Urban sprawl and congestion in The Hague

A system dynamics modeling approach

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Note from author

Anyone who has read my work on “Perfectionism, self-worth and choice” (Bax, 2022), for which I received honorable mentions for the Dana Meadows and Lupina Young Researchers Awards at the System Dynamics conference 2022 in Frankfurt Germany, knows it can be difficult to stick to one’s choices. Even though the thesis process has been challenging sometimes, I am happy that I have made, and stuck to, the choice to extend on Martin Breda Grimeland (2022) his work on sprawl dynamics, and to work on urban sprawl and congestion in collaboration with the Organisation for Economic Co-operation and Development [OECD].

Furthermore, I am proud to say that the work on my thesis is not perfect at all. As such, I look forward to future work, either by myself or others, extending on the work that I have done for this thesis in System Dynamics. Extending on each other’s work is something I consider to be of great importance within the System Dynamics community as increasing the discourse regarding models and the value they can offer has real potential to reach decision makers, by which we can try to make the world a better place for humans, animals and the environment alike.

To anyone who wants to extend on my work, please feel free to reach out.

Ismay Leanne Bax

Abstract

Urban sprawl and congestion have significant detrimental effects on society and on the environment (Hennig, et al., 2016; OECD, 2018), and the phenomenon is regarded as a major challenge for urban Europe (Uhel, 2006). This work uses System Dynamics as a modeling tool to explain the interrelationships of the various mechanisms that are part of the underlying structure which causes urban sprawl and congestion in the Dutch region The Hague. Besides providing an understanding of the processes involved as drivers of urban sprawl and congestion in the The Hague region, this work further aims to explore some basic mobility-oriented policy options that might alleviate the problem. In order to reduce urban sprawl and congestion road network development should be adjusted so that it does not favor peripheral urban areas over central urban areas with regard to their relative attractiveness, home construction and consequent housing availability. Of equal importance is the competitiveness of shared modes of transport relative to private modes of transport when concerning congestion and especially car-dependency.

Keywords: urban sprawl, congestion, mobility

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Chapter 1. Problem formulation

This chapter addresses the problem concerning urban sprawl and congestion which is central to the thesis and describes the nature and importance of the problem by referring to scientific literature. This chapter further discusses the reference modes of behavior and will conclude with the research objective and research questions.

1.1 Theoretical background on urban sprawl

1.1.1 What is urban sprawl?

Urban sprawl is a phenomenon which lacks a homogenous definition in the literature and is rich in ambiguity (Bueno-Suárez & Coq-Huelva, 2020; Galster, Hanson, Ratcliffe, Wolman, Coleman & Freihage, 2001). Galster, et al. (2001) call it an elusive concept and Rubiera-Morollón and Garrido-Yserte (2020) touch on its complex and multidisciplinary nature. Nevertheless, there is consensus regarding some elements that are often linked with the phenomenon. The literature frequently characterizes urban sprawl in a morphological manner where urban sprawl contributes to how the urban form expands over time (Hennig, Jaeger, Soukup, Orlitova, Schwick & Kienast, 2016). The expansion of the urban form due to urban sprawl often goes hand in hand with low density, low proximity and low centrality (Bueno-Suárez & Coq-Huelva, 2020).

Low density is referring to an increasing land uptake per capita which drives spatial urban growth (OECD, 2018), in other words the developed land area grows at a faster pace than the population does. In 1937, Earle Draper was the first to conceive the term "*sprawl*" to describe *"the outward movement of low density urban development"* (Buitelaar & Leinfelder, 2020, p. 46; Su, 2006). In past decades low density development has been induced by increasing real incomes, as demand and preference for bigger and more comfortable homes with private green space increased with increasing real incomes (OECD, 2018; Uhel, 2006). This was especially the case for suburban development as land prices in more distant peripheral areas were lower compared to land prices in central urban areas and areas closer to urban centers. It is important to note however that population density is not always a reliable indicator for the degree of urban sprawl. Suburbanization, representing the shift of a population away from central areas, can hide behind densification and thus the degree of urban sprawl will not always be indicated correctly when solely looking at population density having decreased or increased over time (OECD, 2018). In some OECD countries *"suburbanization has co-evolved with densification"* (OECD, 2018, p. 12). In those countries the average urban population density increases over time, thus not indicating more urban sprawl, yet suburban areas of low density take up a bigger fraction of the total urban footprint, which is a clear indicator of urban sprawl. As such, in the System Dynamics model accompanying this work the developed residential land and the nature of that development [where it fits in the range from high to low density development] is considered to be of greater importance than the average population density. This is in line with Jaeger and Schwick (2014) who considered the degree of urban sprawl to be determined by the amount of built-up area, the spatial configuration of that built-up area [how dispersed it is in the landscape], and the degree of utilization of the built-up area.

Low proximity and centrality in turn are referring to the spatial distance between central urban areas and suburban areas (Bueno-Suárez & Coq-Huelva, 2020). In their report *Transport Strategies for Net-Zero Systems by Design* the OECD (2021) argues that transport policies have focused heavily on supporting mobility [meaning supporting people to move as fast and as far as possible] rather than accessibility [meaning the possibility for people to access places with ease]. This focus on mobility has resulted in decreasing proximity and centrality (OECD, 2021). Road expansion, for example, has allowed people to move further away from central urban areas while places of interest could still be reached within a reasonable timeframe – a feat partly made possible by the diffusion of private vehicles and their technological advancement over time (OECD, 2018; Rubiera-Morollón & Garrido-Yserte, 2020). Mobility-oriented policies have thereby fostered car-dependency as active modes of transport [such as cycling or walking] and shared modes of transport [such as public transport] are less convenient, efficient and/or accessible when travel distances increase and people live further away from services (OECD, 2021). Thus, urban sprawl and current mobility-oriented policies erode active and shared modes of transport. The choice of private vehicles [such as cars] as transport mode is therefore not solely the result of personal preference, but partly dependent on transport and urban systems.

1.1.2 Why is urban sprawl problematic?

In 2016 the European Environment Agency singled out The Netherlands as worst 'offender' of urban sprawl (Evers & Schie, 2019). This title was given to The Netherlands due to the growth in built-up areas relative to the size of the country. The word 'offender' indicates that the phenomenon urban sprawl is generally not considered to be desirable. Uhel (2006, p. 5) states that urban sprawl is *"rightly regarded as one of the major common challenges facing urban Europe today"*. As such, the question why urban sprawl is considered to be problematic is highly relevant. From an individual perspective, urban sprawl can offer important private benefits as low density urban development in more peripheral areas [in comparison to high density central urban areas] can generally offer more space, comfort and privacy in safer neighborhoods with regard to housing. In addition to that low density peripheral areas, compared to high density central areas, generally deal with less air, water and noise pollution and offer more green spaces, thereby meeting important personal preferences and needs (OECD, 2018). On an individual level therefore, one might not consider urban sprawl to be undesirable [this, in the author's opinion, only adds to the problematic nature of urban sprawl as it might lead to resistance when implementing policies to combat urban sprawl]. However, from a holistic and collective perspective, the phenomenon has significant detrimental effects on society and on the environment (Hennig, et al., 2016; OECD, 2018).

The relationship between urban sprawl and the social and environmental efficiency of cities is one of the main reasons why the phenomenon has gained more attention in recent literature (Rubiera-Morollón & Garrido-Yserte, 2020). On a social level, dispersion of the urban area is associated with reduced social interaction, increased social conflict, and increased difficulty of social integration (Brueckner, Mills & Kremer, 2001; Rubiera-Morollón & Garrido-Yserte, 2020; Souza Briggs, 2005). Furthermore, urban sprawl is associated with various health issues, mostly regarding physical health [in particular obesity and subsequent health consequences, as car-dependency fostered by urban sprawl decreases physical activity], but also regarding mental health [for example stress, loneliness and depression due to prior mentioned social issues by urban sprawl] (Frumkin, 2002; Hennig, et al., 2016; OECD, 2018; OECD, 2021; Strum & Cohen, 2004; Uhel, 2006). The health issues associated with increasing urban sprawl in turn result in greater costs for health services and insurances (Hennig, et al., 2016).

On an environmental level, dispersion of the urban area damages natural environments (Hennig, et al., 2016). Urban sprawl is associated with the habitat reduction of plant species and wildlife, and the consequent degradation of ecosystems including reduced resilience of ecosystems and loss of biodiversity (Scalenghe & Marsan, 2008; Shochat, Lerman, Anderies, Warren, Faeth & Nilon, 2010). Most recent literature however, focuses on the effects of urban sprawl on either mobility and its impact on the environment, or on the effects of urban sprawl on energy efficiency and its impact on the environment (Rubiera-Morollón & Garrido-Yserte, 2020).

Environmental impact of urban sprawl – mobility

As mentioned prior in this report, mobility-oriented policies have fostered car-dependency as active modes of transport [such as cycling or walking] and shared modes of transport [such as public transport] are less convenient, efficient, and/or accessible [and in the case of public transport: more costly to construct] when travel distances increase and people live further away from services (OECD, 2021). Since urban sprawl often implies low density, proximity and centrality, resulting thus in a more dispersed population and greater distances between places of interest, the phenomenon urban sprawl hinders active and shared modes of transport and pushes people to rely on private vehicles [such as cars] for transportation (Camagni, Gibelli & Rigamonti, 2002). Private cars are much less environmentally sustainable modes of transport compared to active and shared modes of transport, and they are major polluters accounting for approximately sixty percent of the total CO_2 emissions from road transport in Europe [road transport itself accounts for approximately twenty percent of the total CO_2 emissions in Europe] (EPN, 2023). While cars are becoming more efficient over time due to technological advancement and thus produce lower emissions when in use compared to older cars [which is certainly commendable], the environmental impact of them is still up for debate as the significant and unsustainable emissions from the production and disposal of [parts of] private vehicles should also be taken into account besides the emissions caused by their usage (EPN, 2023; Lakshmi, 2023). The efficiency of private vehicles and their emissions during use, production and disposal is however not a main focus in this work. A greater concern regarding car-dependency is congestion.

Since urban sprawl and mobility-oriented policies foster car-dependency, travel distances and traffic volumes increase (OECD, 2021). Besides resulting in increased emissions, air and noise pollution, and road accidents, both the increasing travel distances and traffic volumes result in increasing congestion levels – which in turn result in even higher emissions and more air pollution due to inefficient stop-and-go driving (OECD, 2021; Su, 2006). Congestion is an imbalance between the capacity of the road network and the traffic volume, where the traffic volume exceeds the capacity of the facilitating road network (Loop & Hamersma, 2018; OECD, 2021). Traditionally, congestion has been 'solved' by road construction, a mobility-oriented policy (OECD, 2021; Sterman, 2000). Sterman (2000, p. 178) points to the open-loop perspective to the problem, where the feedback of road construction is ignored and traffic volume is considered to be exogenous rather than endogenous, which is *"an accurate reflection of the mental models of many politicians, city planners, and transportation officials"* (Sterman, 2000, p. 181).

Besides enormous environmental costs, congestion also generates vast amounts of monetary costs, both direct and indirect, for individual commuters and for companies alike [for example additional costs in fuel, maintenance, insurance, salary, transit, and so on] (Su, 2006;

UA, 2022). These costs can reach billions of Euro's per year (Bremmer, 2018). According to Brueckner, et al. (2001) commuters bear the private costs of commuting [meaning vehicle operation costs and time costs – the latter being a monetary value of consumed time while in transit]. However, in a congested situation additional social costs are generated by the commuter caused by their presence on the road. As such, the true costs of commuting include these additional social costs imposed on other commuters due to the extra created congestion. Even though this extra created congestion is very small, its impact is significant as it affects many other commuters (Brueckner, et al., 2001, p. 74). As these additional social costs are carried by the other commuters, they do not offer an incentive to the individual commuter to take them into account. According to Brueckner, et al. (2001) the failure to account for the additional social costs of congestion means that commuting on a congested road seems unreasonably affordable to the individual commuter. This results in more utilization of congested roads then is socially desirable (Su, 2006). The arguments of Brueckner, et al. (2001) are reflected in the attitude of Dutch employees towards congestion during their daily commute. Even though congestion is a big inconvenience for the Dutch commuter, habituation often occurs and the commuter simply 'deals with it' by waiting it out (JA, 2021). As such, the commuter considers solely their private costs and whether they want bear those costs, and does not consciously take the additional social costs imposed on other commuters into account.

Environmental impact of urban sprawl – energy efficiency

Literature on the environmental impact of urban sprawl in terms of energy efficiency mainly focuses on housing (Rubiera-Morollón & Garrido-Yserte, 2020). Urban sprawl and low density suburban development allow for different types of homes to be constructed in peripheral urban areas compared to high density central urban areas. The further out one goes from central urban areas to the peripheral suburbs, single family homes become increasingly commonplace (OECD, 2021). Single family homes [such as a terraced house or a detached house], compared to multifamily homes [such as an apartment building], are much less energy efficient. This is partly due to the fact that a single family home is bigger in average size compared to a multifamily home, and thus more energy is needed to maintain its temperature. Furthermore, single family homes are more exposed to the weather [outside warm and cold temperatures] compared to multifamily homes (Lasarte-Navamuel, Rubiera-Morollón & Moreno-Cuartas, 2018), which contributes to the amount of energy needed to maintain the inside home temperature. Another possible contributor to the energy consumption of a household is income. It is implied that households with higher incomes restrict energy consumption to a lesser extent when compared to households with lower incomes as single family homes, compared to multifamily homes, are usually occupied by households with higher incomes (OECD, 2018), however Wiesmann, Azevedo, Ferrão and Fernández (2011) found only a small effect of income on energy consumption.

Besides the energy efficiency of the type of home, the construction of single family homes, compared to multifamily homes, is also less energy efficient (Rubiera-Morollón & Garrido-Yserte, 2020). Furthermore, with a more dispersed population [and thus more dispersed homes] and greater distances between places of interest [and thus greater distances between energy suppliers and consumers] providing energy becomes less efficient. A bigger network of pipe- or powerlines is needed to reach households when they are dispersed over a larger urban area, as such this results in a greater resource loss during transport (Rubiera-Morollón & Garrido-Yserte, 2020).

The arguments above provide an answer to the question why urban sprawl is problematic from a holistic perspective. It is a collective problem, while on the individual level urban sprawl might not be considered as a problem at all [although some of its effects, such as congestion, might be considered a nuisance]. Rubiera-Morollón and Garrido-Yserte (2020, p. 1) state that *"cities are successful when they are able to maximize contact and interaction, facilitating the generation of ideas and the dissemination of knowledge while providing an environment that saves energy and resources and minimizes the environmental impact"*. Urban sprawl greatly hinders the successfulness of cities on all these fronts.

As mentioned prior in this report, in 2016 the European Environment Agency singled out The Netherlands as worst 'offender' of urban sprawl (Evers & Schie, 2019). Yet according to Buitelaar and Leinfelder (2020) there currently does not seem to exist a pressing need in the Dutch government to limit further sprawl. A notion which they base on the Dutch government's Draft National Strategy on Spatial Planning and the Environment (Rijksoverheid, 2019) and critique on the strategy by Leinfelder (2019). For this reason, The Netherlands is chosen as country of interest for this work, with a special focus on the The Hague region as this region is persistently one of the most congested in the country (Holtermans, 2022; Quaedvlieg, 2014; RTLZ, 2017).

1.2 Thesis context

1.2.1 The Hague

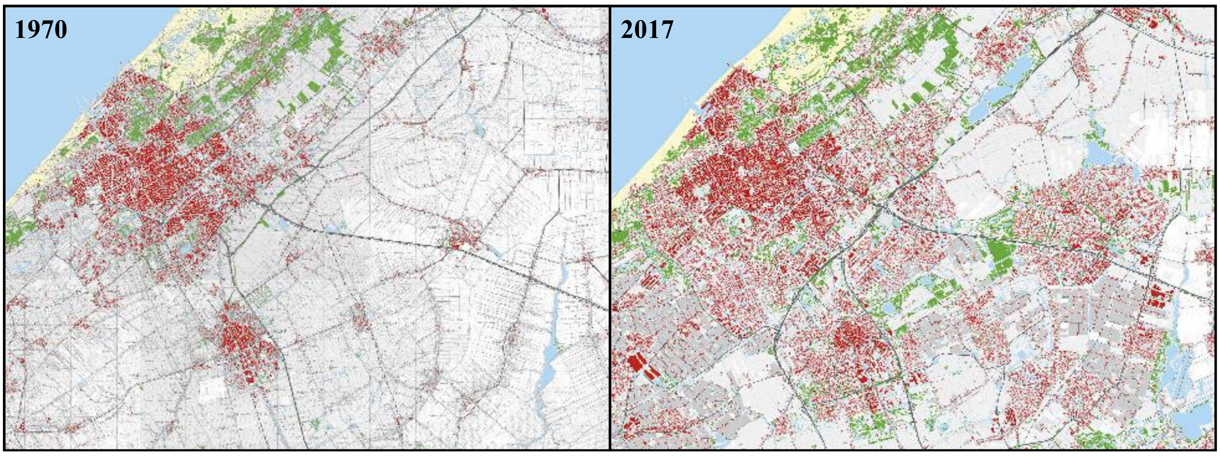
The Hague, located on the west-coast of The Netherlands, is of great importance both considered from a national and an international perspective. Due to its importance, the thriving region attracts many businesses (Lambregts, Kloosterman, Werff, Röling & Kapoen, 2006) and hosts approximately six percent of all jobs in the country (CBS, 2022c). It is also the home of approximately five-and-a-half percent of the country's population, including the Dutch royal family (AlleCijfers, 2023). The Hague is the political capital of The Netherlands as the national Dutch government and parliament [including the senate *"Eerste Kamer"* and House of Representatives *"Tweede Kamer"*] are seated in the city besides various embassies and all ministries. Furthermore, the Supreme Court, International Court of Justice, International Criminal Court and the Peace Palace are located in The Hague, the latter three holding important international functions. In the outer The Hague area intensive, high-tech horticulture industry has made The Netherlands one of the largest exporters of food products in the world (Nadin & Zonneveld, 2021, p. 14).

The Hague is reasonably well connected to other places in The Netherlands via the road network, of which the A4 [to Amsterdam], A12 [to Utrecht] and A13 [to Rotterdam] are the most notable, and by public transport (Lambregts, et al., 2006). The road network in the The Hague region is persistently one of the most congested in the country (Holtermans, 2022; Quaedvlieg, 2014; RTLZ, 2017). As mentioned prior in this report, congestion has traditionally been 'solved' by road construction, a mobility-oriented policy (OECD, 2021; Sterman, 2000). This also holds true for The Netherlands. Approximately eighty percent of road investments in The Netherlands are spend in The Randstad Holland region where the The Hague region is a part of (BNR, 2016). The reason why such a large portion of road investments is spend in this area, is because most of the congestion on the Dutch road network is located here, especially in and around The Hague (PBL, 2006; Rijkswaterstaat, 2020). Various parties in The Netherlands are even warning for permanent traffic jams and, consequently, put pressure on decision makers to invest additional substantial amounts of money in infrastructure in the region in order to 'solve the problem' (Groot, Saitua & Visser, 2016; NRC, 2017; Termaat, 2021; Veldhuis, 2022). However, by expanding the road network [either by constructing additional lanes to existing roads, new roads, or even parking facilities] a larger part of investments and public space will be allocated to parking and driving private vehicles, thereby increasing the attractiveness of private vehicles to the detriment of active and shared modes of transport, reinforcing car-dependency (OECD, 2021). As such, congestion will not be reduced in the long term through road network expansion policies.

1.2.2 Reference modes of behavior

In The Netherlands, suburbanization and decentralization have resulted in a manifestation of urban sprawl (OECD, 2018). This is clearly visible for the The Hague region when comparing the built-up area in the years 1970 and 2017 as shown in Figure 1 below (Rijksoverheid, 2020).

Figure 1 – Built-up area in the The Hague region in the years 1970 [left] and 2017 [right].

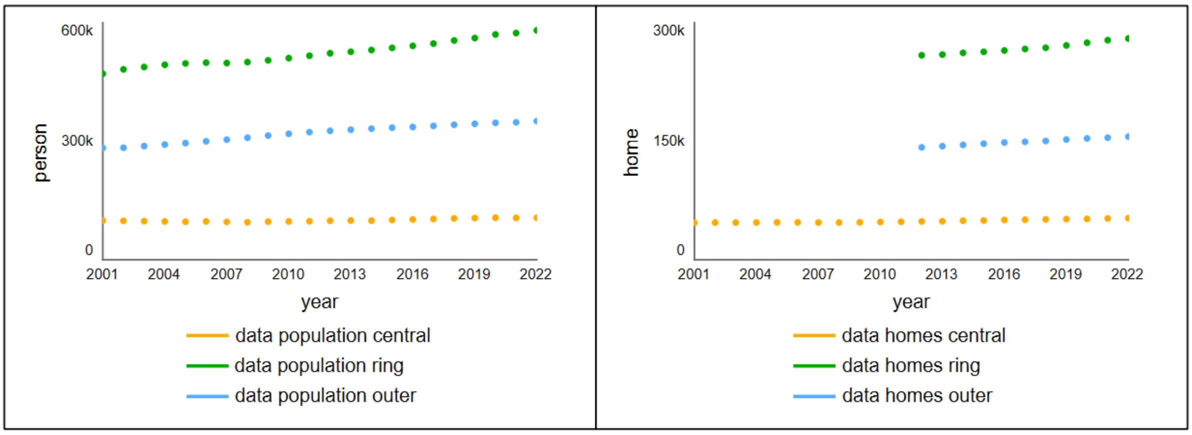


(Rijksoverheid, 2020).

Figure 1 gives a clear indication of how The Hague has sprawled over a timespan of approximately 50 years. The urban area has expanded around the three main roads A4 [to Amsterdam], A12 [to Utrecht] and A13 [to Rotterdam]. Furthermore, it shows how the urban development in the functional urban area becomes less dense when moving from the inner urban area outwards through the metropolitan area and the commuting zone. In the current work, consisting of this report and the accompanying System Dynamics model, these areas will be referred to as the central area, ring area and outer area. Included in the central The Hague area [inner urban area] are the eight districts Archipelbuurt, Centrum, Groente- en Fruitmarkt, Schilderswijk, Stationsbuurt, Transvaalskwartier, Willemspark and Zeeheldenkwartier. Included in the ring The Hague area [remaining metropolitan area – first commuting belt] are the remaining districts of The Hague city, and the municipalities Leidschendam-Voorburg and Rijswijk. Included in the outer The Hague area [commuting zone – second commuting belt] are the municipalities Delft, Lansingerland, Pijnacker-Nootdorp and Zoetermeer.

Figure 2 below shows the reference modes of behavior for population and homes in the central, ring and outer areas of The Hague. Note however that these reference modes do not necessarily show intriguing dynamic behavior, as all of them show linear growth. Nevertheless, population and homes are important stocks to the model accompanying this work for which reliable data per area can be found. As such, they are included as reference modes of behavior. Both population data (AlleCijfers, 2023; CBS, 2023a; DHIC, 2023; EersteKamer, 2022) and homes data (CBS, 2023b; DHIC, 2023; DIC, 2023; LVIC, 2023; PNIC, 2023; RIC, 2023; ZIC, 2023) are derived from multiple sources with a dual purpose, firstly to extend on data wherever needed, and second to validate the reliability of the data. For the central The Hague area the population has increased by approximately seven percent in 22 years, and homes have increased by approximately nine percent in 22 years. For the ring The Hague area the population has increased by approximately twenty-three percent in 22 years, and homes have increased by approximately eight percent in 11 years [data could not be found before the year 2012]. For the outer The Hague area the population has increased by approximately twenty-four percent in 22 years, and homes have increased by approximately nine-and-a-half percent in 11 years [data could not be found before the year 2012]. On a national level, the population has increased approximately ten percent in 22 years (AlleCijfers, 2023). As such, the growth as seen in the central The Hague area is a little below the Dutch national average, and the growth as seen in the ring and outer The Hague areas is much higher. When considering urban sprawl and its detrimental effects it would be harmful if the population growth in the ring and outer The Hague areas would continue at this pace in years to come – especially when new homes are constructed in accordance with current patterns [bigger and more dispersed single family homes the further out one moves from the central urban area] to facilitate this increase in population.

Figure 2 – Reference modes of behavior for population [left] and homes [right] in the central [yellow], ring [green] and outer [blue] The Hague areas during the years 2001 and 2022.*



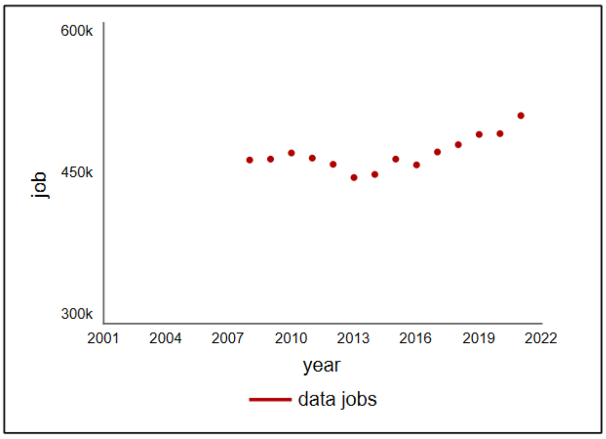
Population data (AlleCijfers, 2023; CBS, 2023a; DHIC, 2023; EersteKamer, 2022).

Homes data (CBS, 2023b; DHIC, 2023; DIC, 2023; LVIC, 2023; PNIC, 2023; RIC, 2023; ZIC, 2023).

*Note that data could not be found before the year 2012 for homes in the The Hague ring and outer areas.

Besides population and homes being important stocks to the accompanying model for this work, another important stock is jobs. The amount of jobs in the region, and in extent the job availability in the region, is an important consideration when migrating in or out of a region. Therefore, the amount of jobs in the The Hague region is included as a reference mode of behavior. Data could only be found for the years 2008 until 2021 and are derived from CBS (2022c). Note that this reference mode is applicable to the region as a whole and jobs are not distinguished between the central, ring and outer The Hague area due to lack of more detailed data. Figure 3 below shows the reference mode of behavior for the amount of jobs in the The Hague region.

Figure 3 – Reference mode of behavior for jobs in the The Hague region during the years 2008 and 2021.

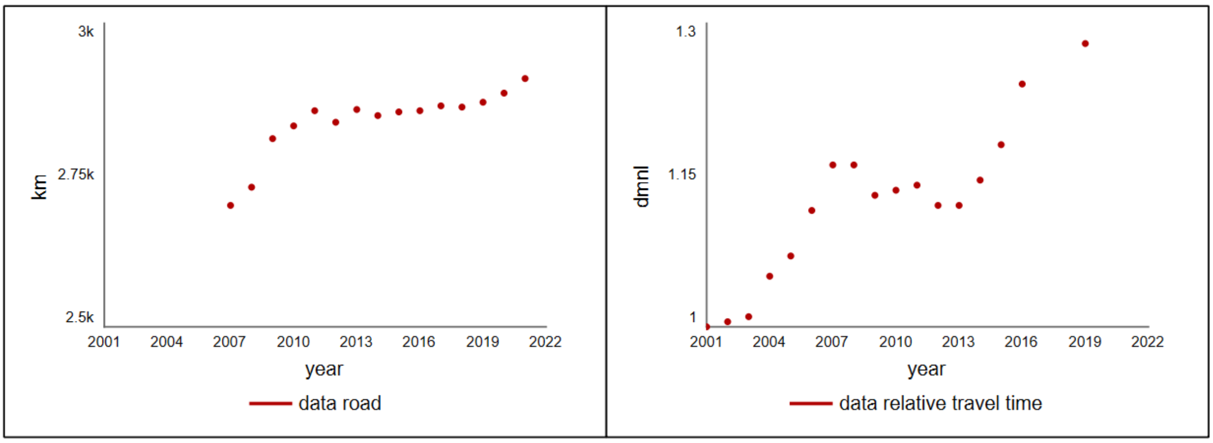


Jobs data (CBS, 2022c).

