table/CD532).

Persons_commuting_into_inner_city = NAN

UNITS: people

Population_County_Dublin = NAN

UNITS: people

Population_County_Dublin_ex_Dublin_City = NAN

UNITS: People

Population_Dublin_City = NAN

UNITS: People

Population_FUA = SUM(PEOPLE[*]) {SUMMING CONVERTER}

UNITS: People

Population_GDA = NAN

UNITS: People

Population_GDA_ex_County_Dublin = NAN

UNITS: People

Pressure_to_reduce_congestion = FUA_average_travel_time/Initial_average_travel_time

UNITS: dmnl

DOCUMENT: The pressure to reduce congestion is the quotient of the FUA average travel time divided by the initial value for the same variable. As travel times rise there is more pressure to reduce congestion from the driving public.

Ratio_of_inner_city_commuters_to_total_commuters = Inner_city_labour_force_by_region[Inner_city]/SUM(Inner_city_labour_force_by_region)

UNITS: dmnl

DOCUMENT: The variable ratio of inner city commuters total commuters is just that, the proportion of the total inner city workforce that lives in the inner city.

Sensitivity_of_distance_driven_to_ratio_of_inner_city_commuters_to_the_total = -1

UNITS: dmnl

DOCUMENT: The parameter Sensitivity of distance driven to ratio of inner city commuters to the total determines the size of the effect any given change to ratio of inner city commuters to total commuters has on average distance driven. The sensitivity is given a negative value since more people living in the inner city reduces the travel time. The value is -1, as travel time does not increase at a faster rate as the input changes more and more in onw or the other direction.

sensitivity_of_housing_construction_to_road_capacity[Inner_city] = 0

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to road capacity is arrayed by region. It determines the size of the effect any given change to ROAD CAPACITY has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and the areas are more developed already. Further out there is less development and any increase in highway capacity opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

sensitivity_of_housing_construction_to_road_capacity[Metropolitan_Area] = 15

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to road capacity is arrayed by region. It determines the size of the effect any given change to ROAD CAPACITY has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and the areas are more developed already. Further out there is less development and any increase in highway capacity opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

sensitivity_of_housing_construction_to_road_capacity[Commuting_Zone] = 30

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to road capacity is arrayed by region. It determines the size of the effect any given change to ROAD CAPACITY has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and the areas are more developed already. Further out there is less development and any increase in highway capacity opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

sensitivity_of_housing_construction_to_travel_time[Inner_city] = 0

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to travel time is arrayed by region. It determines the size of the effect any given change to FUA travel time has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and distances are shorter, so travel times have less of an effect. Further out there is less development and any reduction in travel times opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

sensitivity_of_housing_construction_to_travel_time[Metropolitan_Area] = -2

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to travel time is arrayed by region. It determines the size of the effect any given change to FUA travel time has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and distances are shorter, so travel times have less of an effect. Further out there is less development and any reduction in travel times opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

sensitivity_of_housing_construction_to_travel_time[Commuting_Zone] = -4

UNITS: dmnl

DOCUMENT: The parameter sensitivity of housing construction to travel time is arrayed by region. It determines the size of the effect any given change to FUA travel time has on the housing construction fraction. The effect is successively higher further out from the inner city, the assumption being that areas closer to the inner city already have better highway connections and distances are shorter, so travel times have less of an effect. Further out there is less development and any reduction in travel times opens up more opportunities for developers and families to develop suburbs. It is calibrated to housing statistics by the Irish Central Statistics Office (CSO, 2016, https://data.cso.ie/table/E1071)

Sensitivity_of_migration_to_housing_availability[Inner_city] = -1

UNITS: dmnl

DOCUMENT: The parameter sensitivity of migration to housing availability is arrayed by region. It determines the size of the effect any given change to households to houses ratio has on migration for each of the regions. It is calibrated to population and migration statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections). The effect is successively higher further out from the inner city, the assumption being that housing is more affordable the further out one gets from the expensive housing markets of the inner city.

Sensitivity_of_migration_to_housing_availability[Metropolitan_Area] = -5

UNITS: dmnl

DOCUMENT: The parameter sensitivity of migration to housing availability is arrayed by region. It determines the size of the effect any given change to households to houses ratio has on migration for each of the regions. It is calibrated to population and migration statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections). The effect is successively higher further out from the inner city, the assumption being that housing is more affordable the further out one gets from the expensive housing markets of the inner city.

Sensitivity_of_migration_to_housing_availability[Commuting_Zone] = -17.5

UNITS: dmnl

DOCUMENT: The parameter sensitivity of migration to housing availability is arrayed by region. It determines the size of the effect any given change to households to houses ratio has on migration for each of the regions. It is calibrated to population and migration statistics and official projections by the Irish Central Statistics Office (CSO, 1996, https://data.cso.ie/table/A0101, 2016c, https://data.cso.ie/table/E2001, 2016d, https://www.cso.ie/en/statistics/population/regionalpopulationprojections). The effect is successively higher further out from the inner city, the assumption being that housing is more affordable the further out one gets from the expensive housing markets of the inner city.

SimPopulation_County_Dublin = PEOPLE[Inner_city] + PEOPLE[Metropolitan_Area] {SUMMING CONVERTER}

UNITS: People

Speed_limit = 1

UNITS: km/minute

DOCUMENT: The speed limit is the assumed average speed limit in for a commute in the whole FUA.

State_percentage_of_commuters_using_a_car = NAN

UNITS: vehicle/person

Time_to_react_to_pressure_and_build_roads = 5

UNITS: Years

DOCUMENT: The time to react to pressure and build roads is the adjustment time for the stock Road Capacity and is assumed to be 5 years.

Time_to_switch_transport_mode = 7

UNITS: year

DOCUMENT: The parameter time to switch transport mode is the time it takes, on average, for people to choose either to buy and use a car for their commute or sell it and use some other mode of transport. The value is calibrated to transport data from the Irish Central Statistics Office (CSO, 2016a, https://www.cso.ie/en/releasesandpublications/ep/p-cp6ci/p6cii/p6mtw/)

Traffic_volume = Cars_in_the_region*Average_distance_driven_per_day

UNITS: vehicle-kilometers/day

DOCUMENT: The traffic volume is the daily vehicle-kilometers driven, the total number of kilometers driven by one vehicle. It is the product of cars in the region and the average driven per day.

Workers_living_in_inner_city = Daytime_inner_city_labour_force-Workers_traveling_from_outside

UNITS: People

Workers_traveling_from_outside = Inner_city_labour_force_by_region[Metropolitan_Area]+Inner_city_labour_force_by_region[Commuting_Zone]

UNITS: People