Finally, reference modes of behavior for the road network in the The Hague region and a measure of congestion are necessary due to the effects of urban sprawl and mobility-oriented policies which have fostered car-dependency as discussed prior in this report (OECD, 2021). As such, the road network in the The Hague region is included as a reference mode of behavior. Data could only be found for the years 2007 until 2021 and are derived from CBS (2022e). Note that this reference mode is applicable to the region as a whole and roads are not distinguished between the central, ring and outer The Hague area due to lack of more detailed data. Figure 4 shows the reference mode of behavior for the road network in the The Hague region.

Also shown in Figure 4 is the reference mode of behavior for the relative travel time. This is a relative measure where the year 2001 equals 100%. Travel time is a good summary measure for congestion (Sterman, 2000, p. 179). Data for the relative travel time are collected on roads in the The Hague region [such as the A4, A12 and A13] and are derived from Loop and Hamersma (2018). As these data only included the years 2001 until 2016, data from Tomtom (2023) for The Hague for the year 2019 is used to extend the reference mode of behavior for the relative travel time. This was applicable as Tomtom (2023) also supplied relative measures which could be compared with the 2001 level. Note that this reference mode is applicable to the The Hague region as a whole.

Figure 4 – Reference modes of behavior for roads [left] and relative travel time [right] in the The Hague region during the years 2007 and 2021 for roads, and during the years 2001 and 2019 for relative travel time.*



Roads data (CBS, 2022e).

Relative travel time data (Loop & Hamersma, 2018; Tomtom, 2023).

*Note that data could not be found for the years 2017 and 2018 for relative travel time in the The Hague region.

Especially the reference mode of behavior for relative travel time in the The Hague region shows some interesting dynamic behavior. It gives indication of exponential growth and oscillation. However, some variance could be due to measurement [time of measurement, period of measurement, external circumstances influencing the situation on the road during measurement, and so on]. As such, the structural hypothesis and its logic should provide a more grounded explanation of the simulated historic behavior mode and expected future behavior mode. Nevertheless, it can be said that it would be undesirable should the dynamic of growth in relative travel time continue, regardless of whether this growth will be in a linear, exponential or possibly goal-seeking [including s-shaped] manner.

1.3 Research objective and research questions

1.3.1 Research objective

The objective of this work on urban sprawl and congestion is initially to provide understanding of the processes involved as drivers of urban sprawl and congestion in the The Hague region. Subsequently, this work further aims to move beyond understanding the processes involved towards understanding as a basis for policy analysis. This does not mean that this work provides extensive policy recommendations, however it does aim to explore some basic policy options that might alleviate the problem without regard for possible implementation obstacles.

1.3.2 Research questions

In order to meet the research objective three research questions will be addressed throughout this work. The first and second research question focus on providing an understanding of the processes involved as drivers of urban sprawl and congestion in the The Hague region. The first research question reads:

> ***Research question 1.***
> Which mechanisms offer a causal explanation for
> urban sprawl and congestion in the The Hague region?

Understanding goes beyond identifying the feedback structure and, thus, a second research question will be addressed in addition to the first research question.

> ***Research question 2.***
> How do these mechanisms contribute to the behavior of the system?

Of further interest is the exploration of basic policy options that might alleviate the problem concerning urban sprawl and congestion, thereby moving towards understanding as a basis for policy analysis in the research objective. Therefore, the third research question reads:

> ***Research question 3.***
> What policy options can be identified to reduce urban sprawl
> and congestion in the The Hague region?

The first research question will be addressed in Chapter 2. Chapter 3 will concern the second research question. Finally, the third research question will be addressed in Chapter 4.

Chapter 2. Methodology and structural hypothesis

This chapter addresses the choice of methodology for System Dynamics simulation modeling and provides an account of how the structural hypothesis is developed. The structural hypothesis will be discussed in a more general manner by use of a causal loop diagram [CLD], and thereafter in a more detailed manner by use of the sectors included in the hypothesis showing the stock and flow structure for each sector separately. This chapter addresses the first research question "which mechanisms offer a causal explanation for urban sprawl and congestion in the The Hague region?".

2.1 Methodology

2.1.1 System Dynamics simulation modeling

System dynamics is a modeling method in which computer simulations of real-world systems are created and analyzed to enable the understanding of the structure and the behavior dynamics of complex systems, and to enable ways to design and test more effective policies to complex problems in the long term (Sterman, 2000). Complexity, from a System Dynamics perspective, arises from the interactions and feedback over time between various mechanisms involved in the system, which can be subject to nonlinearities, delays, resistance, and so on (Sterman, 2000, p. 21-23). The choice for System Dynamics simulation modeling fits research regarding urban sprawl and congestion quite well. Urban systems are highly complex and have been subject to System Dynamics research since *Urban Dynamics* (Forrester, 1969) was published in 1969. Alfeld and Graham (1976) have thereafter simplified Forrester's Urban Dynamics model, thereby creating URBAN1, into a version which is well suited for teaching (Sterman, 2000). The influence of URBAN1 can be found in the model accompanying this work as well.

Furthermore, System Dynamics can contribute to the general understanding of congestion and solutions for the problem. As mentioned prior in this report, congestion has traditionally been 'solved' by more road construction (OECD, 2021; Sterman, 2000, p. 178). The linear way of thinking surrounding congestion and its solution has unintendedly added to the problem itself through induced demand [investments in the road network aiming to reduce congestion end up having the opposite result (OECD, 2021)]. System Dynamics breaks through this linear way of thinking and takes the feedback of momentum policies into account.

2.1.2 Research process

The modeling process as discussed by Sterman (2000, p. 83-105) is followed throughout the duration of this research. A conceptual framework regarding urban sprawl and congestion was created by use of scientific and grey literature, the latter including reports from the OECD and Dutch governmental institutions. Through literature review key variables and their interrelationships could be defined representing the concepts as established in the literature. References to the reviewed literature are stated in the model documentation [Appendix II]. The variables and their interrelationships provided the basis for the CLD which will be discussed later in this chapter. Based on the CLD, and by incorporation of data as found in the literature, a quantitative model was constructed using the software Stella Architect. The equations and data used during model creation are either grounded in the literature, based on existing validated models [such as URBAN1 (Alfeld & Graham, 1976), Grimeland's (2022) model concerning sprawl dynamics, and Isee Systems' (n.d.) model on traffic congestion] or, when needed, based on assumptions. In the latter case, this is clearly stated in the model documentation. The quantitative simulation model has been subject to review and feedback by the OECD and an affiliated expert in Dutch Housing and policies (Eskinasi, 2023; Mirabile, 2023). Furthermore, the simulation model has been tested according to the guidelines set by Barlas (1996). Note that the entire modeling process [problem articulation, formulation of dynamic hypothesis, formulation of simulation model, testing, policy formulation and evaluation] has been iterative and subject to continuous questioning, testing and refining.

2.1.3 Research ethics

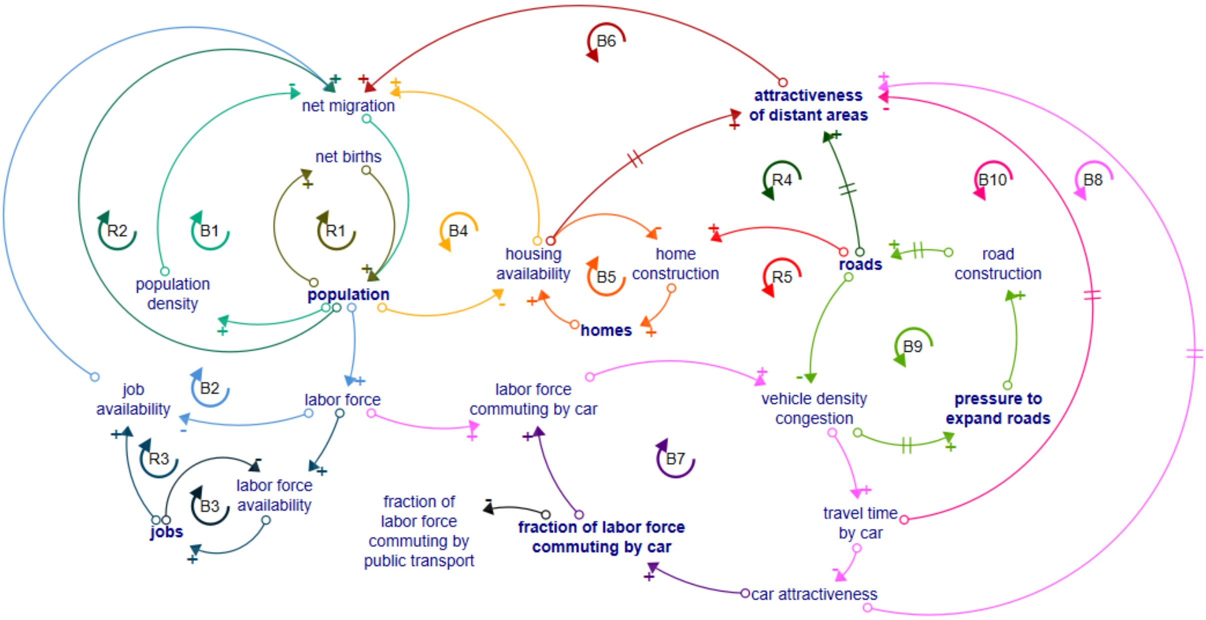
This research has been carried out with rigor, integrity and transparency in order to contribute to society and the scientific community, following generally accepted research ethics throughout the duration of the research (NESH, 2022; Sterman, 2000). The research report, accompanying System Dynamics model and other supplementary materials are publicly available for other researchers. As the research includes solely non-sensitive and publicly available data, ethics approval is not required.

2.2 Model description

2.2.1 Conceptual model – causal loop diagram

This section will discuss the conceptual model in the form of a simplified CLD to address the main feedback loops that drive urban sprawl and congestion in the The Hague region. As the CLD is a simplified version of the simulation model, some discrepancies exist between the CLD and the simulation model due to some structural elements not being included in the CLD. The complete CLD is shown in Figure 5 below, and will be discussed in parts.

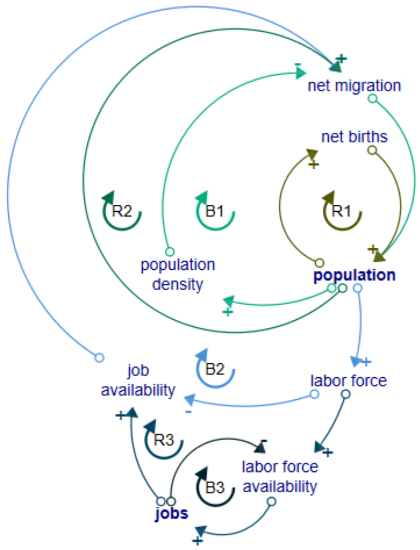
*Figure 5 – Causal loop diagram summarizing the mechanisms which offer a causal explanation for urban sprawl and congestion in the The Hague region.**



*Note that the more homes, roads and jobs there are, the more land will be occupied. After a certain land occupation fraction, the more land occupied will lead to less growth in homes, roads and jobs as there is only a limited amount of space available for growth, and eventually there can be no growth any longer when all available land for homes, roads and jobs is fully occupied. This is not represented in the CLD due to readability considerations.

As mentioned in section 1.2.2 of this report the The Hague region consists of its central, ring and outer area. Each area holds a population which can change through net births and net migration. When the population increases, the higher the net births and net migration will be as well, thus resulting in an even bigger population the next time round. This is represented by the reinforcing feedback loops **R1** and **R2** in Figure 6 below. However, when an area becomes too densely populated and crowding occurs, more people will move away from the area to avoid the overcrowded space. As such, when the population of an area increases towards and beyond its carrying capacity, this will result in a decreasing net migration, resulting in a smaller population the next time round [in case when the population exceeds the carrying capacity which would result in out-migration]. This is represented by the balancing loop **B1** [see Figure 6 below]. Net migration is an important mechanism in the model as which area [central, ring, outer] people migrate to is influenced by feedback from other mechanisms such as the relative attractiveness of an area, its housing availability, and the job availability in the region [see the complete CLD in Figure 5 above].

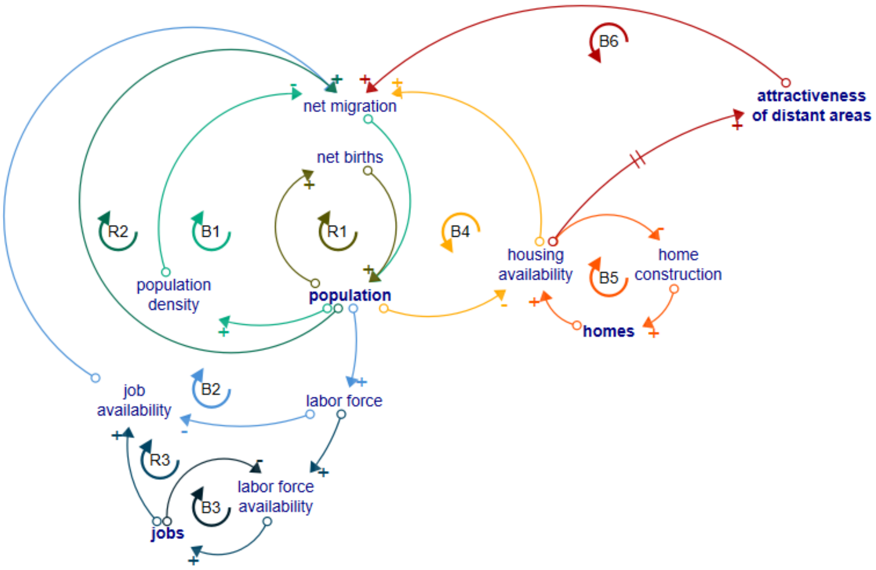
Figure 6 – Feedback loops B1, B2, B3, R1, R2 and R3 of causal loop diagram.



The amount of jobs in the The Hague region, and in extent the job availability in the region, is an important consideration when migrating in or out of the region. When the population of an area [central, ring, outer] increases, the labor force that can occupy a job in the The Hague region increases as well. This results in an increase in labor force availability. From a business perspective, new employees are easier to come by when the labor force availability increases, which makes it easier for businesses to grow, thereby creating more jobs. When the amount of jobs in the region increase, the job availability increases too. From an individual perspective, finding a new job will be easier when job availability increases. As job availability is an important consideration for migration, the higher the job availability, the higher net migration will be, thus resulting in an increasing population the next time round. This is represented by the reinforcing feedback loop **R3** as shown in Figure 6 above. Note that the changes in jobs in the region and the population in an area are not instantaneous processes and take time.

There are also two balancing loops in play here, namely **B2** and **B3**. When the population of an area increases, and the labor force that can occupy a job in the The Hague region increases as well, this labor force will occupy more jobs. Prior jobs in the region that were available become occupied and unavailable, and thus the job availability in the region decreases, which will result in a lower net migration. As such, the growth in population will be limited by balancing loop **B2**. Furthermore, when the amount of jobs in the region increases, the labor force in the region will occupy the available jobs. Prior available employees thereby become unavailable, and thus the labor force availability decreases. Consequently, the growth in jobs will be limited by balancing loop **B3** [see Figure 6 above].

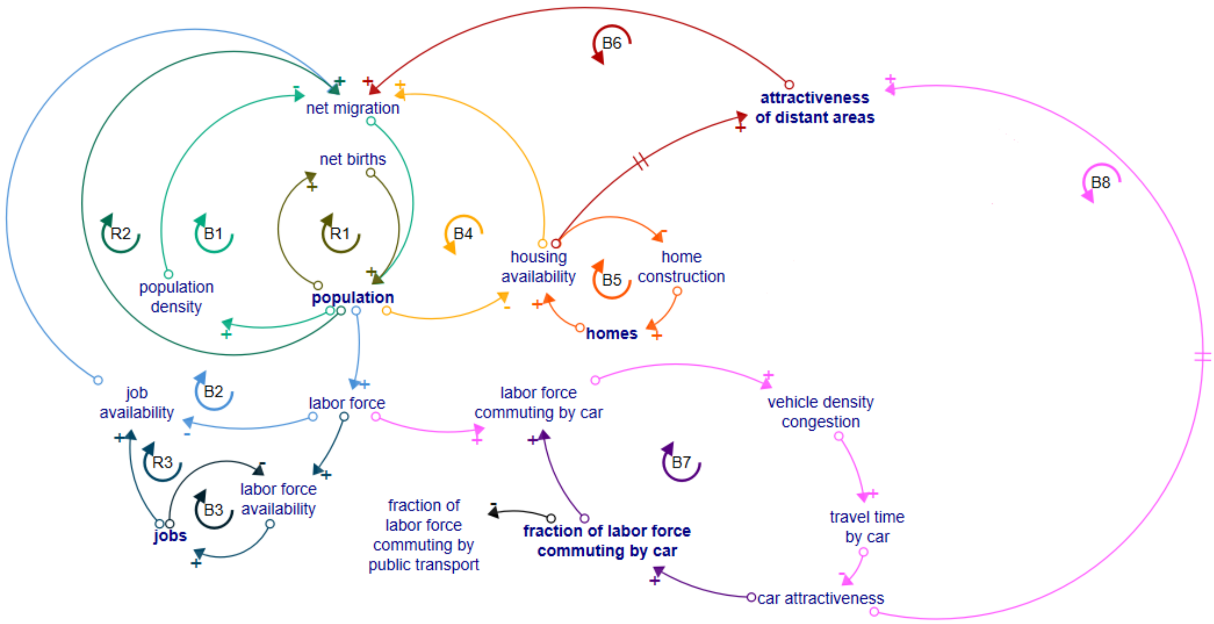
Figure 7 – Figure 6 extended with feedback loops B4, B5 and B6 of causal loop diagram.



Another important consideration when migrating is the amount of homes in the area [central, ring, outer], and in extent the housing availability in the area. When the population of an area increases, they will occupy more homes, thereby decreasing the housing availability of an area. When the housing availability decreases, finding a new home will be more difficult due to a slimmer supply of available homes and increased home prices accompanying the decreased housing availability. Consequently, net migration will decrease as well. The growth of the population in an area will be limited by its housing availability. This is represented by the balancing feedback loop **B4** [see Figure 7 above]. However, there is another balancing loop in play here, namely **B5**. When housing availability decreases, the construction rate of new homes will be increased towards its maximum trying to meet the housing demand in the area. By increasing the home construction, the amount of homes in the area will increase as well, thus increasing the housing availability the next time round [see balancing loop **B5** in Figure 7 above]. As housing availability increases again through balancing loop **B5**, balancing loop **B4** will work to increase net migration, thereby increasing the population and thus decreasing the housing availability again next time round.

Homes, and specifically in which area [central, ring, outer] they are constructed, is an important measure for urban sprawl in this model as homes in more distant areas [the ring area being more distant than the central area, and the outer area being more distant than the ring area] are increasingly bigger and more dispersed, and the fraction of homes that are multifamily homes decreases in favor of single family homes the more distant the area is. Furthermore, as greenfield development [development on prior undeveloped land] is easier and less costly than brownfield or greyfield developments [development on prior developed land], residential development is often implemented in distant, peripheral urban areas rather than more central urban areas (Nagengast, Hendrickson & Lange, 2011). When more homes are constructed in the outer and ring The Hague areas, compared to the central The Hague area, and the housing availability of those more distant areas is higher than the housing availability of the central area, the relative attractiveness of the more distant areas [outer and ring areas] increases to the detriment of the relative attractiveness of the central area. When the relative attractiveness of more distant areas increases, more people will migrate to these areas than they otherwise would. As such, the population of these areas increases. In turn, an increasing population results in decreasing housing availability in the area the next time round. This is represented by the balancing feedback loop **B6** [see Figure 7 above].

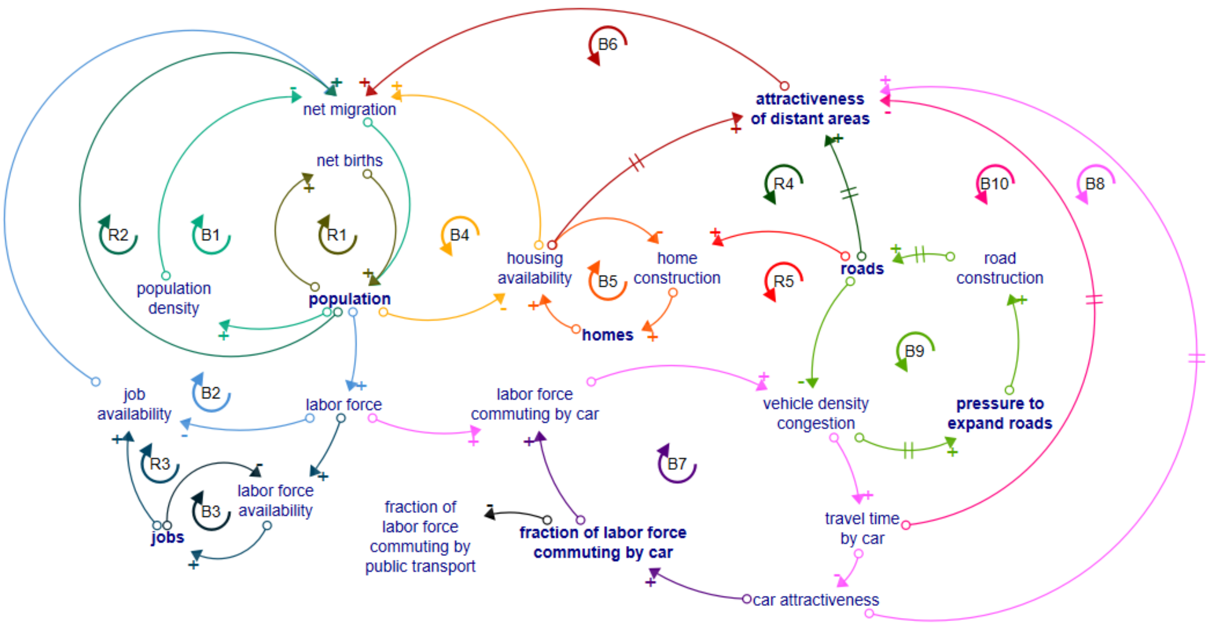
Figure 8 – Figure 7 extended with feedback loops B7 and B8 of causal loop diagram.



When the population of an area [central, ring, outer] increases, the labor force of the area that can occupy a job in the The Hague region increases as well. This labor force has to commute to and from their workplace. The labor force of the central The Hague area commutes predominantly by modes of transport other than public transport or private vehicles as their commute is shorter since on average they live closer to places of interest. Nevertheless, a small fraction of the central labor force commuters commutes by car. The labor force of the ring The Hague area often commutes by modes of transport other than public transport or private vehicles, however a large fraction of the ring labor force commuters does commute by car as their commute is longer compared to central commuters as on average they live further away from places of interest. The labor force of the outer The Hague area predominantly commutes by private vehicles, as their commute is the longest as on average they live furthest away from places of interest. Only a small fraction of the outer labor force commuters commutes by active modes of transport or public transport. When the labor force of an area increases, the total labor force commuting by car increases as well. An increasing population, and thereby increasing labor force, influences the total labor force commuting by car the most when these population increases happen in more distant areas as the commuters from distant areas more often opt for the car as mode of transport compared to commuters from the central area.

As the total labor force commuting by car increases, traffic volume increases as well which leads to a higher vehicle density on the road network. When vehicle density becomes higher than acceptable, congestion occurs. With increasing congestion, the travel time by car increases as well. When the travel time by car increases, the car attractiveness – meaning the attractiveness of private vehicles as transport mode – decreases. When car attractiveness decreases, the fraction of the labor force per area that commutes by car will decrease as well [in favor of the fraction of the labor force per area that commutes by public transport] and thereby, the total labor force commuting by car will decrease the next time round. This is represented by the balancing feedback loop **B7** [see Figure 8 above]. Furthermore, when car attractiveness decreases and private vehicles as a transport mode become less attractive compared to public transport, the relative attractiveness of distant areas will decrease as well, thereby closing another balancing feedback loop **B8** [see Figure 8 above].

Figure 9 – Figure 8 extended with feedback loops B9, B10, R4 and R5 of causal loop diagram.



As mentioned prior in this report, congestion has traditionally been 'solved' by more road construction (OECD, 2021; Sterman, 2000, p. 178). When congestion increases, users of the road network put pressure on decision makers to expand the road network (OECD, 2021). It takes time for this pressure to build. Nevertheless, when the pressure to expand the road network increases, road construction will increase as well, and after a delay the road network will increase. When the road network increases, the density of vehicles on the road network will decrease again. This is represented by the balancing feedback loop **B9** [see Figure 9 above].

When the vehicle density on the road network decreases, the travel time by car will decrease as well. This in turn results in distant areas to become relatively more attractive again as the size of the region within an acceptable travel time increases (OECD, 2021), thereby closing another balancing feedback loop **B10** [see Figure 9 above].

Furthermore, when the road network increases, which facilitates people to locate themselves further away from places of interest (OECD, 2021), the relative attractiveness of more distant areas increases as well. Thereby, another reinforcing feedback loop **R4** [see Figure 9 above] is closed where more roads lead to more net migration into distant areas, which leads to an increasing population in distant areas, the labor force of which predominantly commute by car, adding to the traffic volume and vehicle density on the road network which leads to congestion, increasing pressure to expand the road network and an increase in the road network the next time round.

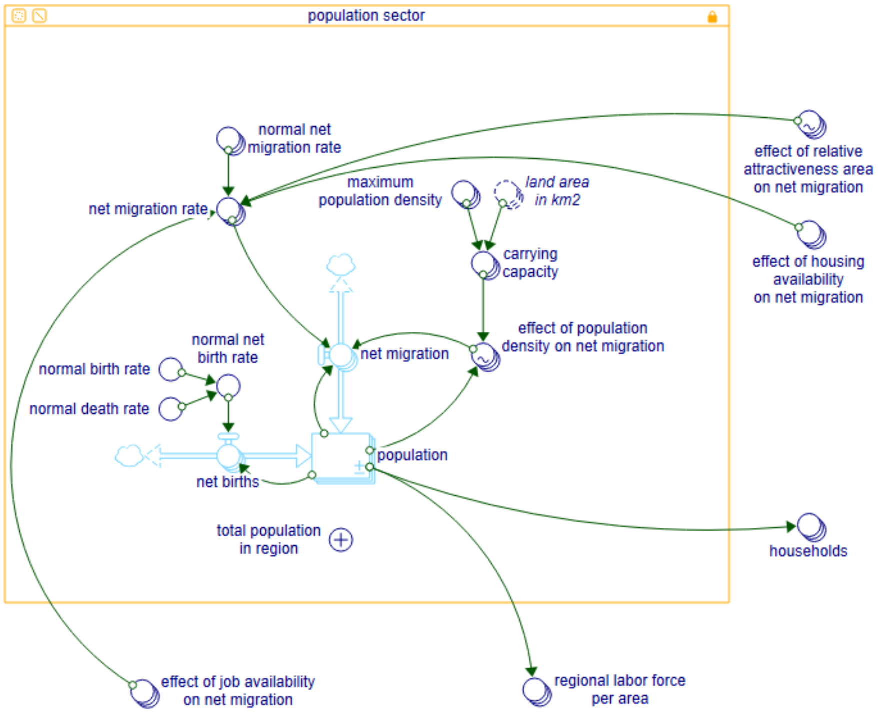
Finally, when the road network increases, which facilitates home construction in places that were less accessible before [usually in more distant areas], the maximum home construction can be increased, which results in more home construction and thus more homes. As such, another reinforcing feedback loop **R5** [see Figure 9 above] is closed where more roads lead to more homes, which in turn leads to higher housing availability, more net migration, an increasing population, the labor force of which often commutes by car, adding to the traffic volume and vehicle density on the road network which leads to congestion, increasing pressure to expand the road network and an increase in the road network the next time round.

It should be noted that land, and the fraction of land that is occupied, is not represented in the CLD due to readability considerations. However, homes, roads and jobs [workplaces] take up space. The more homes, roads and jobs, the more land will be occupied. After a certain land occupation fraction, the more land occupied will lead to less growth in homes, roads and jobs as there is only a limited amount of space available for growth, and eventually there can be no growth any longer when all available land for homes, roads and jobs is fully occupied.

2.2.2 Simulation model – stock and flow structure

This section will discuss the simulation model which was constructed using the software Stella Architect. A visual of the complete model structure can be found in Appendix I and, for more information regarding the mechanisms included in the simulation model, the complete model documentation [including sources], which addresses each variable and its equation separately, can be found in Appendix II. The simulation model will be discussed in parts by use of the nine sectors included in the hypothesis. The simulation model is arrayed by the dimension area, its elements consisting of the central The Hague area, the ring The Hague area and the outer The Hague area. Together these areas form the total The Hague region as included in this work [as shown in Figure 1 and addressed in section 1.2.2 of this report].

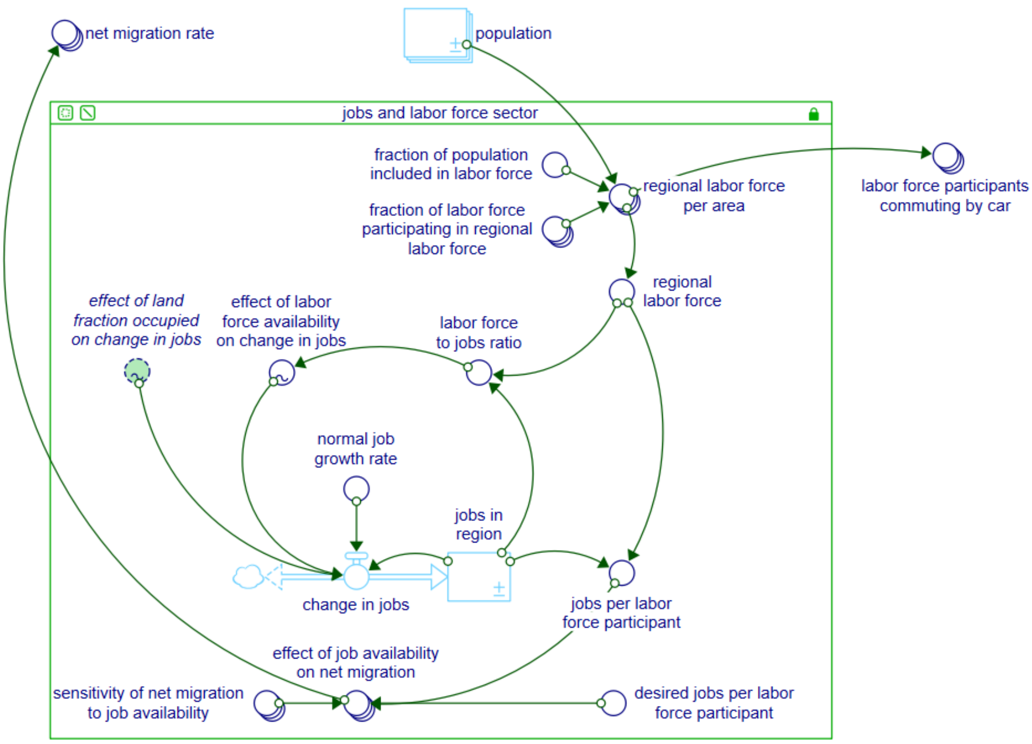
Figure 10 – Population sector included in the simulation model.



The population sector [see Figure 10] represents the population dynamics in the The Hague region. This sector in itself contains the three minor feedback loops **R1**, **R2** and **B1**, and together with other sectors, is part of the minor feedback loops **B2** and **B4**, and the major feedback loops **R3**, **R4**, **R5**, **B6**, **B8** and **B10** as discussed in section 2.2.1 of this report. The stock population is arrayed by area [central, ring, outer] and changes through the two net flows net births and net migration. Net births equals the product of the population by the normal net birth rate [which equals the difference between the normal birth and death rates]. Net migration equals the product of the population by the net migration rate and the effect of population density on net migration. The effect of population density on net migration is a graphical function based on the ratio between the population of an area and the carrying capacity of that area [representing the population density]. When the population increases towards the carrying capacity, the effect will decrease increasingly towards zero. Net migration will be limited by the effect of population density. When the population exceeds the carrying capacity, the effect will return a negative value. Net migration will then represent a net out-migration rather than a net in-migration, and the population will decrease.

The net migration rate variable takes input from three other sectors, being the jobs and labor force sector, the households and housing sector, and the attractiveness areas sector. The effects influencing the net migration rate will be discussed when their respective sectors are addressed. The population sector in turn gives input to two other sectors, being the jobs and labor force sector, and the households and housing sector. The former of the two will be addressed next.

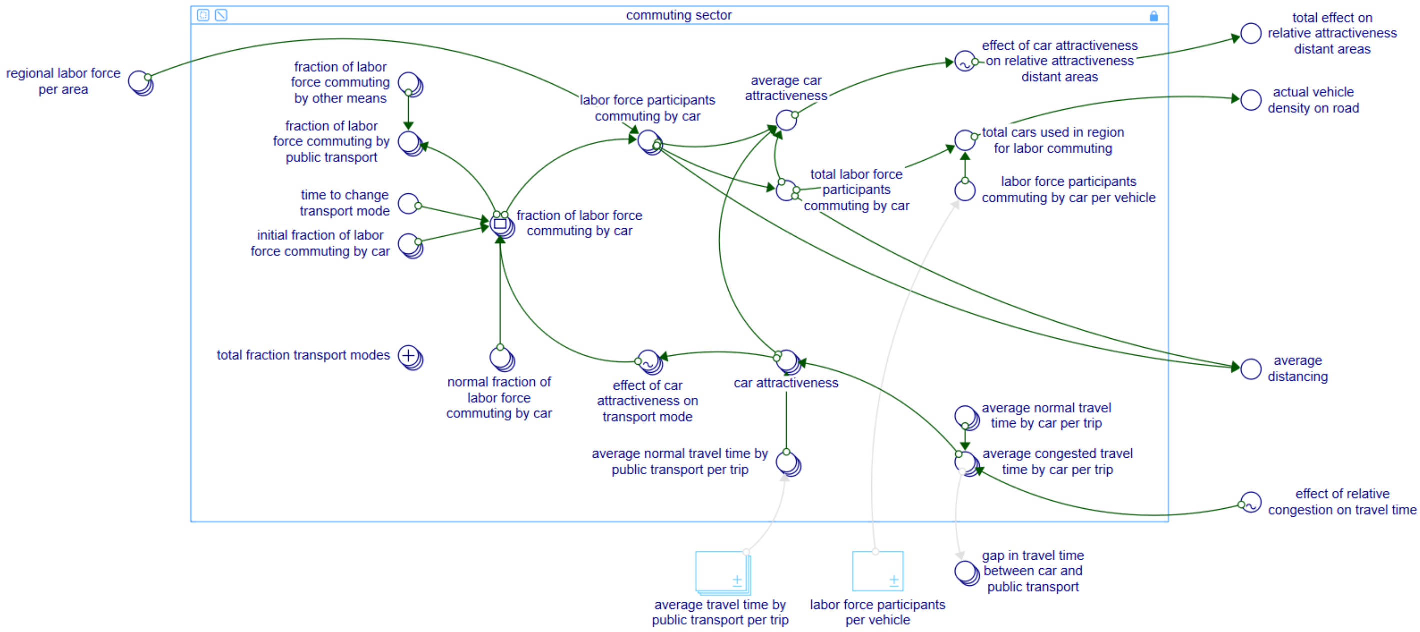
Figure 11 – Jobs and labor force sector included in the simulation model.



The jobs and labor force sector [see Figure 11] represents the labor dynamics in the The Hague region. This sector in itself contains the minor feedback loop **B3** and, together with the population sector, contains the minor feedback loop **B2** and the major feedback loop **R3**, and together with other sectors, is part of the major feedback loops **R4**, **R5**, **B8** and **B10** as discussed in section 2.2.1 of this report. The stock jobs in region [which represents the amount of jobs in the whole The Hague region, and is not arrayed by area] changes through the flow change in jobs. Change in jobs equals the product of the jobs in the region by the normal job growth rate and by two effects being the effect of labor force availability and the effect of occupied land. Both effects are represented by graphical functions. The latter effect of occupied land is based on the land fraction of the The Hague region that is already built-up. When too high a fraction of the available land is built-up, this effect will work to limit and eventually nullify the growth in jobs [via a decreasing increasingly effect from one towards zero for when all land is occupied]. The effect of labor force availability is based on the ratio between the labor force and jobs in the region. The graphical function contains an s-shape. When there is a shortage of labor force, and new employees will be more difficult to find, this will limit the growth in jobs. However, when there is a surplus of labor force, and new employees will be easier to find, this will stimulate the growth in jobs.

The sector takes input from two other sectors, being the land sector [its effect is already addressed] and the population sector. The population stock determines the labor force per area [central, ring, outer] that can occupy a job in the The Hague region through a product equation with the fraction of the population that is included in the labor force, and the fraction of that labor force which practices a job in the The Hague region [and not outside of the The Hague region]. In turn, the sector gives input to three other sectors, being the land sector, the population sector and the commuting sector. The land sector will be addressed later in this section. The input for the population sector is the effect of job availability on net migration. This is a linear function arrayed per area [central, ring, outer]. The sensitivity of net migration to job availability determines the direction and slope of the linear function. This sensitivity has a positive value for all areas as it is assumed that a higher job availability will lead to more people wanting to migrate towards that area. The value for the central area is assumed to be higher compared to the ring area, and the value for the ring area is assumed to be higher compared to the outer area as the central The Hague area is identified with more significant career opportunities compared to the ring area, and in its turn compared to the outer area. As such, changes in job availability will have a bigger impact on net migration for the central The Hague area compared to the ring area, and in its turn compared to the outer area. The commuting sector will be addressed next, in which the input from the jobs and labor force sector for the commuting sector will also come to pass.

Figure 12 – Commuting sector included in the simulation model.



The commuting sector [see Figure 12] represents the commuting dynamics [regarding mode of transport and travel time] in the The Hague region. This sector is, together with the congestion sector, part of the minor feedback loop **B7** and, together with other sectors, part of the major feedback loops **B8**, **B10**, **R4** and **R5** as discussed in section 2.2.1 of this report. The sector takes input from three other sectors, being the jobs and labor force sector, the congestion sector and the policies sector [as such, the former two sectors provide input for the explanatory model].

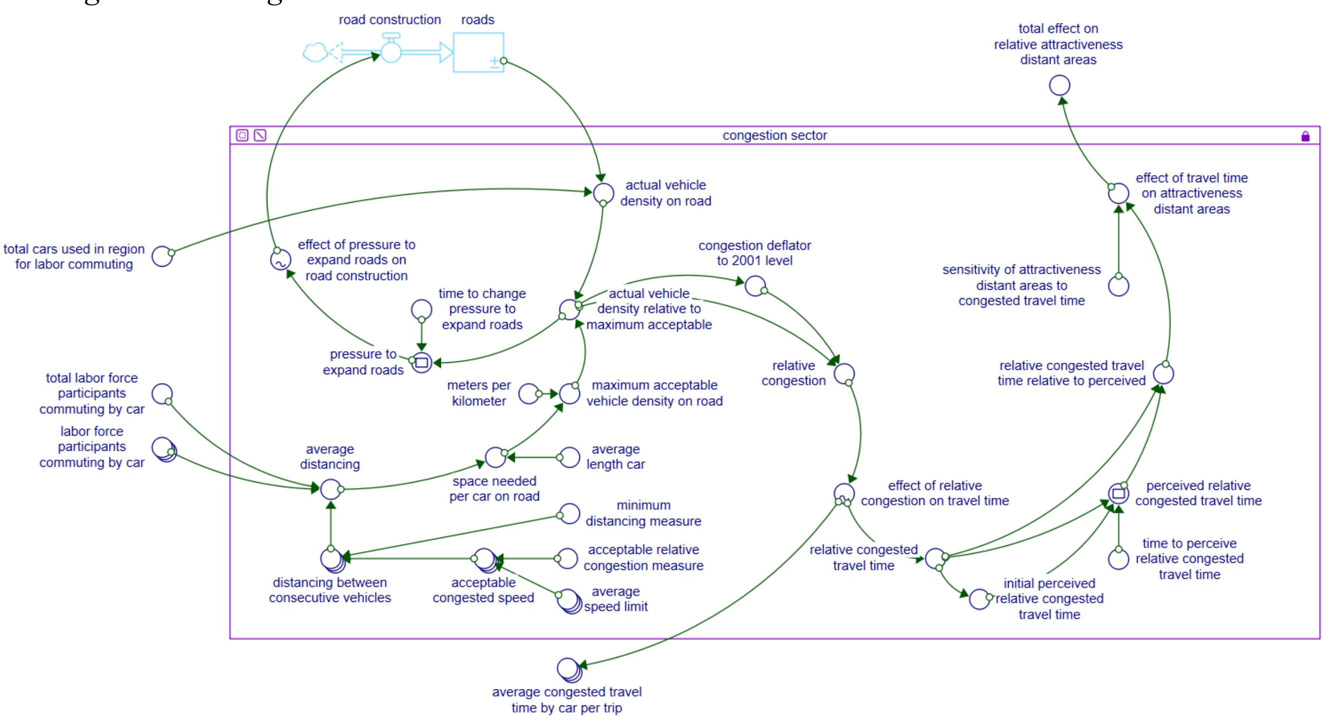
From the jobs and labor force sector, the regional labor force per area determines the amount of labor force participants per area that are commuting by using a private vehicle [such as a car] through a product equation with the fraction of the labor force that commutes by private vehicle per area. This latter fraction further influences the fraction of the labor force per area that commutes by public transport. The environmental impact of urban sprawl and congestion is not part of the model structure as it is outside of the current model boundary. Nevertheless one could imagine that emissions and congestion would decrease when the fraction of the labor force commuting by car decreases in favor of the fraction of the labor force commuting by public transport as public transport is a more environmentally sustainable mode of transport than private vehicles, and the traffic volume would decrease [without regard for changes in the population and road network]. For simplification purposes, it is assumed that the fraction of labor force participants commuting by other means [such as cycling or walking] does not change throughout the time horizon of this model. For future work, the author suggest to endogenize this fraction.

The fraction of the labor force participants commuting by private vehicle per area is influenced through an effect, represented by an s-shaped graphical function, based on car attractiveness. When the car as a transport mode is less attractive than public transport, the fraction of labor force commuters that opt for the car as transport mode decreases down to a lower bound. However, when the car as a transport mode is more attractive than public transport, the fraction of labor force commuters that opt for the car as transport mode increases up to an upper bound. Car attractiveness in turn is based on travel time, where the travel time per trip is compared between the transport modes public transport and car [while taking congestion into account]. The transport mode which takes commuters to places of interest the quickest is deemed more attractive. In reality, more aspects [such as the impact of transport mode on the environment, costs of transport mode, flexibility offered by transport mode, and so on] are taken into consideration when determining the attractiveness of a transport mode. However, these lay outside the model boundary of the current work. The travel time by car per trip is influenced through an effect of congestion on travel time, originating from the congestion sector. According to Asten (2019), travel time will increase exponentially when congestion increases, as such the effect is represented by an exponential growth graphical function. The input from the policies sector will be addressed later in this section.

Besides taking input from other sectors, the commuting sector also gives input to three other sectors, being the congestion sector, the attractiveness areas sector and the policies sector. For the attractiveness areas sector, the relative attractiveness of more distant areas is influenced by an effect of car attractiveness. This effect is represented by a graphical function. The graphical function will only work to decrease the relative attractiveness of more distant areas decreasingly when the car as a transport mode becomes less attractive compared to public transport based on travel time. It will not work to increase the relative attractiveness of more distant areas when the car as a transport mode becomes more attractive compared to public transport based on travel time as it is predominantly the expanding road network that facilitates people to locate themselves further away from places of interest (OECD, 2021). Furthermore, when the car attractiveness increases, this does not imply that the travel time by car between a place of departure and destination decreases [and cars would become faster], it merely implies that the travel time by car between a place of departure and destination is shorter compared to the travel time between the two places when commuting by public transport [thus, car attractiveness could also increase when travel time by public transport increases]. This does not mean that one would want to locate their household in a more distant area elongating the distance, and thereby the minimal travel time, between a household's place of departure and destination. However, the opposite is applicable. When car attractiveness decreases and the travel time by car between a place of departure and destination is longer compared to the travel time between the two places when commuting by public transport, one would want to locate their household in a less distant area as public transport is more accessible in less compared to more distant areas (OECD, 2021). As such, the relative attractiveness of more distant areas would decrease when car attractiveness decreases and a private vehicle as a transport mode becomes less attractive based on travel time compared to public transport.

For the congestion sector, the input of the commuting sector is most significant for determining the actual vehicle density on the road network through a division of the total cars used in the region [derived from the division of the total labor force commuters commuting by car, by the labor force participants commuting by car per vehicle], by the total road network [originating in the roads sector]. The vehicle density on the road network will only be classified as congested when the actual vehicle density exceeds the acceptable vehicle density on the road network as will be discussed when the congestion sector is addressed next.

Figure 13 – Congestion sector included in the simulation model.

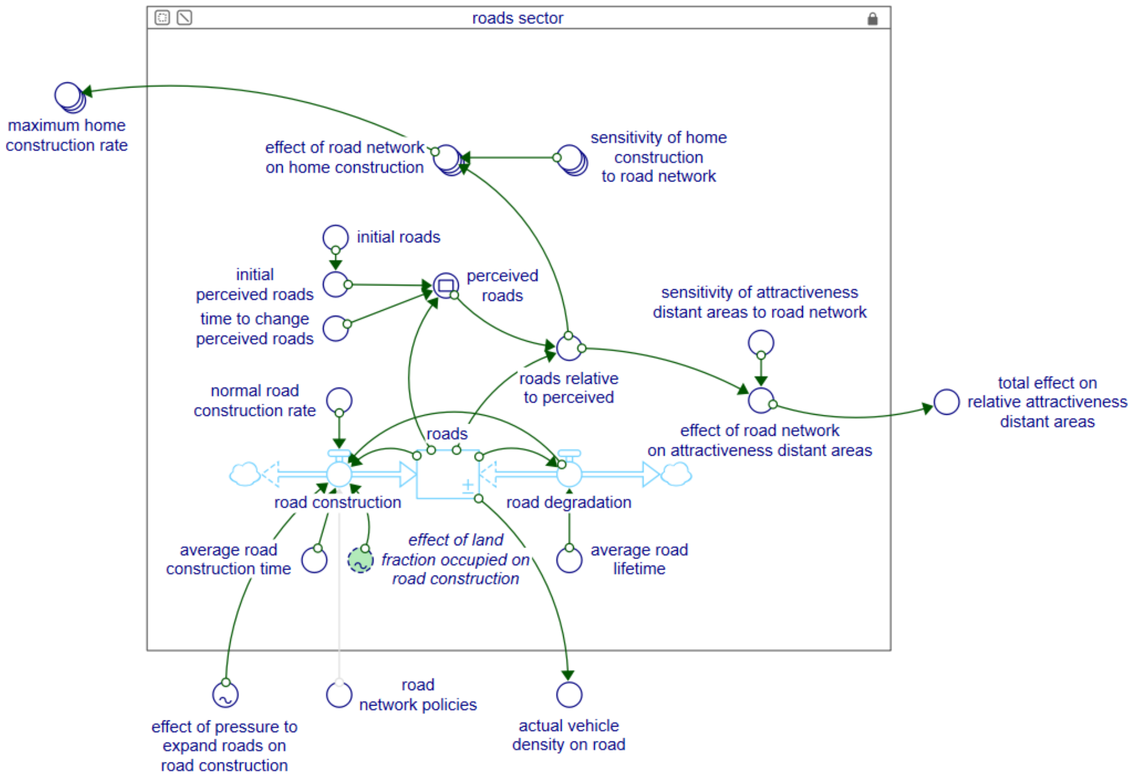


The congestion sector [see Figure 13] represents the congestion dynamics in the The Hague region. Together with the commuting sector, this sector contains the minor feedback loop **B7**, and is furthermore part of the major feedback loops **B8**, **B9**, **B10**, **R4** and **R5** as discussed in section 2.2.1 of this report. The sector takes input from two other sectors, being the commuting sector and the roads sector. Both inputs from these sectors for the actual vehicle density on the road network are addressed prior. There it was also mentioned that the vehicle density on the road network will only be classified as congested when the actual vehicle density exceeds the acceptable vehicle density on the road network. This is determined by the variable actual vehicle density relative to maximum acceptable. As it is unrealistic to never have congestion, some congestion is regarded as acceptable (Rijkswaterstaat, 2022). The maximum acceptable vehicle density on the road network is determined in the bottom left corner of the congestion sector by taking into account the average speed limit, distancing, the acceptable congestion measure and the length of cars. The ratio between the actual vehicle density and the maximum acceptable vehicle density on the road network determines whether there is congestion [when the actual value exceeds the acceptable value] and how congested the road network is, or whether there is no significant congestion [when the actual value is lower or equal to the acceptable value].

As the reference mode for relative travel time (Loop & Hamersma, 2018; Tomtom, 2023) represents a value relative to the year 2001, the relative congestion at the start time of the simulation [which is the year 2001] should equal a dimensionless value of one. Therefore a congestion deflator with a history function in its equation [the variable is explicitly included for transparency rather than an INIT function], makes the congestion value [as determined by the ratio between the actual and acceptable vehicle density on the road network] relative to the year 2001 in the relative congestion variable. The effect of relative congestion on travel time is based on this relative congestion variable. According to Asten (2019), travel time will increase exponentially when congestion increases, as such the effect is represented by an exponential growth graphical function. This effect in the congestion sector provides input to the average congested travel time by car per trip in the commuting sector. Furthermore, this effect determines the relative congested travel time [which equals the value of the effect variable as the normal relative congestion at the start time of the simulation equals a dimensionless value of one]. The ratio between the relative congested travel time and the relative congested travel time a commuter perceives then determines the effect of congested travel time on the relative attractiveness of more distant areas. This is a linear function. The sensitivity of the relative attractiveness of more distant areas to the relative congested travel time determines the direction and the slope of the linear function. This sensitivity has a negative value as it is assumed that when the relative congested travel time is higher than perceived, people find more distant areas less attractive compared to the central area as it would take a longer time than expected to travel from distant locations to one's destination and back. This effect in the congestion sector provides input to the attractiveness areas sector.

Besides giving input to the commuting sector and attractiveness areas sector, the congestion sector also gives input to the roads sectors. When congestion increases, by the actual relative to the acceptable vehicle density on the road network, pressure on decisions makers will build to expand the road network, the mental model behind this pressure is that congestion will decrease again with a bigger road network (OECD, 2021; Sterman, 2000). It takes time before pressure is exerted, recognized and accepted. When this pressure is accepted however, it will work through an effect to increase road construction. This effect is represented with an s-shaped graphical function. When the road network is congested, there is a limit to how much road construction can be increased when pressure to expand the road network increases.

Figure 14 – Roads sector included in the simulation model.

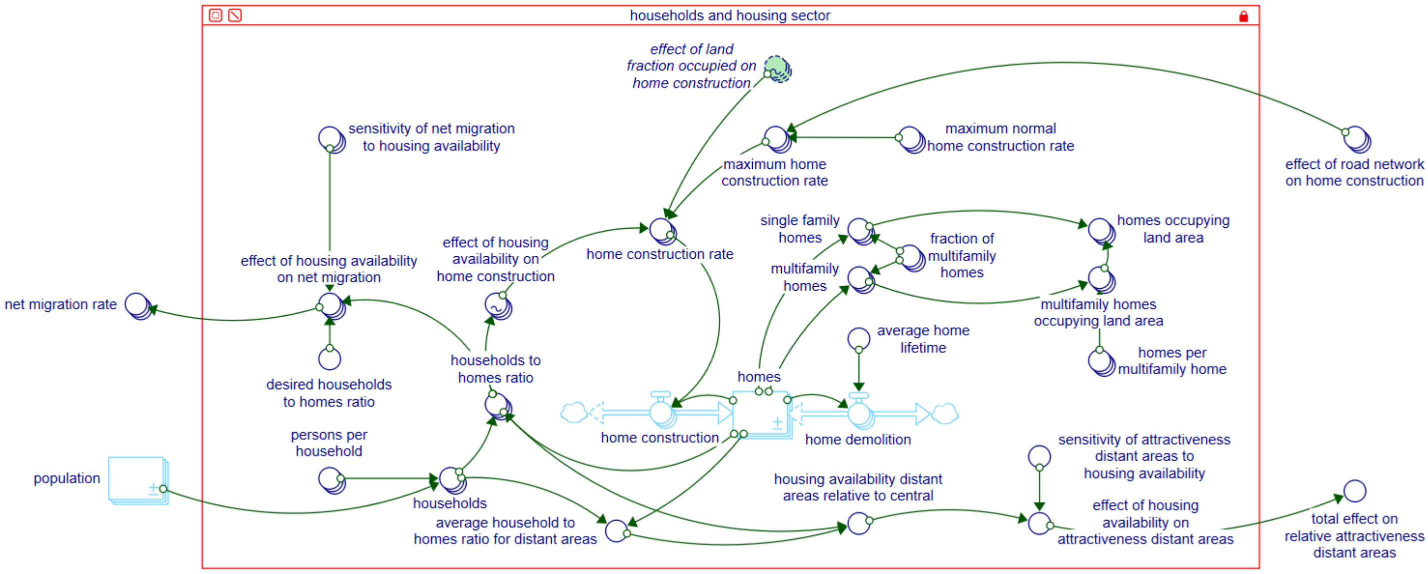


The roads sector [see Figure 14] represents the road network dynamics in the The Hague region. This sector, together with the congestion sector, contains the major feedback loop **B9**, and is furthermore part of the major feedback loops **R4** and **R5** together with other sectors as discussed in section 2.2.1 of this report. The stock roads [which represents the road network in the whole The Hague region, and is not arrayed by area] changes through the flows road construction and road degradation. Road construction takes input from the congestion sector, land sector and the policies sector. The input from the policies sector will be addressed later in this section.

Road construction contains a delay function as it takes a significant amount of time to plan and execute road construction. The input to the delay function equals the product of the road network by the normal road construction rate, by the effect of pressure to expand roads and by the effect of occupied land. Furthermore, road degradation is added to this input as it is assumed that roads will be repaired when they degrade. Both effects are represented by graphical functions. The effect originating from the congestion sector [effect of pressure to expand roads] is already addressed prior in this section. The effect of occupied land is based on the land fraction of the The Hague region that is already built-up. When too high a fraction of the available land is built-up, this effect will work to limit the road construction, and to eventually equal road construction to road degradation so roads can solely be repaired but no new roads can be constructed. The graphical function contains a decreasing increasingly effect from one towards zero for when all land is occupied.

The roads sector gives input to four other sectors, being the land sector, the congestion sector, the attractiveness areas sector and the households and housing sector. The input of the stock roads for the congestion sector is already addressed prior in this sector [the bigger the road network, the smaller the actual vehicle density on the road network]. For the attractiveness areas sector, the ratio between the road network and the perceived road network determines the effect of the road network on the relative attractiveness of more distant areas. This is a linear function. The sensitivity of the relative attractiveness of more distant areas to the roads relative to perceived determines the direction and the slope of the linear function. This sensitivity has a positive value as it is assumed when the road network is bigger than perceived, people find more distant areas more attractive compared to the central area as it is predominantly the expanding road network that facilitates people to locate themselves further away from places of interest (OECD, 2021). For the households and housing sector, the ratio between the road network and the perceived road network determines the effect of the road network on home construction. This is a linear function. The sensitivity of home construction to the roads relative to perceived determines the direction and the slope of the linear function. This sensitivity has a positive value for all areas as it is assumed that a bigger road network creates opportunities for homes to be constructed more easily in places that were less accessible before. The value for the outer area is assumed to be higher compared to the ring area, and the value for the ring area is assumed to be higher compared to the central area as central areas are usually more accessible already when compared to ring areas and in turn outer areas (Grimeland, 2022). As such, changes in the road network are expected to have a bigger influence on home construction for the outer area compared to the ring area and in turn the central area.

Figure 15 – Households and housing sector included in the simulation model.



The households and housing sector [see Figure 15] represents the home dynamics in the The Hague region. This sector in itself contains the minor feedback loop **B5**, and together with the population sector contains the minor feedback loop **B4**. Furthermore the sector is part of the major feedback loops **B6** and **R5** as discussed in section 2.2.1 of this report. The sector takes input from three other sectors, being the population sector, the land sector and the roads sector. The input from the roads sector [by the effect of the road network on home construction] is already addressed prior in this section. The effect of occupied land is a graphical function based on the land fraction of each area [central, ring, outer] in the The Hague region that is already built-up. When too high a fraction of the available land in the area is built-up, this effect will work to limit and eventually nullify the home construction rate in that area [via a decreasing increasingly effect from one towards zero for when all land in the area is occupied]. For the population sector, the stock population determines the amount of households per area through a division of the population in the area by the amount of people per household in the area. The amount of households per area in turn determines the housing availability, represented by the households to homes ratio, together with the arrayed stock homes [note that the higher the households to homes ratio is, the lower housing availability is].

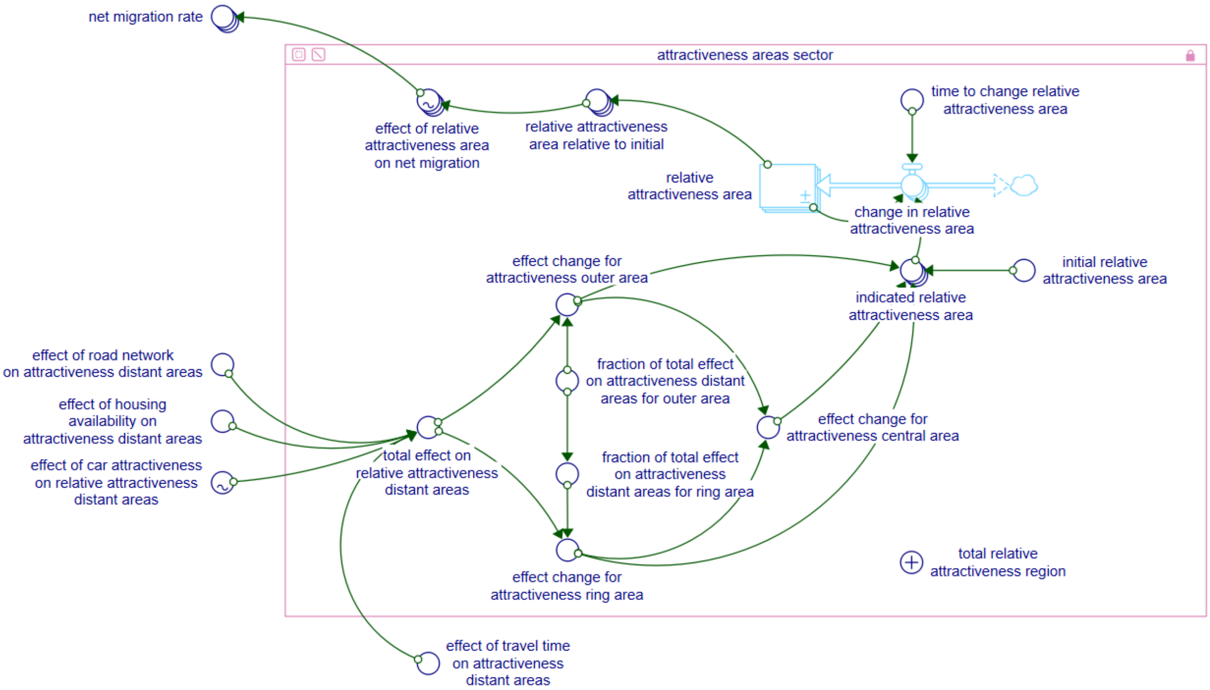
The stock homes is arrayed by area [central, ring, outer] and changes through the two flows home construction and home demolition. Home construction equals the product of the stock homes and the home construction rate. The home construction rate in turn equals the product of the maximum home construction by the effect of land occupied and by the effect of housing availability. As in general The Netherlands suffers from a housing shortage since the

Second World War (BZK, n.d.; Linden, n.d.) it is assumed that the home construction rate will equal the maximum home construction rate unless this is not possible due to land restrictions, or it is not desirable due to sufficient housing availability in the area. The effect of land occupied is already discussed prior in this section. The effect of housing availability is represented by a graphical function and is based on the households to homes ratio. When the households to homes ratio decreases from one to zero, meaning there are less households than homes and there thus is sufficient housing availability, the effect of housing availability on home construction decreases decreasingly towards zero to limit the home construction rate.

The households and housing sector gives input to three other sectors, being the population sector, the land sector, and the attractiveness areas sector. The land sector will be addressed later in this section. The input for the population sector is the effect of housing availability on net migration. This is a linear function arrayed per area [central, ring, outer]. The sensitivity of net migration to housing availability determines the direction and slope of the linear function. This sensitivity has a negative value for all areas as it is assumed that a higher housing availability will lead to more people wanting to migrate towards that area. However, as housing availability is modeled as the households to homes ratio [where the higher the households to homes, the lower housing availability], the negative value is necessary to align the direction of the linear effect function with reality. The value for the central area is assumed to be higher [higher means a bigger, more negative value] compared to the ring area, and the value for the ring area is assumed to be higher [higher means a bigger, more negative value] compared to the outer area as homes are usually less affordable in the central area and more affordable in the ring and in turn the outer area. As such, net migration is expected to react more strongly to changes in housing availability for the central area compared to the ring and in turn the outer area. When the housing availability decreases, home prices are expected to increase much more in the central area compared to the ring and in turn the outer area [this expectation is based on changes in housing prices over time for the areas included in this model (AlleCijfers (2023)], which limits migration in to the central area more so than it will limit migration in to the ring area and in turn the outer area. Thus, changes in housing availability will have a bigger impact on net migration for the central The Hague area compared to the ring area, and in its turn compared to the outer area.

For the attractiveness areas sector, the ratio between the housing availability of more distant areas relative to the housing availability of the central area determines the effect of housing availability on the relative attractiveness of more distant areas. This is a linear function. The sensitivity of the relative attractiveness of more distant areas to housing availability determines the direction and the slope of the linear function. This sensitivity has a positive value as it is assumed that when the housing availability of distant areas is higher than the housing availability of the central The Hague area, people find the more distant areas more attractive compared to the central area as it would be relatively easier for them to find a new home there. This is applicable as The Hague is a thriving region [the opposite would be the case for regions that are emptying too much].

Figure 16 – Attractiveness areas sector included in the simulation model.

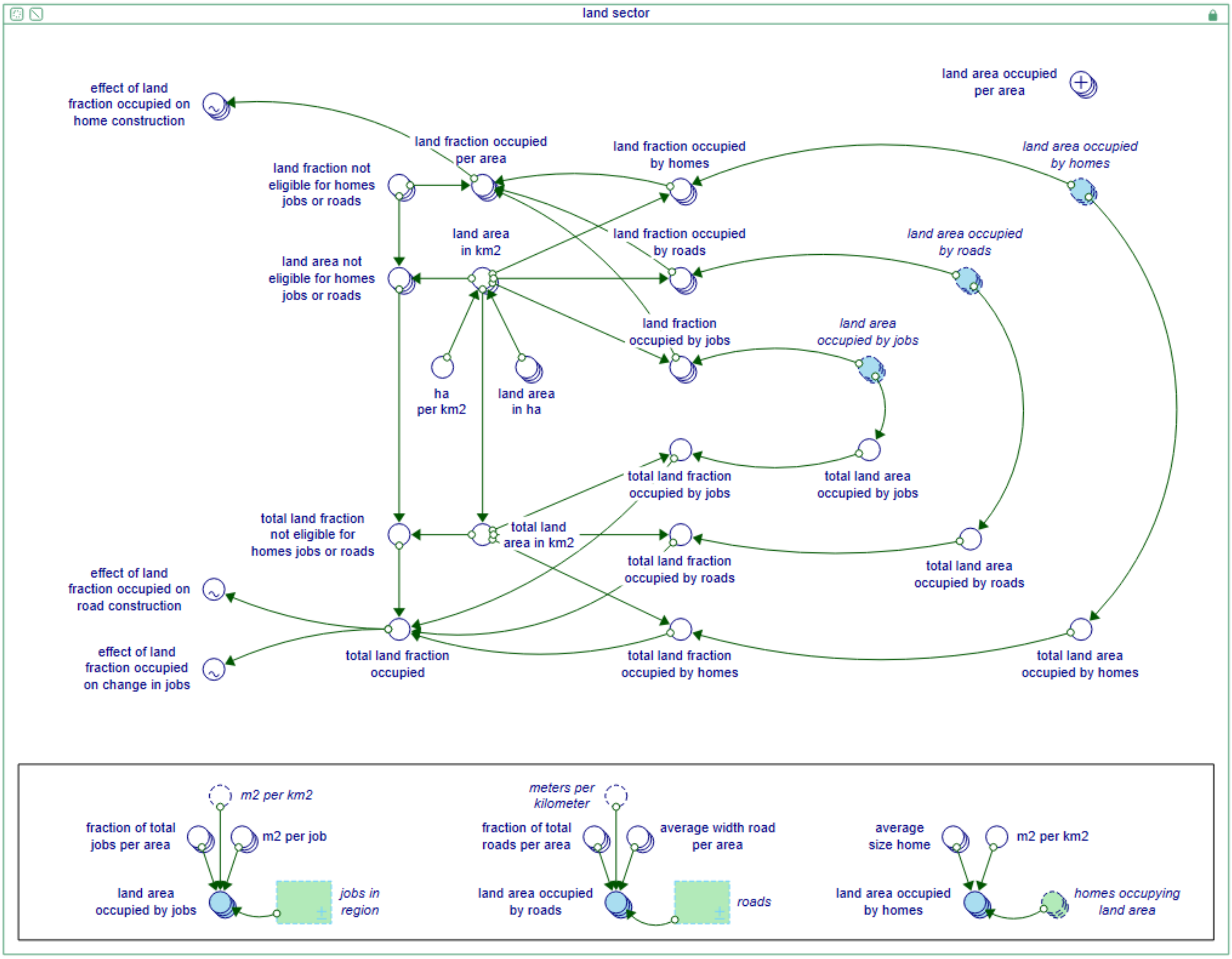


The attractiveness areas sector [see Figure 16] represents the attractiveness dynamics of the three areas [central, ring, outer] in the The Hague region. This sector is, together with other sectors, part of the major feedback loops **B6**, **B8**, **B10** and **R4** as discussed in section 2.2.1 of this report. The stock relative attractiveness area is arrayed by area [central, ring, outer] and changes through the flow change in relative attractiveness area which adjusts the stock towards an indicated relative attractiveness for the area over time. Note that the relative attractiveness of an area is not representing how attractive an area actually is, merely that over time the attractiveness of the area might have changed. For example, when the relative attractiveness of the outer area has increased over time and the relative attractiveness of the central area has decreased over time, this does not mean that the outer area is necessarily more attractive than the central area, rather it shows that the outer area has become more attractive than it initially was where the central area has become less attractive than it initially was. These changes in the attractiveness of an area influence the net migration rate of the area in the population sector to which this sector thus provides input. This effect is represented by an s-shaped graphical function. It is assumed that the more attractive an area becomes over time, more people would want to migrate in to that area as they otherwise would. The opposite is also applicable as when an area becomes less attractive over time, less people would want to migrate in to that area as they otherwise would.

Besides providing input for the population sector, the attractiveness areas sector takes input from four other sectors, being the commuting sector, congestion sector, roads sector and households and housing sector. All four effects of these sectors on the relative attractiveness of an area have already been discussed prior in this section. The effects are combined by multiplication in the total effect on relative attractiveness distant areas variable. As this total effect is applicable to more distant areas, containing both the ring area and outer area, the total effect has to be distributed between those areas [a bigger part of which is attributed to the outer area as this area is more distant than the ring area]. Furthermore, it is assumed that the attractiveness of the The Hague region as a whole does not change throughout the time horizon of this model, as such when more distant areas become more attractive, this implies that they become more attractive relative to the central area, and thus their relative attractiveness increases to the detriment of the central area. How the input effects change the relative attractiveness of an area is therefore determined for all three areas [central, ring, outer] and lead to an indicated value for the relative attractiveness of an area towards which the stock is adjusted over time.

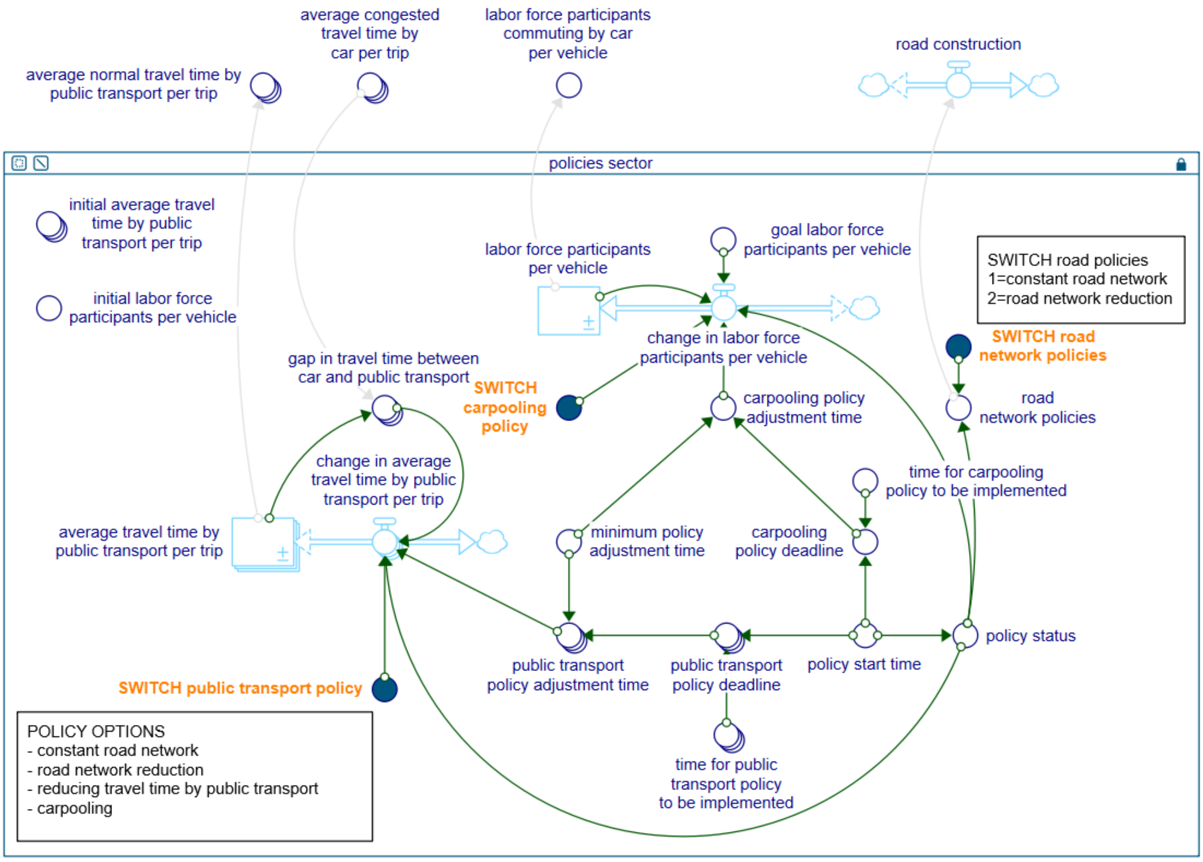
The land sector [see Figure 17 below] represents the land dynamics in the The Hague region. The land sector is not portrayed in the CLD as discussed in section 2.2.1 of this report due to readability considerations. Nevertheless, the sector does provide input to three other sectors, being the households and housing sector, jobs and labor force sector, and the roads sector. The three effects, represented by graphical functions, are already addressed prior in this section. The feedback the land sector gives to other sectors is all balancing in nature. When too high a fraction of the available land is built-up, the land sector will work to limit or stop growth, regardless of whether this is growth in homes, jobs or roads. Naturally the land sector receives input from these three sectors in return as well [by the stock jobs in region, the stock roads, and the variable homes occupying land area, the latter taking vertical building of multifamily homes into account] to determine the amount and fraction of land that is currently occupied. As not all land is eligible for homes, jobs or roads, this is also taken into account.

Figure 17 – Land sector included in the simulation model.



The policies sector [see Figure 18 below] represents the policies as tested in this work. The policies are mobility-oriented as urban sprawl and congestion are heavily intertwined with mobility as discussed in section 1.1 of this report. The four policy options focus on the road network [either by keeping the road network constant, or by decreasing it], car attractiveness [by decreasing the travel time by public transport thus reducing the attractiveness of private vehicles relative to public transport based on travel time], and the traffic volume [by carpooling, thus increasing the people per car when commuting, thereby reducing the traffic volume]. Both road network policy options can be implemented immediately after the policy start time. The remaining two policy options need time to be implemented. As such, stock and flow structures are created for adjusting the travel time by public transport per trip per area over time and for adjusting the labor force participants per vehicle over time.

Figure 18 – Policies sector included in the simulation model.



2.3 Additional model information

2.3.1 Model boundary

The Hague is part of various regions in The Netherlands, such as the Randstad Holland region, the Metropolitan Region Rotterdam The Hague and the county South Holland, which are all somewhat different. As such, the selection of the region to which the simulation model is applicable is important when determining the reference modes of behavior and to ensure that one is modeling the problem and not the system. The built-up area in the The Hague region in the years 1970 and 2017 as shown in Figure 1 has heavily influenced the selection of the region included in this model and has thereby also influenced the model boundary of this work. Included in the model boundary are the municipalities The Hague, Leidschendam-Voorburg, Rijswijk, Delft, Lansingerland, Pijnacker-Nootdorp and Zoetermeer.

Furthermore, the problem of urban sprawl and congestion is modeled in this work. The social and environmental impact of this problem lays outside of the model boundary for the current work. To visualize the importance of reducing urban sprawl and congestion, model structure and simulation results concerning the social and/or environmental impact [by including for example measures of well-being or emissions] of urban sprawl and congestion are recommended to be included in future iterations on this work.

Furthermore, decisions regarding which transport mode to travel with are much more complicated than how they are currently modeled as this model solely concerns travel time. Considerations such as the impact of transport mode on the environment, the costs of a transport mode and the flexibility offered by a transport mode currently lay outside the model boundary of this work. These could however influence the effectiveness of suggested policies. Another important modeling decision that should be addressed here is modeling the fraction of labor force commuting by other means [such as cycling or walking] as a constant exogenous variable, and modeling the fraction of labor force commuting by public transport merely as the remaining fraction [as 100% of the labor force commutes by private vehicle, public transport, or other means]. As this work is predominantly interested in congestion for private vehicles, the current model structure is deemed sufficient. Nevertheless, in order to test the effectiveness of various policies [for example a road reallocation policy] it is strongly recommended to endogenize these fractions properly in future iterations of this work. Finally, extensive policy testing and costs associated with the implementation of policies lays outside the current model boundary.

2.3.2 Modeling assumptions

Aside from modeling assumptions that were already mentioned in section 2.2 of this report, some additional modeling assumptions should be mentioned. An important modeling assumption that has not yet been addressed concerns the change in jobs flow. It is assumed that the amount of jobs in the The Hague region will not decrease throughout the time horizon of this model as The Hague is a thriving region which attracts many businesses (Lambregts, Kloosterman, Werff, Röling & Kapoen, 2006) and consistently hosts approximately six percent of all jobs in the country (CBS, 2022c). As such, the flow acts as an inflow and works only to maintain or increase the stock jobs in region. Furthermore, the value of some exogenous variables are assumed not to change throughout the time horizon of this model. These variables include the normal birth and death rates, normal net migration rate, maximum population density per area, the normal job growth rate, the distribution of jobs between the areas [fraction of total jobs per area], the amount of persons per household, the average size of a home per area, the maximum normal home construction rate and the normal road construction rate. The model behavior proved to be numerically sensitive in some degree during sensitivity analysis to some of these variables as discussed in Appendix III. Other assumptions are stated in the model documentation [see Appendix II].

2.3.3 Time settings

The start time of the model is the year 2001. This decision is made as the reference mode of behavior for the relative travel time as derived from Loop and Hamersma (2018) and Tomtom (2023) starts in the year 2001 and contains a measure relative to that same year. The end time of the model is the year 2050. This decision is made based on the time horizon between the two snapshots depicting the built-up area in the The Hague region for 1970 and 2017 as shown in Figure 1 (Rijksoverheid, 2020). As the time between these two snapshots is approximately 50 years and depicts both urban sprawl and the expansion of the road network [if one looks closely at the two snapshots], a time horizon of approximately 50 years seemed appropriate. By this time horizon both historic and future behavior can be simulated. As the time settings are in years, and the time horizon spans approximately 50 years, the model runs in the time units years. Other model settings can be found at the end of Appendix II.

2.4 Chapter conclusion

This chapter addresses the first research question "which mechanisms offer a causal explanation for urban sprawl and congestion in the The Hague region?". The research question has been addressed following the method System Dynamics simulation modeling. The box below provides a concise summary in answer to the research question.

Which mechanisms offer a causal explanation for urban sprawl and congestion in the The Hague region?

People locate themselves in places that are attractive, where housing is available [and thus more affordable] and that facilitate access to places of interest, such as their workplace. Housing is usually more available in more distant areas. However, in more distant areas people often opt to commute by private vehicle as they live further away from places of interest. Consequently, the traffic volume and vehicle density on the road network increases leading to congestion. The road network is then expanded to 'solve' this congestion. However, by doing so the increased road network facilitates more home construction in peripheral areas, which is predominantly low density development, and allows people to live further away from places of interest as the road network facilitates access. As active modes of transport and public transport are less convenient, efficient and/or accessible, car-dependency is enhanced. As such, the urban area sprawls and the road network becomes congested.

Chapter 3. Model validation and analysis

Model validation is essential to inspire confidence in the constructed simulation model and, in extent, the simulation results it produces (Forrester & Senge, 1980; Sterman, 2000). This chapter addresses model validation and provides an analysis of the baseline model simulation results in a business as usual situation. The baseline simulation results are compared to the reference modes of behavior. Validation guidelines set out by Barlas (1996), Forrester and Senge (1980) and Sterman (2000), and preferred model reporting requirements as set by Rahmandad and Sterman (2012) were followed. Further information regarding model documentation and validation can be found in Appendices II and III. This chapter addresses the second research question "how do the mechanisms that offer a causal explanation for urban sprawl and congestion in the The Hague region contribute to the behavior of the system?".

3.1 Model validation

3.1.1 Direct structure tests

The structural validity of a simulation model is of primary concern in the validation process as without a robust structure, the behavior a simulation model produces will not be as meaningful. To inspire confidence in the model structure – at this stage without taking its simulation results into account – direct structure tests assess its validity by comparing the model structure to knowledge about the real-world counterparts of [parts of] the system from literature and other available sources. The direct structure tests conducted for this work include the structure-confirmation test, parameter-confirmation test, dimensional consistency test and direct extreme-conditions test.

Structure-confirmation test

The structure-confirmation test is carried out by comparing the model structure to the real-world counterparts of [parts of] the system as portrayed in the literature to ensure that the model structure is consistent with existing knowledge about the real-world system and does not contradict the existing knowledge (Barlas, 1996; Forrester & Senge, 1980). The structure-confirmation test is carried out throughout the iterative modeling process. The final simulation model is grounded in existing literature and data, and has been subject to review by experts with experience from the real-world system (Eskinasi, 2023; Mirabile, 2023). Wherever assumptions had to be made, this is stated in the model documentation which can be found in Appendix II and taken into consideration during sensitivity analysis [see Appendix III].

Parameter-confirmation test

The parameter-confirmation test is carried out by comparing the auxiliary parameters to knowledge about their real-world counterparts to ensure that the parameters are consistent with existing knowledge and correspond both conceptually and numerically to the real-world. Conceptual correspondence concerns whether parameters match elements of the real-world system structure, whereas numerical correspondence concerns whether parameter values fall within a plausible range of values for that parameter (Forrester & Senge, 1980). The final simulation model, including its auxiliary parameters, is grounded in existing literature and data, and has been subject to review by experts with experience from the real-world system (Eskinasi, 2023; Mirabile, 2023). Wherever assumptions had to be made, this is stated in the model documentation which can be found in Appendix II and taken into consideration during sensitivity analysis [see Appendix III].

Dimensional consistency test

The dimensional consistency test is carried out by a dimensional analysis of the equations in the simulation model. The variables included in the simulation model all have a relevant real-world counterpart and no dummy variables have been used to force dimensional consistency.

Direct extreme-conditions test

The direct extreme-conditions test is carried out by examining the equations in the model and tracing them back to auxiliary parameters on which they depend. Implications of imaginary, yet meaningful, minimum and maximum values for auxiliary parameters are then considered (Forrester & Senge, 1980). This test is carried out to ensure that the simulation model is robust under extreme conditions. Based on the direct extreme-conditions test equations had to be adjusted in two sectors being the attractiveness areas sector and the congestion sector. For the attractiveness areas sector the equation for indicated relative attractiveness area had to be adjusted where a MIN-MAX function had to be deleted from the equation to ensure that the total relative attractiveness of the region would always be equal to one, even in extreme conditions. For the congestion sector the graphical function effect of pressure to expand roads on road construction had to be adjusted to limit road construction when the pressure to expand the road network decreases below one. Initially the effect function held an increasing decreasingly shape for pressure varying from one to two, now this graphical function holds an s-shape for pressure varying from zero to two. Finally, an IF, THEN, ELSE function had to be introduced in the relative congestion variable. It is not preferable to integrate this discontinuous element into the model structure, however this was deemed necessary due to the variable being made relative to the year 2001. If for example the initial actual vehicle density on the road network is much lower than the maximum acceptable vehicle density on the road network [for example due to almost nobody opting for the car as a transport mode, or a lot of commuters commuting together in the same car], then such a situation would not be classified as congestion. Due to the congestion deflator the relative congestion at the start of the simulation would return a value of one. Without the IF, THEN, ELSE statement in the equation however, the next time round when the actual vehicle density on the road network increases, but is still lower than the maximum acceptable vehicle density on the road network, the variable actual vehicle density relative to maximum acceptable would not indicate congestion and have a value lower than one, but the relative congestion variable would return a value higher than one as the relative vehicle density is higher compared to the relative vehicle density on the road network in the year 2001, and thereby it would indicate congestion. As a result travel time increases, which would not be the case in reality. The IF, THEN, ELSE equation in the variable relative congestion solves this initialization issue in the extreme condition of very low actual vehicle density on the road network as relative congestion will not return a value higher than one if the actual vehicle density on the road network is lower than maximum acceptable [IF actual_vehicle_density_relative_to_maximum_acceptable > 1 THEN actual_vehicle_density_ relative_to_maximum_acceptable/congestion_deflator_to_2001_level ELSE 1].

3.1.2 Structure-oriented behavior tests

To further inspire confidence in the model structure – at this stage with taking its simulation results into account – structure-oriented behavior tests assess its validity by observing the behavior the simulation model generates. The structure-oriented behavior tests conducted for this work include the integration error test, boundary-adequacy test, partial model test, indirect extreme-conditions test and behavior-sensitivity test.

Integration error test

The integration error test is carried out by simulating the model using the various integration methods provided by Stella Architect software and determines whether the simulation model is sensitive to the integration method used. The test is carried out for the integration methods Euler, second-order Runge-Kutta and fourth-order Runge-Kutta. As the behavior of the system does not change when changing integration method, the simulation model is not sensitive to the integration method used. As such, Euler is selected as integration method.

Boundary-adequacy test

The boundary-adequacy test is carried out to ensure that the model aggregation is appropriate and includes the structural relationships necessary and relevant to satisfy the purpose and objective of the simulation model and to address the problem for which the simulation model is created (Forrester & Senge, 1980). The objective of this work on urban sprawl and congestion is to provide understanding of the processes involved as drivers of urban sprawl and congestion in the The Hague region and further aims to move beyond understanding the processes involved towards understanding as a basis for policy analysis as described in section 1.3.1 of this report. The model structure is addressed in the prior chapter in which feedback relations are identified that offer a causal explanation for urban sprawl and congestion in the The Hague region. Additionally, the model structure provides various options for policy explorations. As such, the structure is deemed sufficient for understanding as a basis for policy analysis.

Partial model test

The partial model test is carried out by simulating the behavior of functional components of the simulation model, rather than the behavior of the whole model. As the size of the model structure and its uncertain parameters increases, the potential for misperception of behavior due to particular parameters also increases (Homer, 2012). The partial model test is carried out for the various sectors in the simulation model. With constant inputs from other sectors, no model inadequacies became apparent.

Indirect extreme-conditions test

The indirect extreme-conditions test is carried out by setting auxiliary parameters to meaningful minimum and maximum values and simulating the behavior of the whole model. This test is carried out to ensure that the simulation model is robust under extreme conditions. For example, if there are almost no homes in an area, migration to that area will be strongly discouraged (Forrester & Senge, 1980). By simulating the behavior in such a condition, net migration in the current simulation model will represent an outflow rather than an inflow as was anticipated.

Behavior-sensitivity test

The behavior sensitivity test is carried out by changing the auxiliary parameters in the model structure to values between minus-twenty percent and plus-twenty percent of the model value. Each auxiliary parameter is tested separately using Latin Hypercube sampling. Furthermore, the behavior sensitivity test is carried out by distorting the graphical functions in the model structure manually. Again, each graphical function is tested separately. The effect of changes in the auxiliary parameters and graphical functions on behavior of the key variables homes for each area [central, ring, outer] and the relative congested travel time are determined. The behavior sensitivity test determines whether possible changes in auxiliary parameters or graphical functions can cause the model to fail other behavior tests [such as the behavior-reproduction test] which were passed prior to the changes (Forrester & Senge, 1980). However, when a simulation model is found to be sensitive to changes in auxiliary parameters or graphical functions, this does not necessarily invalidate the model. Some sensitive variables can indicate a potential leverage point for policy input rather than a model limitation. The current simulation model proved to be numerically sensitive to various auxiliary parameters and graphical functions. This sensitivity was expected. The simulation model proved not to be really sensitive in terms of behavior mode to changes in auxiliary parameters and graphical functions. Further details regarding the behavior sensitivity test and its results can be found in Appendix III.

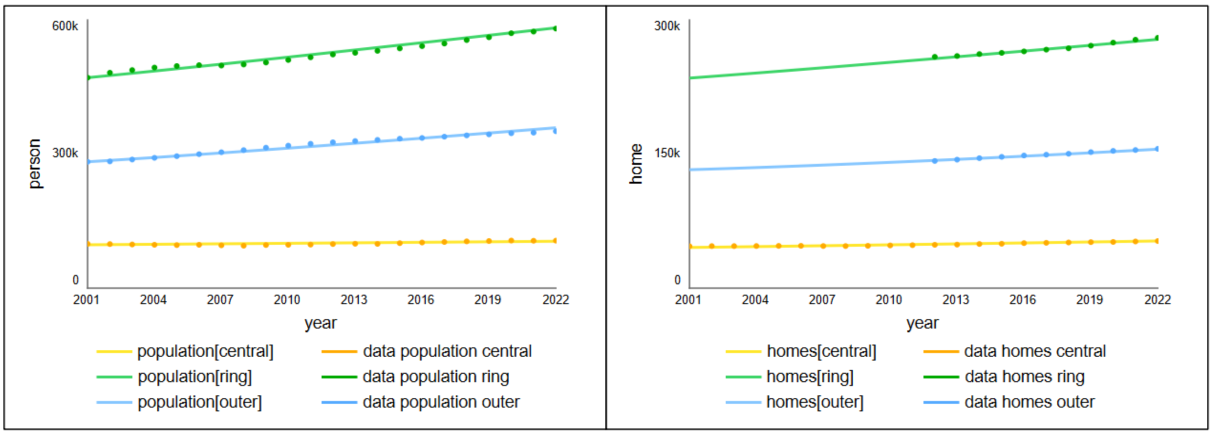
3.1.3 Behavior pattern tests

When the model structure inspires confidence after direct structure tests and structure-oriented behavior tests have been carried out, the behavior the simulation model produces is observed specifically to assess whether the simulation model produces the right behavior for the right reasons [wrong behavior at this point would indicate missing structure]. Behavior pattern tests do not aim to point-by-point match historic behaviors, instead their focus lays on the behavior pattern (Barlas, 1996; Sterman, 2000). Behavior pattern tests are limited by available data of historic behavior. Yet, where data of historic behavior is available, the reproduction of the historic behavior pattern gives an indication of the reliability of the model output. The behavior pattern tests conducted for this work include the behavior reproduction test.

Behavior reproduction test

The behavior reproduction test is carried out by simulating the behavior of the whole model and by assessing whether the behavior generated by the model matches observed historic behavior of the real system (Forrester & Senge, 1980). As discussed in section 1.2.2 of this report the reference modes of behavior concern the population and homes per area [central, ring, outer] as included in this work, the jobs in the The Hague region, the road network in the The Hague region and the relative travel time in the The Hague region. The results of the behavior reproduction tests for the reference modes of behavior for population and homes per area can be found in Figure 19.

Figure 19 – Results behavior reproduction test for the reference modes of behavior for population [left] and homes [right] in the central [yellow], ring [green] and outer [blue] The Hague areas during the years 2001 and 2022.*



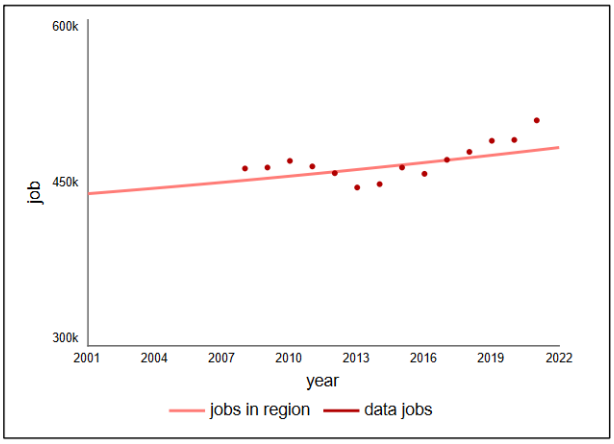
Population data (AlleCijfers, 2023; CBS, 2023a; DHIC, 2023; EersteKamer, 2022).

Homes data (CBS, 2023b; DHIC, 2023; DIC, 2023; LVIC, 2023; PNIC, 2023; RIC, 2023; ZIC, 2023).

*Note that data could not be found before the year 2012 for homes in the The Hague ring and outer areas.

Figure 19 shows a good fit between the behavior generated by the model, represented by the solid lines, and the observed historic behavior of the real system, represented by the dotted lines for both the population and homes per area. The result of the behavior reproduction test for the reference mode of behavior for jobs in the The Hague region can be found in Figure 20.

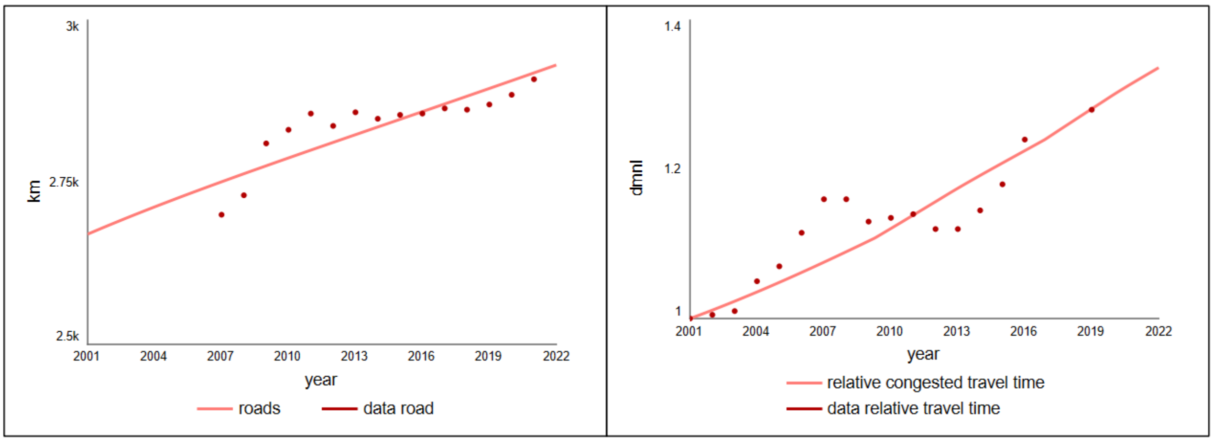
Figure 20 – Result behavior reproduction test for the reference mode of behavior for jobs in the The Hague region during the years 2001 and 2022.*



*Jobs data (CBS, 2022c) is available for the years 2008 to 2021.

Figure 20 shows a good enough fit between the behavior generated by the model, represented by the solid line, and the observed historic behavior of the real system, represented by the dotted line for jobs in the The Hague region. The results of the behavior reproduction tests for the reference modes of behavior for the road network and the relative travel time in the The Hague region and the can be found in Figure 21.

Figure 21 – Results behavior reproduction test for the reference modes of behavior for roads [left] and relative travel time** [right] in the The Hague region during the years 2001 and 2022.*



*Roads data (CBS, 2022e) is available for the years 2007 to 2021.
**Relative travel time data (Loop & Hamersma, 2018; Tomtom, 2023) is available for the years 2001 to 2019. Note that data could not be found for the years 2017 and 2018 for relative travel time in the The Hague region.

Figure 21 shows a good enough fit between the behavior generated by the model, represented by the solid lines, and the observed historic behavior of the real system, represented by the dotted lines for the road network and relative travel time in the The Hague region.

Model validation is essential to inspire confidence in the constructed simulation model and, in extent, the simulation results it produces (Forrester & Senge, 1980; Sterman, 2000). Based on the various validation tests performed the model can be deemed significantly robust and the behavior it generates can be deemed logical, as such the simulation model inspires enough confidence to address the problem of urban sprawl and congestion in the The Hague region and can be deemed appropriate as a basis for policy testing. Nevertheless, the model does contain some uncertainties where assumptions had to be made and some limitations which will be further discussed in the final chapter of this report. The modeling and validation processes [including model documentation] are crucial in forming an understanding of the model structure and its behavior and gives valuable insights into improvements for future iterations of the model structure addressing the problem of urban sprawl and congestion.

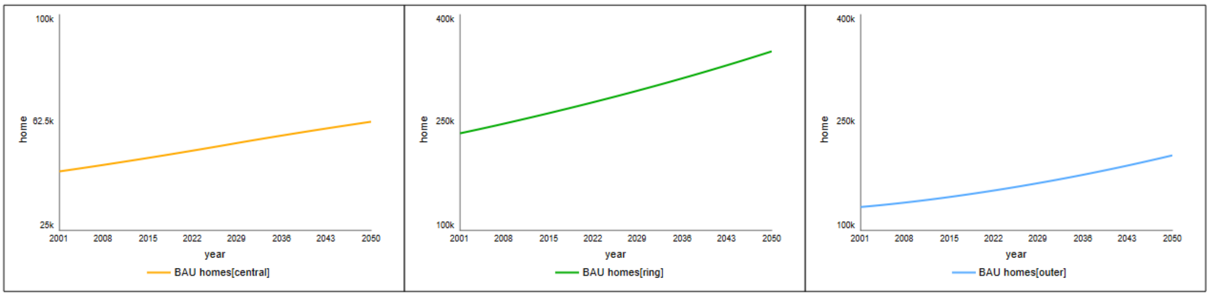
3.2 Model analysis

The simulation model as developed for the current work approximates the real-world system that causes urban sprawl and congestion in the The Hague region. This section addresses the behavior generated by the simulation model in a business as usual [BAU] situation and discusses the mechanisms and feedbacks that drive the generated behavior. In the BAU situation the generated behavior is based on the default values and conditions of the system, and depicts what is possible and expected to happen when policies are not adjusted.

3.2.1 Business as usual simulation results

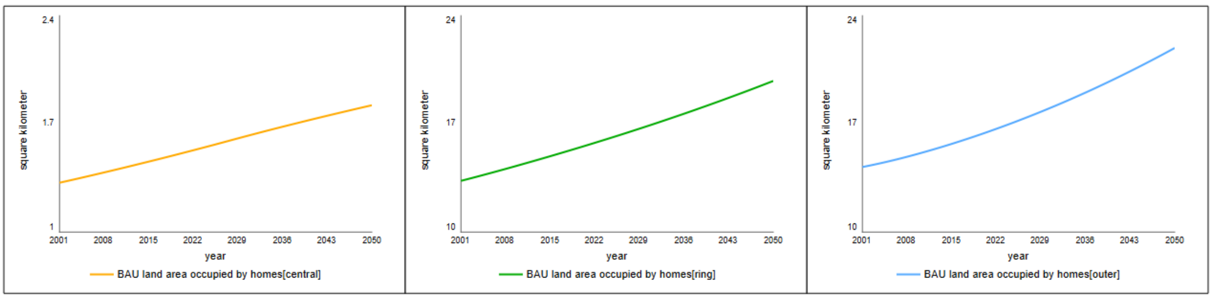
The behavior of two mechanisms and related constructs are of particular interest concerning urban sprawl and congestion, being housing in an area [central, ring, outer] and the relative congested travel time in the The Hague region. For urban sprawl Figures 22 and 23 show the behavior over time for homes and the amount of land that is occupied by them per area.

*Figure 22 – BAU simulation behavior over time for homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



* Note that the upper and lower bound on the y-axis for the graph representing the central area is four times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

*Figure 23 – BAU simulation behavior over time for the land occupied by homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**

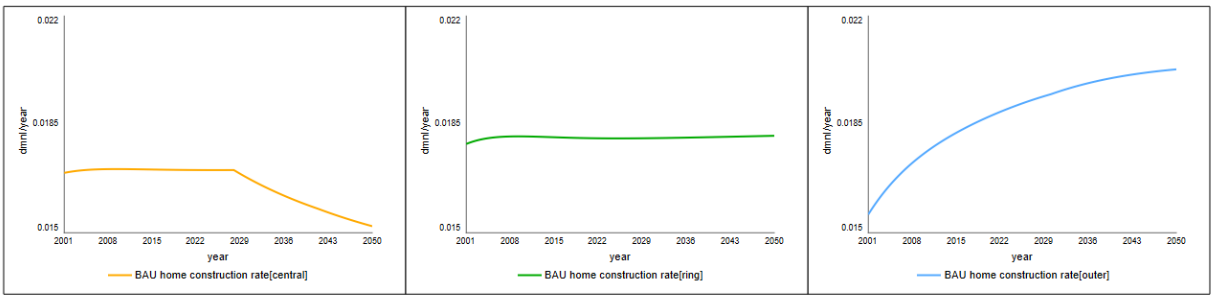


*Note that the upper and lower bound on the y-axis for the graph representing the central area is ten times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

As can be seen in Figure 22 above the amount of homes in the central area grows fairly linear over time with a very slight inclination towards goal seeking behavior at the end of the simulation. For the ring area, the amount of homes also grows fairly linear over time. For the outer area, the amount of homes grows exponentially over time. The latter might be a little difficult to see due to the selected y-axis. However, this y-axis is selected with a purpose. The y-axis for the graphs representing the ring and outer The Hague areas are equal in both Figure 22 and 23 to make an important comparison intertwined with urban sprawl. When comparing the graphs of Figures 22 and 23 for the ring and outer areas one notices that even though the amount of homes in the outer area is lower compared to the amount of homes in the ring area over time [Figure 22], the amount of land that is occupied by them is higher for the outer area compared to the ring area over time [Figure 23] which is due to the density of the home development. The further out homes are constructed from central areas, the lower the density of development becomes. By low density construction in more distant areas, the urban form expands and sprawls more so than it would by higher density construction in less distant areas. As such, the exponential growth behavior for homes in the outer area is especially worrisome.

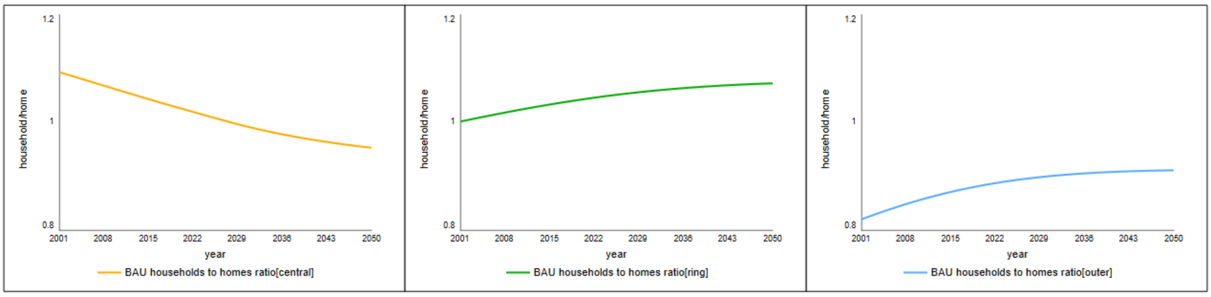
The question remains what causes the homes in the central area to show linear growth with a tendency towards goal seeking behavior at the end of the simulation, the homes in the ring area to show linear growth, and the homes in the outer area to show exponential growth over time. Figure 24 shows the home construction rate for each area. The home construction rate is higher than the home demolition rate [which equals one percent per year], which causes the stock homes to increase. As can be seen, for the central area the home construction rate is rather constant between the years 2001 and 2028, after which the home construction rate decreases. For the ring area the home construction rate is rather constant throughout the entire simulation. For the outer area the home construction rate increases decreasingly between the years 2001 and 2050. These variations in home construction rate drive the behavior shown by

Figure 24 – BAU simulation behavior over time for the home construction rate in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



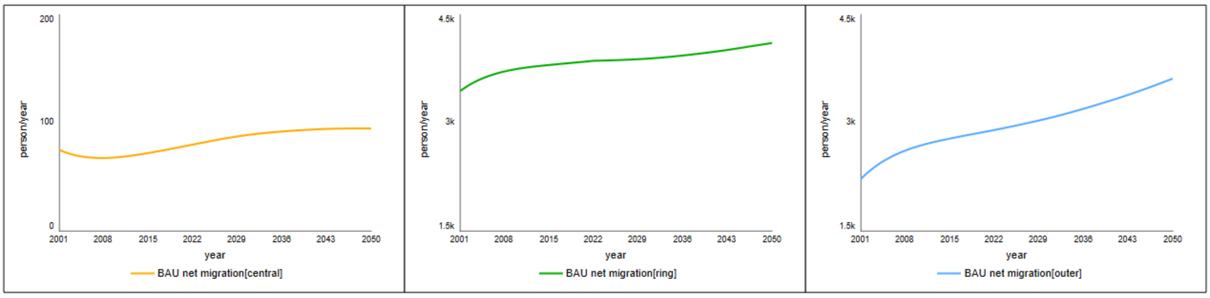
homes for each area. The available land occupied plays only a marginal role in decreasing the home construction rate for the central The Hague area. What predominantly determines the home construction rate is the housing availability in the area. Figure 25 below shows the households to homes ratio per area. For the central The Hague area the households to homes ratio initially is higher than one. This indicates a low housing availability. That being the case, the home construction rate will match the maximum home construction rate for the area. However, the households to homes ratio decreases over time and from the year 2028 onwards the households to homes ratio holds a value lower than one. With sufficient housing availability the home construction rate decreases. For the ring The Hague area the households to homes ratio initially equals approximately one. Over time the households to homes ratio increases decreasingly. This indicates a low housing availability in the ring The Hague area throughout the duration of the simulation. Consequently, the home construction rate will match the maximum home construction rate for the area, and thus remains fairly constant. For the outer The Hague area the households to homes ratio is initially lower than one. Over time the households to homes ratio increases decreasingly, yet it remains lower than one throughout the duration of the simulation which indicates sufficient housing availability. As such, the home construction rate will not yet match the maximum home construction rate for the area [it holds a value below the maximum value] and can be increased decreasingly throughout the duration of the simulation. This process is captured by feedback loop **B5** as discussed in section 2.2.1.

Figure 25 – BAU simulation behavior over time for the households to homes ratio in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



The households to homes ratio, representing housing availability, is an important mechanism in the simulation model. When housing availability decreases, the population grows at a faster pace than the homes in the area do, and when it increases the population grows at a slower pace than the homes in the area do. Besides home construction, housing availability influences net migration and the relative attractiveness of more distant areas, the latter in turn also influencing net migration. Net migration is especially influential for population growth in the ring and outer The Hague areas and much less so for the central The Hague area where crowding further limits migration in to the area [loop **B1**]. Figure 26 represents the net migration per area [central, ring, outer]. For all areas, net migration has a positive value meaning there is more in-migration than out-migration in each area. As such, net migration works together with net births to increase the population of each area throughout the duration of the simulation [loops **R1** and **R2**].

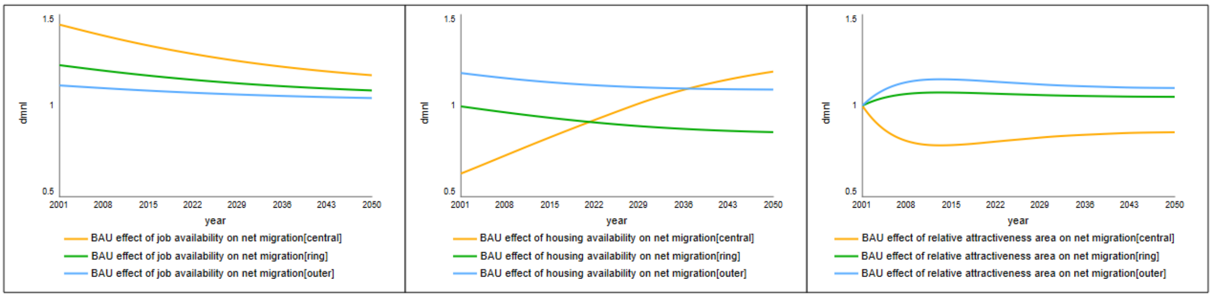
*Figure 26 – BAU simulation behavior over time for the net migration in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

Net migration increases over time for all areas, its increase is most predominant in the outer The Hague area. The increases in net migration are mostly due to increases in the population, yet certain effects play a part in influencing net migration. Figure 27 shows the effects of job availability, housing availability and relative attractiveness areas on net migration for each area. The behavior of these effects will not be discussed in depth. In short however, an effect will stimulate migration in to an area if its value is higher than one, and it will limit migration in to an area if its value is lower than one. For the outer area all effects work to stimulate migration

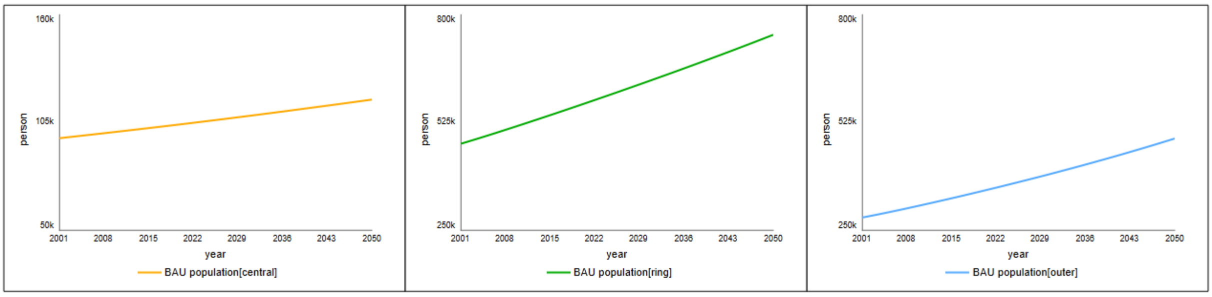
Figure 27 – BAU simulation behavior over time for the effects of job availability [left], housing availability [middle] and relative attractiveness areas [right] on net migration for the central [yellow], ring [green], and outer [blue] The Hague areas during the years 2001 and 2050.



in to the area over time. For the ring area the effects of job availability and relative attractiveness of the area work to stimulate migration in to the area and the effect of housing availability limits it. Together initially these effects work to stimulate migration in to the ring area, yet towards the end of the simulation [2040 onwards] the effects of job and housing availability have decreased considerably enough to overall work to limit migration in to the ring area. For the central area the effect of job availability stimulates migration in to the area, the effect of relative attractiveness of the area limits migration in to the area, and the effect of housing availability initially limits migration in to the area but over time works to stimulate migration in to the area. Multiple loops are responsible for changes in these effects, such as loops **B2**, **B4**, **B6**, **B10** and **R4**.

Figure 28 shows the population for each area. As net migration works together with net births to increase the population of each area throughout the duration of the simulation, and the populations of the ring and outer areas increase more so than the population of the central area [comparing the population at the start and end of the simulation, the population for the central area has increased by approximately twenty percent, the population for the ring area has increased by approximately sixty percent, and the population for the outer area has increased by approximately seventy percent], this has important implications for congestion.

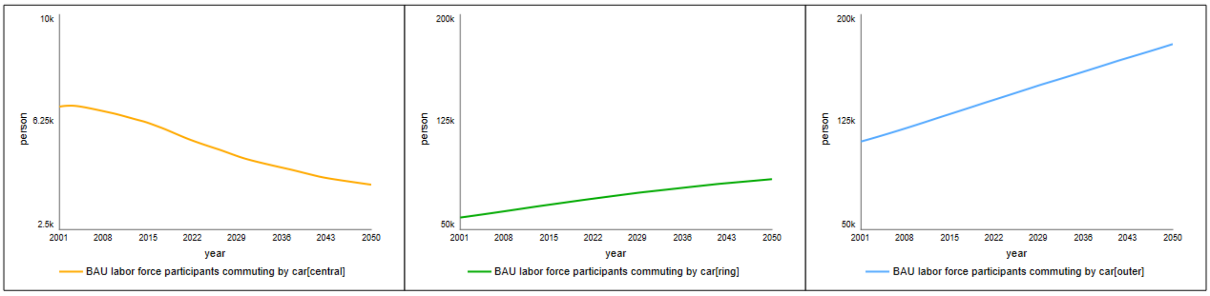
*Figure 28 – BAU simulation behavior over time for the population in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is five times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

When the population of an area increases, the labor force of that area also increases. As active modes of transport [such as cycling and walking] and shared modes of transport [such as public transport] are less convenient, efficient and/or accessible in more distant areas, people often opt to commute by private vehicle the further away they live from places of interest. Population growth in the ring and outer areas thereby contribute more to the problem of congestion than population growth in the central area. Figure 29 shows the labor force participants commuting by car for each area. Two things in particular are of note, firstly that it is predominantly the labor force in the outer The Hague area which adds to the traffic volume in the region, and secondly that the labor force commuting by car increases throughout the duration of the simulation for the ring and outer The Hague areas, but decreases for the central The Hague area. This highlights both the relation between urban sprawl and congestion [by the first point of note], and the relation between urban sprawl and car-dependency fostered by policies focused on mobility rather than accessibility [by the second point of note] (OECD, 2021). Figures 30, 31 and 32, showing the car attractiveness for each area, the roads and relative congested travel time in the The Hague region, and the fraction of the labor force participants that commute by private vehicle per area, and loops **B7** and **B9** give further insight into the latter relation.

*Figure 29 – BAU simulation behavior over time for the labor force participants commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is twenty times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

As shown in Figure 30 below the car attractiveness decreases decreasingly over time for all areas. Car attractiveness decreases as the travel time by car between places of interest increases. The right graph of Figure 31 below shows that the relative congested travel time by car increases over time in an s-shape [with very low curvature]. Even though the relative congested travel

Figure 30 – BAU simulation behavior over time for the car attractiveness in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.

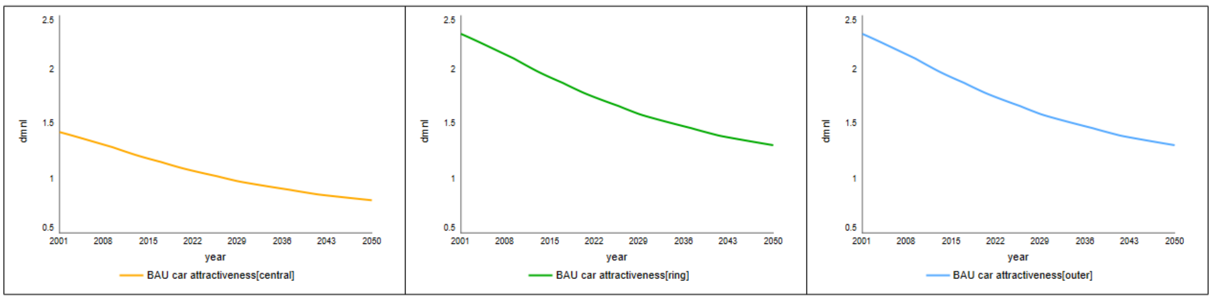


Figure 31 – BAU simulation behavior over time for the roads [left] and relative congested travel time [right] in the The Hague region during the years 2001 and 2050.

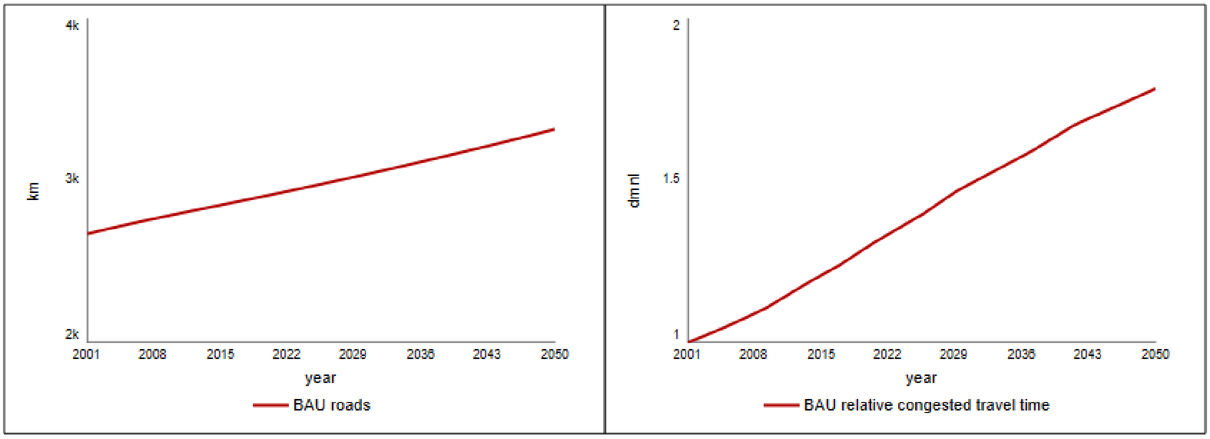
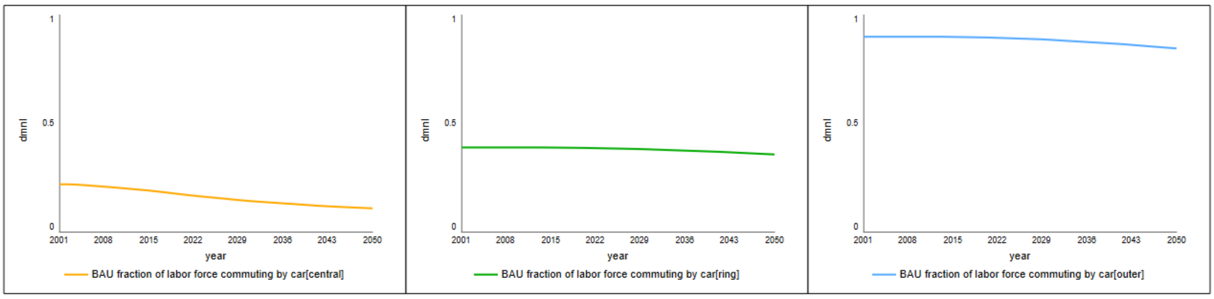


Figure 32 – BAU simulation behavior over time for the fraction of labor force commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



time by car increases, car attractiveness for both the ring and outer The Hague areas does not decrease enough [Figure 30] to significantly limit the fraction of commuters that opt for the car as a transport mode over public transport [Figure 32]. Regardless of the increasing congestion, the travel time by public transport is still much higher than the travel time by car. Thus, for the ring and outer The Hague areas loop **B7** does not have enough power to combat the increasing labor force and, that being the case, for both the ring and outer areas the labor force participants commuting by car increases [Figure 29]. This process is aided by loop **B9** as road construction is increased due to pressure to expand the road network which builds as congestion increases, representing a mobility-oriented policy. By road construction the road network increases [left graph of Figure 31] which works to limit the growing congestion. Thus congestion increases less so than it otherwise would have. As congestion increases less so than it otherwise would have, the car attractiveness decreases less so than it otherwise would have, thereby inhibiting loop **B7** which works to decrease the fraction of the labor force participants opting for the car when commuting. As such, loops **B7** and **B9** work against each other.

For the central The Hague area, where public transport is more convenient, efficient and accessible compared to more distant areas, the increase in relative congested travel time [right graph of Figure 31] is enough to significantly limit the fraction of commuters that opt for the car as a transport mode over public transport [Figure 32]. The travel time by public transport is competitive with, or even more attractive than, the travel time by car. Thus, for the central The Hague area loop **B7** does have enough power to combat the increasing labor force and the labor force participants commuting by car decreases [Figure 29]. However, as the labor force participants commuting by car in the central The Hague area only has a small influence on congestion [since the amount of commuters is much smaller compared to the ring and outer areas and thus adds much less to the traffic volume] this does not significantly change the behavior of the relative congested travel time [right graph of Figure 31].

Furthermore, as the average car attractiveness in the The Hague region does not decrease significantly enough in the BAU situation to favor public transport over car transport, loop **B8** does not contribute in decreasing the relative attractiveness of more distant areas. For the relative congested travel time loop **B10**, while contributing in decreasing the attractiveness of more distant areas, does not influence changes in the attractiveness of more distant areas much as shown in the left graph of Figure 33 below. As mentioned prior in this report habituation often occurs and the commuter simply 'deals with congestion' by waiting it out (JA, 2021). Even though congestion is a big inconvenience for the Dutch commuter, a little more congestion than already expected [and maybe even accepted] thus does not sway people away from locating in more distant areas. At the same time, while loops **B8** and **B10** aim to decrease the relative attractiveness of more distant areas but are only slightly effective in doing so, loops **R4** and **B6** work to increase the relative attractiveness of more distant areas and are fairly effective in doing so. While loop **B6** becomes less effective in increasing the attractiveness of more distant areas over time as housing availability of more distant areas decreases comparing to the housing availability of the central area [and even works to slightly decrease the attractiveness of more distant areas from the year 2029 onwards as the effect decreases below a value of one], loop **R4** remains consistent and effective [right graph in Figure 33 below] in increasing the attractiveness of more distant areas as the road network keeps expanding over time [left graph of Figure 31 above] allowing people to locate themselves further away from places of interest (OECD, 2021). Overall, more distant areas will consequently be relatively more attractive than they initially were while the central area will be relatively less attractive.

Figure 33 – BAU simulation behavior over time for the effects of car attractiveness and relative congested travel time on the attractiveness of more distant areas [left] and the effects of housing availability and the road network on the attractiveness of more distant areas [right] in the The Hague region during the years 2001 and 2050.

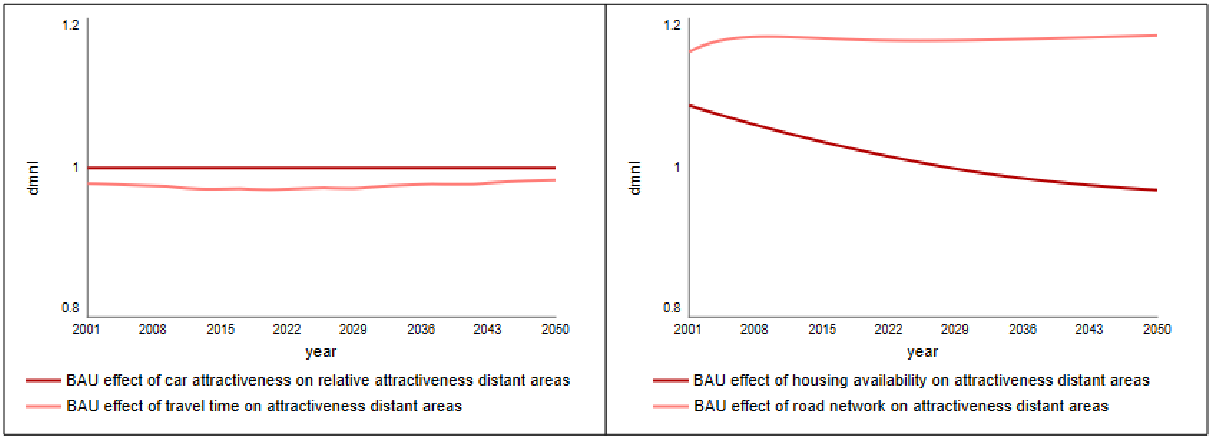
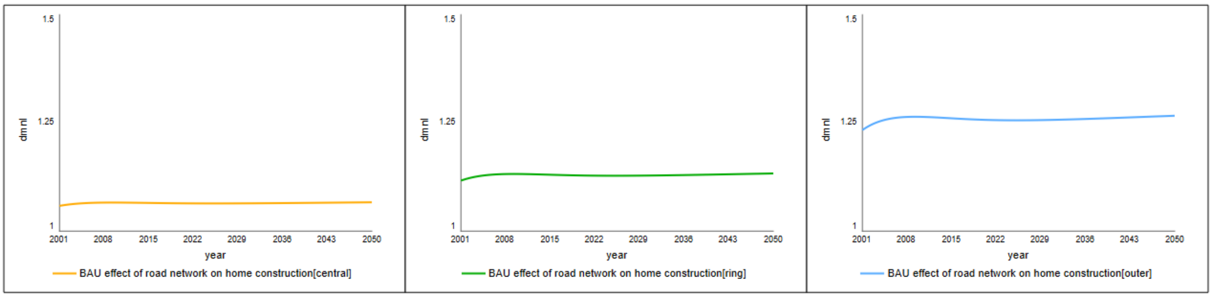


Figure 34 – BAU simulation behavior over time for the effect of the road network on home construction in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



Furthermore, as the road network keeps expanding over time [left graph of Figure 31 above], creating opportunities for homes to be constructed more easily in places that were less accessible before, loop **R5** also remains consistent and effective in increasing the maximum home construction. The effect of the road network on home construction is shown in Figure 34 above and remains constant over time at values higher than one for all areas. The more distant the area, the more effective the effect is in increasing the maximum home construction as central areas are usually more accessible already when compared to ring areas and in turn outer areas (Grimeland, 2022), thus changes in the road network are especially influential on home construction in more distant areas. With more low density home construction in peripheral areas, the urban form expands and sprawls.

3.3 Chapter conclusion

This chapter addresses the second research question "how do the mechanisms that offer a causal explanation for urban sprawl and congestion in the The Hague region contribute to the behavior of the system?". The box below provides a concise summary in answer to the research question.

How do the mechanisms that offer a causal explanation for urban sprawl and congestion in the The Hague region contribute to the behavior of the system?

The current simulation model and the behavior it generates is not dominated by a single powerful loop or a few loops between which dominance shifts. Rather, the various loops existing in the system all contribute somewhat to the behavior of the system, and some of those loops oppose each other. Nevertheless a few mechanisms can be identified that especially contribute to the behavior of the system being the housing availability, the road network [and road construction], the traffic volume [and car attractiveness], the relative attractiveness of more distant areas and net migration. Furthermore, mobility holds a key function. By the expanding road network both the relative attractiveness of peripheral areas and home construction in peripheral areas can be increased and maintained. People are stimulated to migrate in to these attractive more distant areas where, while decreasing, housing is relatively available for most of the duration of the simulation. As especially the populations of the ring and outer The Hague areas grow, the traffic volume increases as commuters from these areas more often opt for the car as transport mode. As such, congestion and travel time by car increases. Where this leads to increasing pressure to expand the road network, and in turn more road construction [with its consequences for congestion, home construction and area attractiveness], it does not sufficiently lead to a decreasing fraction of the labor force from the ring and outer areas opting for the car when commuting as the car is still considered to be a far more attractive mode of transport compared to public transport based on travel time. This is aided by the increasing road network. With habituation regarding travel time and a sufficiently high car attractiveness, the attractiveness of peripheral areas does not decrease enough to dissuade people to migrate in to more distant areas. The above summary is in line with the real-world system and literature as discussed in Chapter 1.

Chapter 4. Policy design and analysis

This chapter addresses the part of the research objective that aims to move towards understanding as a basis for policy analysis. This does not mean that this work provides extensive policy recommendations, rather it aims to explore some basic policy options that might alleviate the problem of urban sprawl and congestion in the The Hague region. Implementation obstacles are not taken into regard in the policy model structure, yet policy resistance is briefly discussed. This chapter addresses the third research question "what policy options can be identified to reduce urban sprawl and congestion in the The Hague region?".

4.1 Policy design

Prior chapters in this work have highlighted the importance of mobility and its relation to urban sprawl and congestion. Due to its importance the policies tested in this work will focus on influencing mobility aspects in the simulation model. Though the policy design is predominantly concerned with mobility, this does not imply that policies with a focus outside of mobility are not capable of reducing urban sprawl and congestion, but merely that these policies are not explored in the current work. The four policy options included concern the road network [either by keeping the road network constant, or by decreasing it], car attractiveness [by decreasing the travel time by public transport thus reducing the attractiveness of private vehicles relative to public transport based on travel time], and the traffic volume [by carpooling, thus increasing the people per car when commuting, thereby reducing the traffic volume]. Thereby, these policies attempt to directly influence the feedback from loops **R4**, **R5**, **B7**, **B8**, **B9** and **B10** and through these loops indirectly influence the feedback from other loops. The policy options are tested singularly and in combination.

4.2 Policy analysis

4.2.1 Singular policy tests

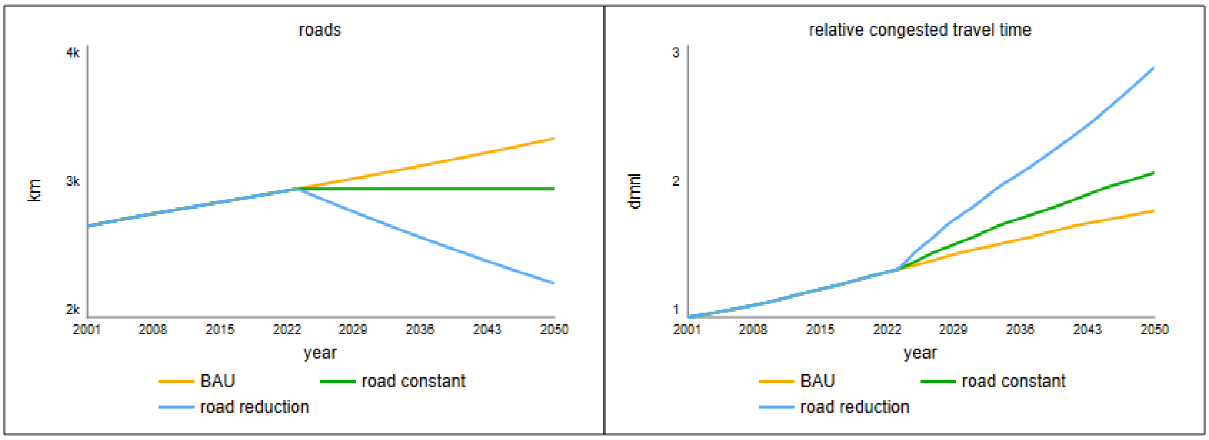
This section addresses the behavior generated by the simulation model when one of the policy options [keeping the road network constant, decreasing the road network, decreasing the travel time per trip by public transport, or carpooling] is implemented.

Road network policies

As a long standing momentum policy, congestion has traditionally been 'solved' by road construction (OECD, 2021; Sterman, 2000). As discussed prior in this report the expanding road network, besides influencing vehicle density on the road network, also influences home construction [especially in more distant areas] and the relative attractiveness of more distant areas. As such, it is interesting to explore what behavior the simulation model generates should the road network no longer be expanded, thus no new roads are constructed or existing roads widened. In the constant road network policy scenario, the road network that already exists up until the policy start time [the year 2023] will thereafter be maintained and all roads that degrade each year will be repaired, thereby keeping the existing road network constant for the remainder of the simulation. In the road network reduction policy scenario, the road network that already exists up until the policy start time [the year 2023] will thereafter mostly be maintained, yet not all roads that degrade each year will be repaired and a small fraction of the road network will become unavailable for private commuting each year. In the latter scenario, the road network will decrease by one percent per year. Either road network policy option can be implemented immediately after the policy start time.

Again, the behavior of two mechanisms and related constructs are of particular interest concerning urban sprawl and congestion, being housing in an area [central, ring, outer] and the relative congested travel time in the The Hague region. Figure 35 shows the generated model behavior for roads and relative congested travel time for both road network policy options, and Figure 38 shows the generated model behavior for homes per area for both road network policy options. In order to compare the generated behaviors for the policy options with the BAU simulation results, the BAU simulation is also shown in each figure. As can be seen in the left graph of Figure 35 after the year 2023 the road network remains constant for the constant road network policy and decreases for the road network reduction policy, as intended.

Figure 35 – Road network policies simulation behavior over time for the roads [left] and relative congested travel time [right] in the The Hague region during the years 2001 and 2050.



The effect of either road network policy on the relative congested travel time is undesirable as the relative congested travel time increases compared to the BAU scenario, thus indicating more congestion which in turn results in higher emissions and more air pollution due to inefficient stop-and-go driving (OECD, 2021; Su, 2006). These results are not surprising however. While loop **B9** no longer works to limit the power of loop **B7**, for the constant road network policy the labor force participants commuting by car still proves to be difficult to decrease even though the fraction of labor force participants commuting by car does decrease [Figure 36] due to decreasing car attractiveness based on the travel time. However, the decrease in the fraction of labor force participants commuting by car is combatted by the increasing population and thus labor force. Consequently, for the ring and outer The Hague areas – which contribute most to congestion as discussed prior – the labor force participants commuting by car still increase, albeit decreasingly, in the constant road network policy scenario as shown in Figure 37. As the labor force participants commuting by car for the ring and outer The Hague areas increases while the road network remains constant, vehicle density on the road network will increase thus leading to more congestion and higher travel times [right graph of Figure 35]. For the road network reduction policy the decreasing fraction of labor force participants commuting by car does decrease enough [Figure 36] to combat the increasing population and thus labor force. As such, the labor force participants commuting by car do decrease in the road network reduction policy scenario for all areas [most importantly the ring and outer The Hague area] as shown in Figure 37. However, even while the labor force participants commuting by car decreases in the road network reduction policy scenario, the available road network decreases much more so [left graph of Figure 35]. For this reason, the vehicle density on the road network will increase, leading to more congestion and higher travel times [right graph of Figure 35].

Figure 36 – Road network policies simulation behavior over time for the fraction of labor force commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.

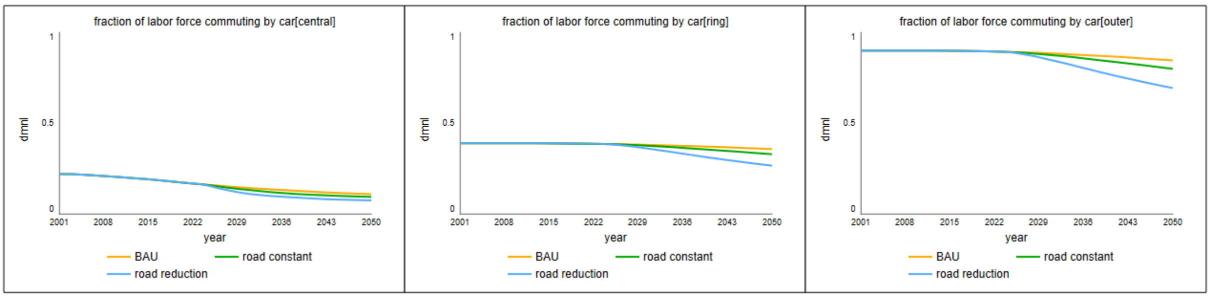
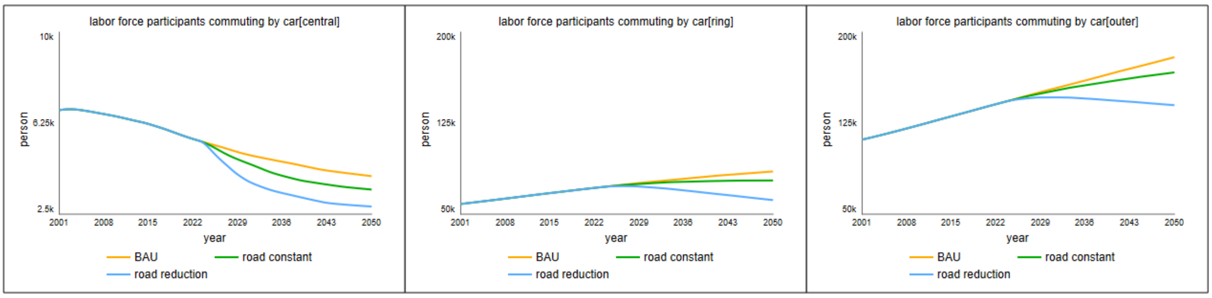


*Figure 37 – Road network policies simulation behavior over time for the labor force participants commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**

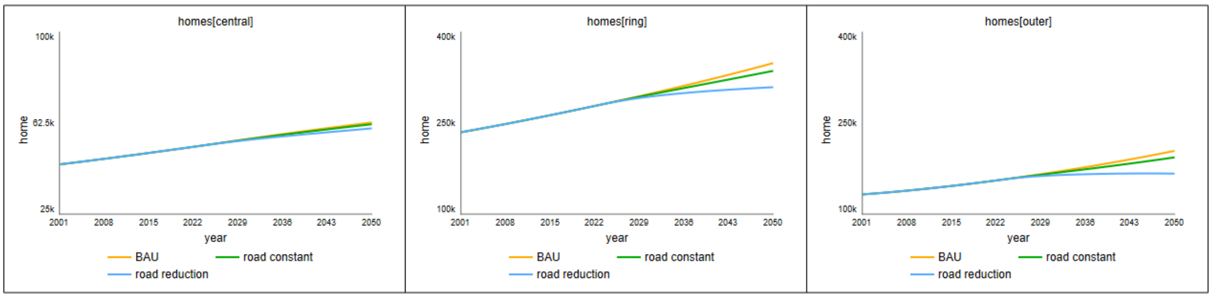


*Note that the upper and lower bound on the y-axis for the graph representing the central area is twenty times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

On the contrary, the effect of either road network policy on urban sprawl is desirable. Figures 38 and 39 show the homes and the amount of land they occupy per area. Either road network policy ceases to facilitate the maximum home construction rate to increase, thereby reducing the strength of loop **R5**. For the constant road network policy the maximum home construction rate will be decreased decreasingly towards its maximum normal value [without regard for the effect of land occupation], and for the road network reduction policy the maximum home construction rate will be decreased decreasingly to a value below its maximum normal value. For the constant road network policy the amount of homes in the ring and outer The Hague areas might not be reduced by a lot compared to the BAU scenario [Figure 38], nevertheless as the amount of homes increases less so, this results in a considerable amount of land not to be occupied. The difference in the amount of land occupied by homes between the constant road network policy scenario and the BAU scenario at the end of the simulation for the ring and outer areas combined is greater than the size of the entire central area [Figure 39].

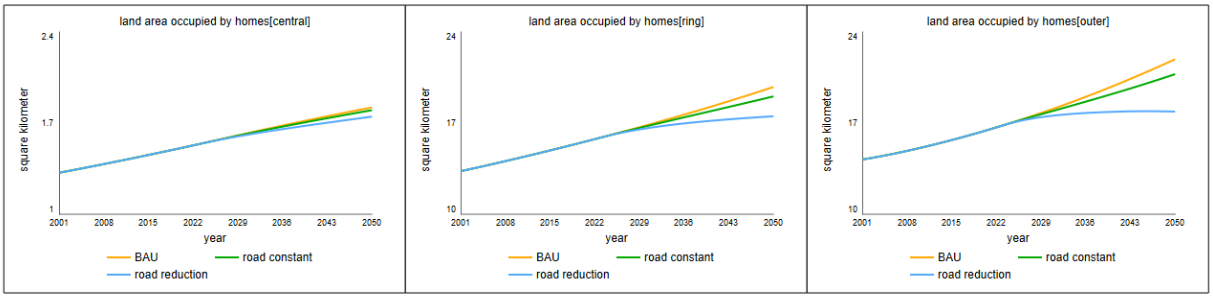
For the road network reduction policy scenario homes are reduced by a significant amount compared to the BAU scenario [Figure 38] where homes for all areas show increasing decreasingly behavior after the policy implementation start time. This effect is most pronounced in the ring and outer The Hague areas as expected. Furthermore, the amount of land that is occupied by homes is considerably less for the road network reduction policy scenario compared to the BAU scenario [Figure 39]. When less land is occupied, especially in more distant areas, the expansion of the urban form [and thereby sprawl] is less excessive. However, while both road network policies might be desirable concerning urban sprawl, the road network policies, especially the road network reduction policy, have important side effects concerning housing availability which will be discussed in the policy resistance section.

*Figure 38 – Road network policies simulation behavior over time for homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



* Note that the upper and lower bound on the y-axis for the graph representing the central area is four times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

*Figure 39 – Road network policies simulation behavior over time for the land occupied by homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is ten times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

Public transport policy

Ambitious plans exist to improve public transport in the The Hague region (Asten, 2019; Den Haag, 2022). While the current model structure is not equipped to test all aspects intertwined in these plans, the model is capable to explore what behavior the simulation model generates should the average travel time by public transport per trip decrease and match the congested travel time per trip by car [thereby influencing the car attractiveness per area as public transport becomes a more competitive alternative to transport by private vehicle]. As public transport is generally less convenient, efficient and/or accessible in more distant areas, there is more to gain in these areas by a public transport policy (OECD, 2021). As public transport cannot become significantly more efficient immediately after the policy start time, it is assumed that the implementation of this policy takes some time depending on the area [the implementation time is shorter for the central area compared to the ring area, and in turn compared to the outer area].

Figure 40 – Public transport policy simulation behavior over time for the roads [left] and relative congested travel time [right] in the The Hague region during the years 2001 and 2050.

Figure 40 shows the generated model behavior for roads and relative congested travel time for the public transport policy scenario, again the BAU simulation results are also shown. The effect of the public transport policy on the relative congested travel time [as shown in the right graph of Figure 40] is desirable as the relative congested travel time has decreased compared to the BAU scenario, thus indicating less congestion which in turn results in lower emissions and less air pollution due to inefficient stop-and-go driving (OECD, 2021; Su, 2006). Even as the relative congested travel time increases again between the years 2035 and 2050, due to increasing populations in the three areas, this increase is less steep compared to the start of the simulation as the public transport policy directly influences loop **B7** through car attractiveness and a smaller fraction of the labor force participants opts for the car as mode of transport in the ring and outer areas [Figure 41]. The left graph of Figure 40 shows that roads do not decrease significantly compared to the BAU scenario. Even though there is less congestion, there is still some congestion which thus stimulates more road construction.

Figure 41 – Public transport policy simulation behavior over time for the fraction of labor force commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.

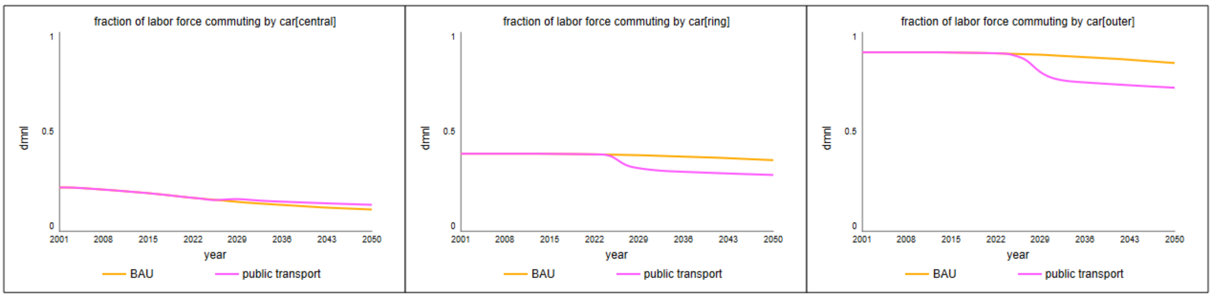
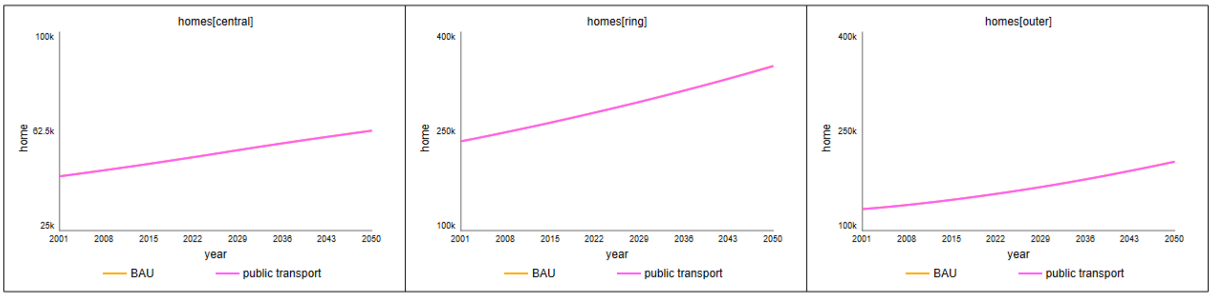


Figure 41 shows the fraction of the labor force participants commuting by car per area and shows an unexpected side effect of the public transport policy, albeit quite small. Where the fraction of the labor force commuting by car for the ring and outer areas decreases due to the public transport policy, the fraction of the labor force commuting by car for the central area actually increases a little. As public transport is already more convenient, efficient and accessible in the central area compared to the ring and outer areas, the decrease in travel time by public transport due to the public transport policy is less significant for the central area when compared to the decrease in travel time by car for the central area due to the decreasing congestion facilitated by the policy. As such, for the central area car attractiveness decreases less so in the public transport policy scenario compared to the BAU scenario, and thus a bigger fraction of commuters will travel by car. The opposite is applicable to the ring and outer areas.

*Figure 42 – Public transport policy simulation behavior over time for homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



* Note that the upper and lower bound on the y-axis for the graph representing the central area is four times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

While the effect of the public transport policy through loop **B7** on the relative congested travel time is desirable, the public transport policy does not significantly affect urban sprawl. Figure 42 shows the homes per area. Differences between the simulation behavior in the BAU and public transport policy scenarios are not distinguishable. Where the public transport policy does work through loop **B8** to decrease the attractiveness of more distant areas by decreasing car attractiveness, it also works through loop **B10** to increase the attractiveness of more distant areas by decreasing the relative congested travel time. While the former effect is stronger than the latter, and the effect of relative attractiveness areas on net migration does favor migration in to the central area more so and migration in to the ring and outer areas less so in the public transport policy scenario, when compared to the BAU scenario these differences are not significant enough to influence the overall population per area. As the populations of the ring and outer areas do not decrease significantly, housing availability will not increase and thus not limit home construction in the public transport policy scenario. Furthermore, as mentioned prior, as the road network does not significantly decrease [left graph of Figure 40] in the public transport policy scenario home construction will not be limited through loop **R5**.

Carpooling policy

According to EPN (2023) increasing the occupancy rate of private vehicles when commuting by carpooling could help to reduce transport emissions. This makes sense as increasing the occupancy rate of private vehicles would reduce the traffic volume. A smaller traffic volume implies less vehicle density on the road network and thus less congestion which in turn results in lower emissions and less air pollution due to inefficient stop-and-go driving (OECD, 2021; Su, 2006). As carpooling includes behavioral change in the commuting population it is assumed that the implementation of this policy takes some time. The occupancy rate per car is increased from one person per private vehicle to one-and-a-half persons per private vehicle.

Figure 43 – Carpooling policy simulation behavior over time for the roads [left] and relative congested travel time [right] in the The Hague region during the years 2001 and 2050.

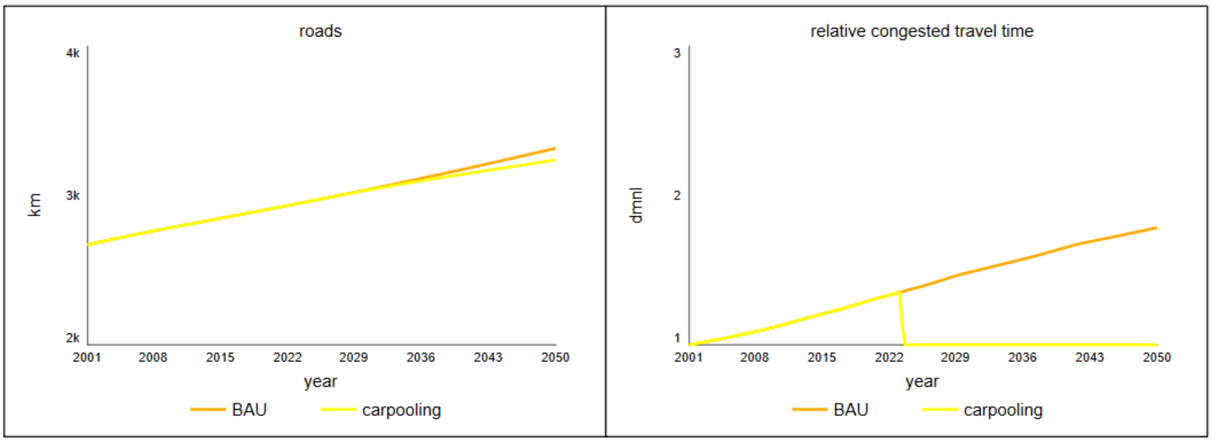
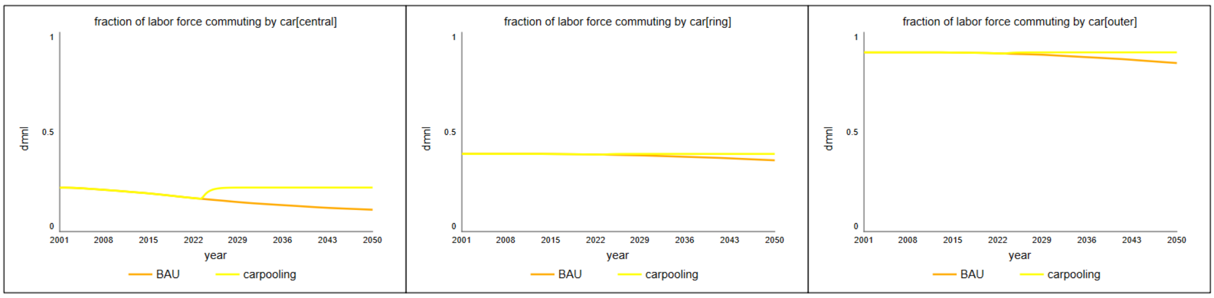


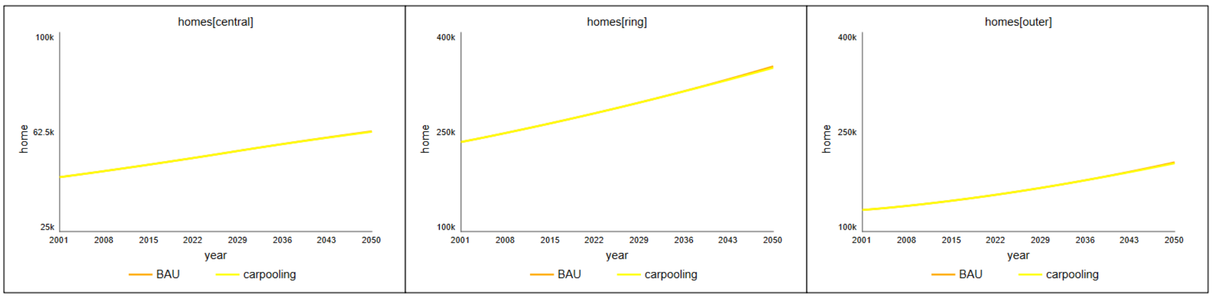
Figure 43 shows the generated model behavior for roads and relative congested travel time for the carpooling policy scenario, again the BAU simulation results are also shown. The effect of the carpooling policy on the relative congested travel time [as shown in the right graph of Figure 43] is desirable as the relative congested travel time has decreased compared to the BAU scenario [thus indicating less congestion] and does not increase during the remainder of the simulation. The effect of carpooling on the traffic volume successfully combats the increasing populations of the three areas. Furthermore, the left graph of Figure 43 shows that roads also increase less compared to the BAU scenario. The decrease in congestion is sufficiently high to alleviate the effect of pressure to expand the road network on road construction somewhat, and consequently the road network does not increase as much as it does in the BAU scenario [Figure 43]. Nevertheless, this policy has an important side effect. The carpooling policy still coincides with high car-dependency [even though the road network has increased less]. Figure 44 shows the fraction of the labor force participants commuting by car per area, which remains at its maximum value throughout the entire duration of the simulation for the ring and outer areas, and increases again after the policy start time towards its maximum value for the central area. This is undesirable.

Figure 44 – Carpooling policy simulation behavior over time for the fraction of labor force commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



Similar to the public transport policy scenario, while the effect of the carpooling policy on the relative congested travel time is desirable, the carpooling policy does not significantly affect urban sprawl. Figure 45 shows the homes per area. Significant differences between the simulation behavior in the BAU and carpooling policy scenarios are not distinguishable.

*Figure 45 – Carpooling policy simulation behavior over time for homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



* Note that the upper and lower bound on the y-axis for the graph representing the central area is four times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

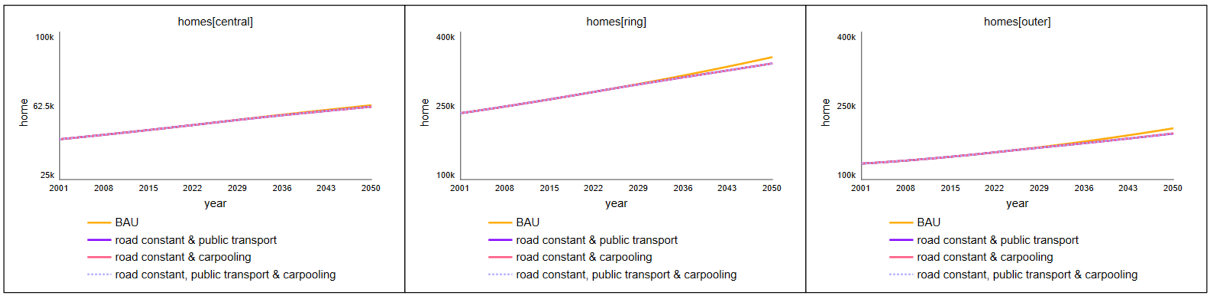
As shown by the four policy options included in this work, a singular implemented policy can alleviate either urban sprawl or congestion, but does not successfully alleviate both aspects of the problem. That being the case, a combination of the policies is necessary in an attempt to alleviate both aspects of the problem concerning urban sprawl and congestion.

4.2.2 Combination policies tests

This section addresses the behavior generated by the simulation model when multiple policy options are combined. Due to the undesirable effect the road network reduction policy scenario has on housing availability [which will be discussed in the upcoming policy resistance section] it is excluded from the combination policy tests. Both public transport and carpooling scenarios produce behavior desirable with regard to congestion. The constant road network policy produces behavior desirable with regard to urban sprawl. For this reason, the public transport policy and carpooling policy are both combined with the constant road network policy to test whether a combination of these policies might alleviate both aspects of the problem concerning urban sprawl and congestion. Furthermore, a combination of all three policy options is tested. In the figures shown in this section the BAU simulation results are also displayed.

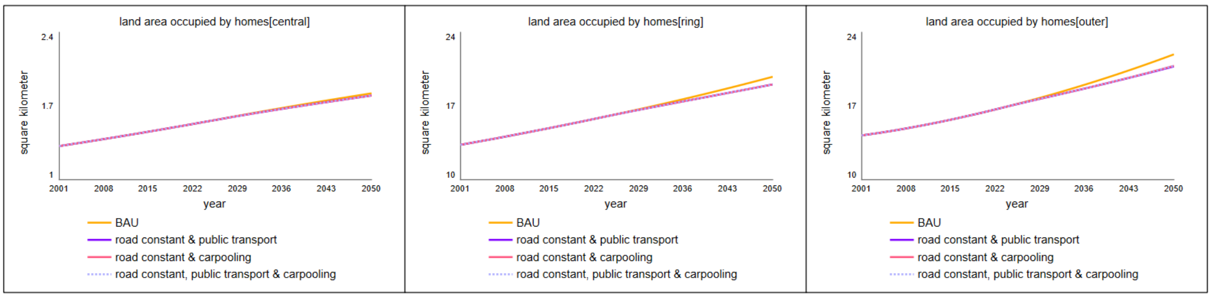
Figures 46 and 47 show the homes and the amount of land they occupy per area. As the constant road network policy ceases to facilitate the maximum home construction rate to increase, thereby reducing the strength of loop **R5** from the policy start time onwards, the homes per area increase less so than they do in the BAU scenario for all three combination policies [Figure 46]. Even though the amount of homes might not be reduced by a lot compared to the BAU scenario, the resulting amount of land that is occupied by homes does differ considerably between the combination policy scenarios and the BAU scenario [Figure 47]. Again, the difference in the amount of land occupied by homes between the combination policy scenarios and the BAU scenario at the end of the simulation for the ring and outer areas combined is greater than the size of the entire central area [Figure 47]. When less land is occupied, especially in more distant areas, the expansion of the urban form [and thereby sprawl] is less excessive. Therefore, the combination policy scenarios all produce a more desirable result when compared to the BAU scenario as they alleviate urban sprawl somewhat. Figure 48 shows the households to homes ratio [representing housing availability] in each area. Due to the limiting effect of the combination policy scenarios on home construction, homes will not increase as much and therefore housing is less available over time in these scenarios compared to the BAU scenario. For the central and outer The Hague areas the difference in housing availability between the combination policy scenarios and the BAU scenario might not be as detrimental, yet for the ring area where housing availability already posed an issue in the BAU scenario the difference in housing availability can be quite harmful. For further discussion please refer to section 4.2 of this report.

*Figure 46 – Combination policies simulation behavior over time for homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



* Note that the upper and lower bound on the y-axis for the graph representing the central area is four times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

*Figure 47 – Combination policies simulation behavior over time for the land occupied by homes in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is ten times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

Figure 48 – Combination policies simulation behavior over time for the households to homes ratio in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.

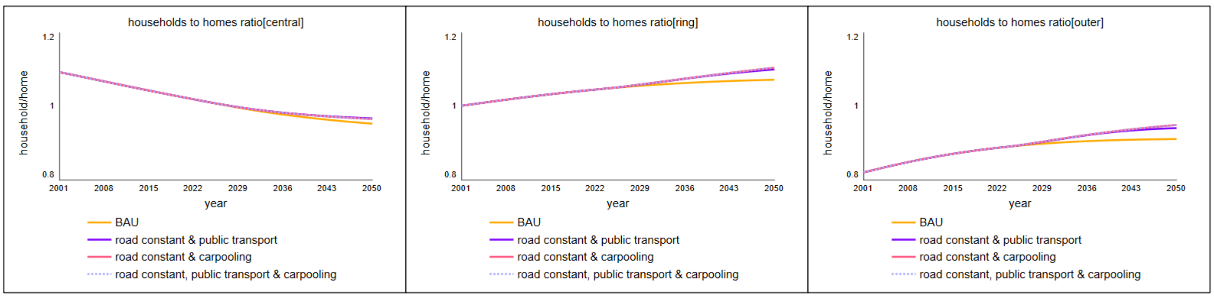
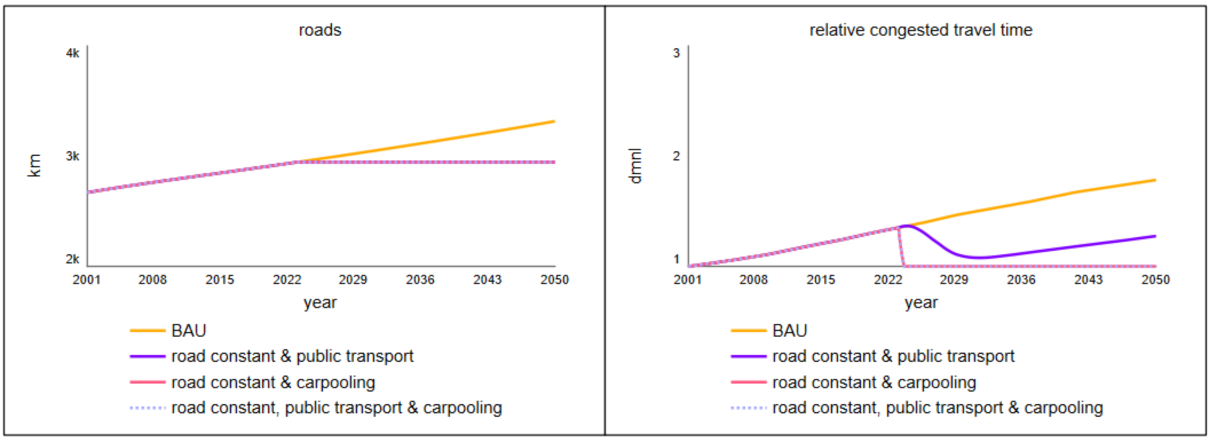


Figure 49 shows the generated model behavior for roads and relative congested travel time for the combination policy scenarios and the BAU scenario. As can be seen in the left graph of Figure 49 after the year 2023 the road network remains constant for the combination policy scenarios, as intended. Furthermore, all combination policy scenarios produce more desirable behavior concerning the relative congested travel time compared to the simulation behavior in the BAU scenario [right graph of Figure 49] due to either decreasing the traffic volume [through carpooling], decreasing the car attractiveness [through public transport], or both. The results from the combination policies with carpooling are most desirable with regard to the relative congested travel time as without carpooling [in the constant road network and public transport policy scenario] the relative congested travel time will eventually increase again [and it does so steeper when compared to the singular public transport policy due to the road network remaining constant in the combination policy, thereby adjusting the feedback from loop **B9**].

Figure 49 – Combination policies simulation behavior over time for the roads [left] and relative congested travel time [right] in the The Hague region during the years 2001 and 2050.



However, one must also consider possible side effects of a policy. The side effect of high car-dependency coinciding with the singular carpooling policy is still applicable to the combination policy of the constant road network and carpooling policy scenario. Figures 50 and 51 show the fraction of the labor force commuting by car and the labor force participants commuting by car for the various combination policy scenarios and the BAU scenario [note that for combination policies including carpooling the labor force participants commuting by car are distributed over a smaller amount of cars when compared to policies not including carpooling]. As shown in Figure 50 the fraction of the labor force participants commuting by car per area remains at its maximum value throughout the entire duration of the simulation for the ring and outer areas, and increases again after the policy start time towards its maximum value for the central area in the constant road network and carpooling combination policy. This is undesirable as it results in a higher amount of labor force participants commuting by car [Figure 51] which is still unhealthy for people even if it does not create as much congestion due to carpooling. Thus, in that regard the results from the constant road network and public transport combination policy scenario are most desirable, followed by the combination policy scenario including all three policy options. In those combination policies the public transport policy part works to reduce car attractiveness and through loop **B7** aims to limit the labor force commuting by car.

Figure 50 – Combination policies simulation behavior over time for the fraction of labor force commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.

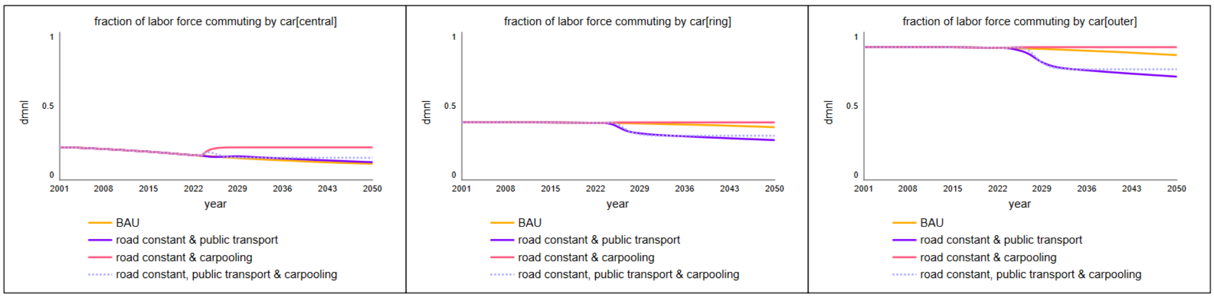
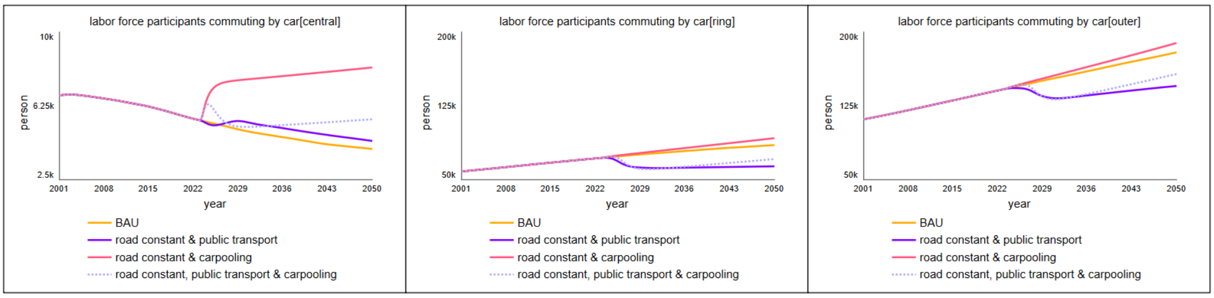


*Figure 51 – Combination policies simulation behavior over time for the labor force participants commuting by car in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.**



*Note that the upper and lower bound on the y-axis for the graph representing the central area is twenty times smaller than the upper and lower bounds on the y-axis for the ring and outer areas, the latter two having the same bounds.

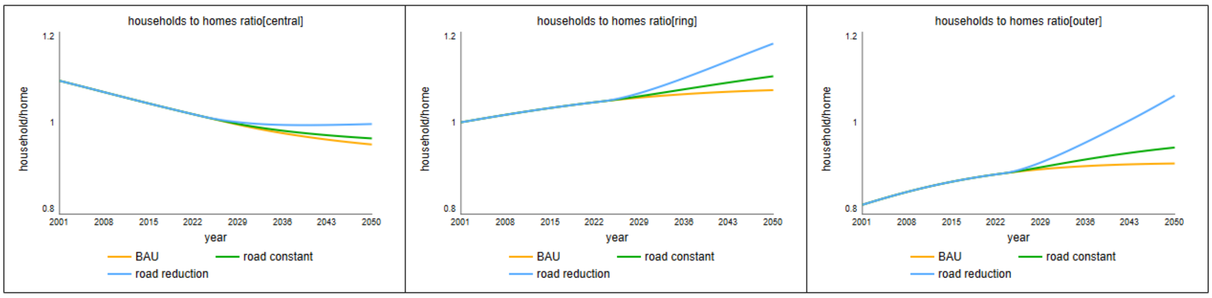
Overall, the combination policy where all three policy options [constant road network, public transport and carpooling] are combined seems most desirable in alleviating both aspects of the problem urban sprawl and congestion while taking possible side effects into account. However, each policy option will face resistance in varying degrees which might limit its effectiveness or implementation feasibility. Thus, policy resistance will be discussed briefly in the next section.

4.3 Policy resistance

4.3.1 Road network policy resistance

While both road network policy options [constant road network, road network reduction] might produce more desirable behavior concerning urban sprawl as discussed in the prior section, the road network options, especially the road network reduction option, have important side effects concerning housing availability which occur both when a road network policy option is implemented singularly and in combination with a public transport and/or carpooling policy option. Due to the limiting effect of a smaller road network [compared to the BAU scenario] on home construction, homes will not increase as much when a road network policy is implemented and therefore housing is less available over time in such a scenario compared to the BAU scenario. Figure 52 shows the households to homes ratio [representing housing availability] in each area for the road network policy options and the BAU scenario. In the scenario where the constant road network policy option is implemented the difference in housing availability for the central and outer The Hague areas in comparison with the BAU scenario might not be as detrimental, yet for the ring area where housing availability already posed an issue in the BAU scenario the difference in housing availability can be quite harmful. In the scenario where the road network reduction policy option is implemented the difference in housing availability poses even greater threats as housing becomes much less available at a fairly quick pace in both the ring and outer The Hague areas. When housing becomes less available it also becomes less affordable.

Figure 52 – Road network policies simulation behavior over time for the households to homes ratio in the central [left], ring [middle], and outer [right] The Hague areas during the years 2001 and 2050.



While the overall housing availability might still be manageable [and thereby acceptable] for the constant road network policy option, for the road network reduction policy option the change in housing availability, and thereby affordability, is expected not to be manageable and the much increased households to homes ratio poses a real problem in especially the ring and outer The Hague areas. This would cause unrest within the population. Gentrification [the process whereby the urban area changes by wealthier people moving into the area displacing less wealthy current inhabitants in the process] might occur in these areas. Furthermore, from a politically perspective a policy which strongly decreases housing availability, such as the road network reduction policy option, will be unfeasible to implement (Mirabile, 2023).

4.3.2 Public transport policy resistance

While the public transport policy option might produce more desirable behavior concerning the relative congested travel time [a summary measure for congestion] as discussed in the prior section, improving public transport in its conveniency, efficiency and/or accessibility is very costly (Koolen & Stoelinga, 2005). Nevertheless, in order for public transport to become more competitive to private vehicles, especially in more distant areas [which is important as commuters from more distant areas contribute most to the traffic volume and congestion issue] high investments are necessary [yet the costs of improving public transport in more distant areas is more costly compared to the costs of improving public transport in less distant areas since public transport in the latter area are usually more convenient, efficient and accessible already]. Small investments are expected to not make enough difference to significantly drive behavioral change in opting for a mode of transport for commuting. However, the costs necessary to properly implement the public transport policy option might be considered too costly for some decisionmakers. Furthermore, even when the funds are available to implement the public transport policy option, other capacity needed for implementation might not [fully] be available.

4.3.3 Carpooling policy resistance

While the carpooling policy option might produce more desirable behavior concerning the relative congested travel time [a summary measure for congestion] as discussed in the prior section, people might not want to commute despite the many financial, time and environmental benefits it offers (Geuze, 2017). According to Geuze (2017) commuters might be hesitant to carpool as concerns exist regarding one's privacy, flexibility and freedom when commuters share a vehicle together. In 1993 a campaign was launched in the middle of The Netherlands [around the regions Amsterdam, Almere and Utrecht] to motivate commuters to carpool. While some commuters started carpooling together, most commuters did not. As such, the campaign did not achieve its desired outcome. However, the results of a carpooling policy option are most effective when a large part of the commuting population partakes in it. If only a small fraction of the commuting population carpools, a significant difference in congestion is not expected as the traffic volume might not decrease enough despite the carpooling policy.

4.4 Chapter conclusion

This chapter addresses the third research question "what policy options can be identified to reduce urban sprawl and congestion in the The Hague region?". The box below provides a concise summary in answer to the research question.

> ***What policy options can be identified to reduce urban sprawl and congestion in the The Hague region?***
>
> Four policy options with a focus on mobility have been tested in this work. These policy options have directly addressed the road network [constant road network policy, road network reduction policy], car attractiveness [public transport policy] and the traffic volume [carpooling], thereby attempting to influence the feedback from loops **R4**, **R5**, **B7**, **B8**, **B9** and **B10** directly, and through these loops indirectly influence the feedback from other loops. A singular implemented policy can alleviate either urban sprawl or congestion, but does not successfully alleviate both aspects of the problem. As such, a combination of the policy options is necessary. Overall, combining the constant road network, public transport and carpooling policy options seems most desirable in alleviating both aspects of the problem urban sprawl and congestion while taking possible side effects of the policy options into consideration. However, each of these policy options might meet some resistance in varying degrees which might limit its effectiveness or implementation feasibility.

Chapter 5. Discussion

Urban sprawl and congestion have significant detrimental effects on society and on the environment (Hennig, et al., 2016; OECD, 2018). The current work provides a system dynamics modeling approach to the problem of urban sprawl and congestion in the The Hague region. This chapter summarizes the answers to the three posed research questions and addresses limitations to this work and opportunities for future research.

5.1 Answers to research questions

The objective of this work on urban sprawl and congestion has been to provide understanding of the processes involved as drivers of urban sprawl and congestion in the The Hague region. Subsequently, this work further aimed to move beyond understanding the processes involved towards understanding as a basis for policy analysis. In order to meet the research objective three research questions have been addressed throughout this work. Concise answers to these research questions will be discussed below.

> ***Research question 1.***
> Which mechanisms offer a causal explanation for
> urban sprawl and congestion in the The Hague region?

In order to answer the first research question scientific and grey literature have been reviewed, the latter including reports from the OECD and Dutch governmental institutions. Through literature review key variables and their interrelationships could be defined representing the concepts as established in the literature. Based thereon, a quantitative model was constructed [references to the reviewed literature are stated in the model documentation in Appendix II]. In short, the model captures that urban sprawl and congestion manifest by people locating themselves in places that are attractive, where housing is available [and thus more affordable] and that facilitate access to places of interest [such as their workplace], and by momentum policies involved in these processes. Housing is usually more available in more distant areas. However, in more distant areas people often opt to commute by private vehicles as they live further away from places of interest. Consequently, the traffic volume and vehicle density on the road network increases leading to congestion. The road network is then expanded to ‘solve’ this congestion. However, by doing so the increased road network facilitates more home construction in peripheral areas, which is predominantly low density development, and allows people to live further away from places of interest as the road network facilitates access. As active modes of transport and public transport are less convenient, efficient and/or accessible, car-dependency is enhanced. As such, the urban area sprawls and the road network becomes congested.

> ***Research question 2.***
> How do these mechanisms contribute to the behavior of the system?

In order to answer the second research question the created simulation model and the behavior as generated by the simulation model has been analyzed. In short, the simulation model and the behavior it generates is not dominated by a single powerful loop or a few loops between which dominance shifts. Rather, the various loops existing in the system all contribute somewhat to the behavior of the system, and some of those loops oppose each other. Nevertheless a few mechanisms can be identified that especially contribute to the behavior of the system being the housing availability, the road network [and road construction], the traffic volume [and car attractiveness], the relative attractiveness of more distant areas and net migration. Furthermore, mobility holds a key function. By the expanding road network both the relative attractiveness of peripheral areas and home construction in peripheral areas can be increased and maintained. People are stimulated to migrate in to these attractive more distant areas where, while decreasing, housing is relatively available for most of the duration of the simulation. As especially the populations of the ring and outer The Hague areas grow, the traffic volume increases as commuters from these areas more often opt for the car as transport mode. As such, congestion and travel time by car increases. Where this leads to increasing pressure to expand the road network, and in turn more road construction [with its consequences for congestion, home construction and area attractiveness], it does not sufficiently lead to a decreasing fraction of the labor force from the ring and outer areas opting for the car when commuting as the car is still considered to be a far more attractive mode of transport compared to public transport based on travel time. This is aided by the increasing road network. With habituation regarding travel time and a sufficiently high car attractiveness, the attractiveness of peripheral areas does not decrease enough to dissuade people to migrate in to more distant areas.

> ***Research question 3.***
> What policy options can be identified to reduce urban sprawl
> and congestion in the The Hague region?

In order to answer the third research question the behavior generated by the created simulation model has been analyzed while certain policy options were implemented [without regard for implementation obstacles]. The policy options are mobility-oriented due to the importance of mobility in the system. In short, four policy options have been tested in this work. These policy options have directly addressed the road network [constant road network policy, road network reduction policy], car attractiveness [public transport policy] and the traffic volume [carpooling policy], thereby attempting to influence the feedback from loops **R4**, **R5**, **B7**, **B8**, **B9** and **B10** directly, and through these loops indirectly influence the feedback from other loops. Resulting from the analysis of the generated model behavior, a singular implemented policy can alleviate either urban sprawl or congestion, but does not successfully alleviate both aspects of the problem. As such, a combination of the policy options is necessary. Overall, combining the constant road network, public transport and carpooling policy options seems most desirable in alleviating both aspects of the problem urban sprawl and congestion while taking possible side effects of the policy options into consideration. However, each of these policy options might meet some resistance in varying degrees which might limit its effectiveness or implementation feasibility.

5.2 Limitations

All research has its limitations, including this work. Some of these limitations concern the level of detail implemented in the model structure. While simplification can be commendable as it benefits a model's comprehensibility and/or generalizability, it could hinder the testing of policies or influence their effectiveness, and/or it could result in some people not being able to fully identify with a model structure and therefore doubt the behavior it generates. For example, it should be mentioned that considerations such as the impact of transport mode on the environment, the costs of a transport mode and the flexibility offered by a transport mode lay outside the model boundary of this work. The model accompanying this work solely concerns travel time, yet decisions regarding which transport mode to travel with are much more complicated than how they are currently modeled. This also holds true for how the relative attractiveness of an area changes over time. These changes are currently based on changes in the road network, housing availability, car attractiveness and relative travel time. However, other considerations such as changes in crime, green spaces and noise pollution also influence how the relative attractiveness of an area changes.

Furthermore, due to the lack of data some mechanisms are modeled representing the

The Hague region rather than one of its areas [central, ring, outer], yet the distinction between areas can be important for policy and decision makers. Again, this could hinder the testing of policies or influence their effectiveness. The road network is such a mechanism. With regard to the effects of land occupation on various mechanisms in the model [homes, roads, jobs], it would also be preferable if these mechanisms contained the same level of aggregation either all representing the various areas in The Hague [central, ring, outer] or the region as a whole.

A final limitation to this work concerns the uncertainty embedded in some variables in the model structure, for which values had to be assumed rather than being based on literature. As the created simulation model proved to be numerically sensitive to some auxiliary parameters and graphical functions, but did not really prove to be sensitive in terms of behavior mode to changes in auxiliary parameters and graphical functions, the severity of this limitation concerning uncertainty is rather low, yet worth mentioning. Further details regarding the behavior sensitivity test and its results can be found in Appendix III.

5.3 Future research

The current work extends on the work done by Grimeland (2022) on urban sprawl for the OECD. His work was an early attempt at modeling the phenomenon. A key conclusion of Grimeland's (2022) work is that a new perspective is warranted concerning road network development in order for urban sprawl to be reduced. This work agrees with that conclusion and adds to it by stressing the importance of attractive alternative modes of transport, such as public transport, relative to transport by private vehicles when concerning congestion and especially car-dependency. As mentioned in the note from author section in this thesis, the author considers extending on each other's work to be of great importance within the System Dynamics community. Therefore, this section will provide three recommendations for future research to take a next step and further extend on the work concerning urban sprawl and congestion.

As mentioned in Chapter 1 of this work, urban sprawl can offer important private benefits and thus on an individual level urban sprawl might not be considered undesirable. This could lead or add to resistance when implementing policies to combat urban sprawl. In future work an interactive learning environment targeted at individuals might be created to communicate the importance of the problem concerning urban sprawl and congestion and the insights derived from simulation results and policy tests. In this case, it is highly recommended to include model structure and simulation results concerning the social and/or the environmental impact of urban sprawl and congestion. This could be done by including measures for well-being [social impact] and/or greenhouse gas emissions [environmental impact]. Extending the model to include social and/or environmental mechanisms, and creating an interactive learning environment visualizing the impact of urban sprawl and congestion on these social and/or environmental mechanisms, allows people to gain insights into the problem and experience the importance of and the need to reduce it. Furthermore, through the interactive learning environment individuals can explore the effects of various policies which might aid in reducing policy resistance on an individual level.

Second, as this work is more explanatory in nature, future work might focus more on dedicated policy modeling where for example the implementation of a road space reallocation policy could be explored [which according to Mirabile (2023) is potentially promising in reducing urban sprawl and congestion]. The road network reduction policy option included in this work is a partial road space reallocation policy. When road is being reallocated and used for purposes other than private commuting, the road network available to private commuters decreases [just as the road network decreases in the road network reduction policy]. However, road reallocation compared to road reduction influences certain mechanisms in the model differently [such as home construction and thereby housing availability, relative attractiveness of more distant areas, car attractiveness and the attractiveness of active or shared modes of transport]. This depends on where roads are reallocated and what roads are reallocated into. Roads could be reallocated into more sustainable modes of transport or even into uses beyond transport such as recreational areas (OECD, 2021). Before creating a dedicated policy structure in order to test a road reallocation policy [and variations in where road is reallocated and what it is reallocated into] the current explanatory model structure should be adjusted somewhat. It is recommended to endogenize all three fractions of the labor force commuting by active, shared or private modes of transport [as the transport mode by which people commute might change depending on what roads are reallocated into] and by including more detail in the structure representing the road network [as it is of importance where roads are being reallocated].

Finally, as this work has explored some basic mobility-oriented policy options that might alleviate the problem concerning urban sprawl and congestion without taking implementation obstacles into account, future iterations of this work might explore policies which are not mobility-oriented [for example policies regarding home construction] or combinations of mobility-oriented and non-mobility-oriented policies. It would be interesting as well to acquire a better understanding of possible resistance accompanying these policies and implementation obstacles involved.

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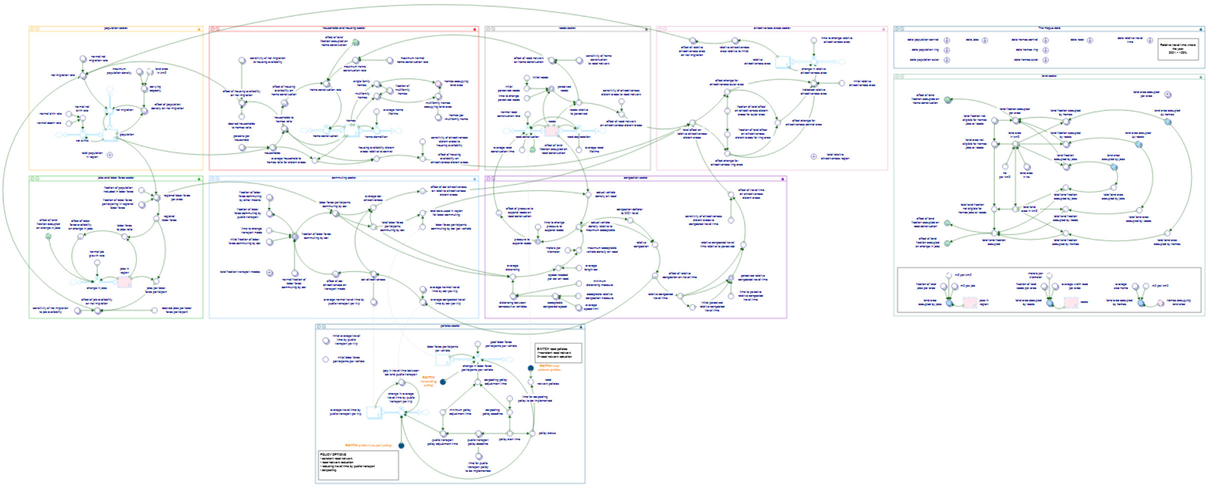
Appendices

Appendix I – Model structure

Appendix I shows the created model structure as a guiding image for recreation purposes. The necessary model documentation for which can be found in Appendix II.



Appendix II – Model documentation

Appendix II reports the model documentation for the created model structure. The model documentation is ordered by sector. The model is arrayed by the dimension area with the three elements The Hague CENTRAL, RING and OUTER.

ATTRACTIVENESS AREAS SECTOR

Change in relative attractiveness area

Equation (indicated_relative_attractiveness_area-relative_attractiveness_area)/ time_to_change_relative_attractiveness_area
Unit dmnl/year
Documentation The arrayed flow change in relative attractiveness area represents the adjustment of the relative attractiveness of an area per year. It is the rate at which the relative attractiveness of an area increases or decreases per year.

The equation for this flow is the same for each arrayed area and equals the difference between the indicated relative attractiveness of the area and the stock relative attractiveness area, divided by the time to change the relative attractiveness of an area.

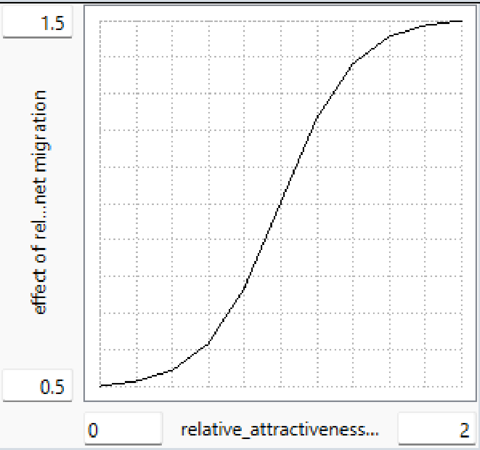
When the indicated relative attractiveness of an area is equal to the stock relative attractiveness area, the flow will equal a dimensionless value of 0 per year and the stock will not be adjusted.
When the indicated relative attractiveness of an area is lower than the stock relative attractiveness area, the flow will equal a negative value per year and will work to decrease the stock.
When the indicated relative attractiveness of an area is higher than the stock relative attractiveness area, the flow will equal a positive value per year and will work to increase the stock.

As it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) will always equal 1, meaning 100%, the relative attractiveness of one area should decrease when the relative attractiveness of another area increases.
Effect change for attractiveness central area
Equation -1*(effect_change_for_attractiveness_outer_area+effect_change_for_attractiveness_ring_area) **Unit** dmnl **Documentation** The variable effect change for attractiveness central area represents the size and direction of the change that should occur in relative attractiveness for the central area. Distant areas are areas located further away from the central area. As such, the ring area is a more distant area than the central area, and the outer area is a more distant area than the ring area. The total effect on relative attractiveness distant areas is therefore distributed between the ring and the outer area. However, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of the ring and outer areas increases, the relative attractiveness of the central area has to decrease, and the other way around. The equation for effect change for attractiveness central area equals the product of -1 by the sum of the effect changes for attractiveness outer and ring areas. By doing so, when the relative attractiveness of the ring and outer areas increases, the relative attractiveness of the central area decreases, and the other way around. And the total relative attractiveness region will not increase or decrease below one as the size of the adjustments in relative attractiveness for the ring and outer areas is matched, yet opposite in direction, for the central area.
Effect change for attractiveness outer area
Equation -1*(1-total_effect_on_relative_attractiveness_distant_areas)* fraction_of_total_effect_on_attractiveness_distant_areas_for_outer_area **Unit** dmnl **Documentation** The variable effect change for attractiveness outer area represents the size and direction of the change that should occur in relative attractiveness for the outer area. The equation for effect change for attractiveness outer area equals the product of the difference between 1 and the total effect on relative attractiveness distant areas by -1 and by the fraction of total effect on attractiveness distant areas for outer area. The difference between 1 and the total effect on relative attractiveness distant areas is written in between parentheses. This difference represents the size of the change that should occur for the distant areas in total. When the total effect on relative attractiveness distant areas is higher than 1, meaning that the attractiveness of distant areas should increase due to the total effect, the part in between the parentheses will return a negative value. To ensure that the attractiveness of distant areas increases (instead of decreases due to the negative value) when the total effect on relative attractiveness distant areas is higher than 1, the negative value as returned by the part in between parentheses is multiplied with -1 to give the change the right direction. The value that is returned now represents the size and direction of the change that should occur for the distant areas in total. This value has to be multiplied by the fraction of the total effect on attractiveness distant areas for outer area to

determine the size and direction of the change that should occur for the outer area alone. This is also applicable when the total effect on relative attractiveness distant areas is lower than 1, meaning that the attractiveness of distant areas should decrease due to the total effect. The part in between the parentheses would then return a positive value which should be multiplied with -1 to give the change the right direction. It is necessary to determine the effect change for the attractiveness of the outer area. Usually indicated values are determined by the initial value multiplied with an effect. This is not possible here as the total effect is distributed over the ring and outer area. When one would calculate the indicated relative attractiveness for the outer area by multiplying the total effect on relative attractiveness distant areas (for example 1.2) with the fraction of the total effect on attractiveness distant areas for the outer area (2/3 * 1.2 = 0.8), and then multiply that value with the initial relative attractiveness outer area (1/3 * 0.8 = 0.2666...), the indicated relative attractiveness of the outer area would lead the stock value for the relative attractiveness outer area to decrease, where is should in reality increase based on the total effect on relative attractiveness distant areas.
Effect change for attractiveness ring area
Equation -1*(1-total_effect_on_relative_attractiveness_distant_areas)*fraction_of_total_effect_on_attractiveness_distant_areas_for_ring_area **Unit** dmnl **Documentation** The variable effect change for attractiveness ring area represents the size and direction of the change that should occur in relative attractiveness for the ring area. The equation for effect change for attractiveness ring area equals the product of the difference between 1 and the total effect on relative attractiveness distant areas by -1 and by the fraction of total effect on attractiveness distant areas for ring area. The difference between 1 and the total effect on relative attractiveness distant areas is written in between parentheses. This difference represents the size of the change that should occur for the distant areas in total. When the total effect on relative attractiveness distant areas is higher than 1, meaning that the attractiveness of distant areas should increase due to the total effect, the part in between the parentheses will return a negative value. To ensure that the attractiveness of distant areas increases (instead of decreases due to the negative value) when the total effect on relative attractiveness distant areas is higher than 1, the negative value as returned by the part in between parentheses is multiplied with -1 to give the change the right direction. The value that is returned now represents the size and direction of the change that should occur for the distant areas in total. This value has to be multiplied by the fraction of the total effect on attractiveness distant areas for ring area to determine the size and direction of the change that should occur for the ring area alone. This is also applicable when the total effect on relative attractiveness distant areas is lower than 1, meaning that the attractiveness of distant areas should decrease due to the total effect. The part in between the parentheses would then return a positive value which should be multiplied with -1 to give the change the right direction. It is necessary to determine the effect change for the attractiveness of the ring area. Usually indicated values are determined by the initial value multiplied with an effect. This is not possible here as the total effect is distributed over the ring and outer area. When one would calculate the indicated relative attractiveness for the ring area by multiplying the total effect on relative attractiveness distant areas (for example 1.2) with the fraction of the total effect

on attractiveness distant areas for the ring area (1/3 * 1.2 = 0.4), and then multiply that value with the initial relative attractiveness ring area (1/3 * 0.4 = 0.1333...), the indicated relative attractiveness of the ring area would lead the stock value for the relative attractiveness ring area to decrease, where is should in reality increase based on the total effect on relative attractiveness distant areas.

Effect of relative attractiveness area on net migration



Equation GRAPH(relative_attractiveness_area_relative_to_initial) Points: (0.000, 0.500), (0.200, 0.5126), (0.400, 0.5434), (0.600, 0.6165), (0.800, 0.7676), (1.000, 1.000), (1.200, 1.232), (1.400, 1.383), (1.600, 1.457), (1.800, 1.487), (2.000, 1.500)
Unit dmnl
Documentation This graphical function represents the effect of relative attractiveness area on net migration. Thus it represents how the net migration rate of an area changes based on changes in the relative attractiveness of the area. It is assumed that the more attractive an area becomes over time, more people would want to migrate in to that area as they otherwise would. The graphical function is the same for each area.

When the relative attractiveness area relative to initial equals 1, meaning that the relative attractiveness of an area has not changed over time, the effect of relative attractiveness area on net migration will also equal 1 and will not work to change the net migration rate.
When the relative attractiveness area relative to initial equals a value lower than 1, meaning that the relative attractiveness of an area has decreased over time, less people would want to migrate in to that area as they otherwise would. As such, when the relative attractiveness of an area relative to initial decreases from 1 to 0, the effect of relative attractiveness area on net migration will decrease decreasingly from 1 to 0.5 - the lower the relative attractiveness of an area relative to initial becomes, small changes will make less of a difference. Furthermore, there will always be some people that will want to migrate in to an area, as such the effect does not range down to 0.
When the relative attractiveness area relative to initial equals a value higher than 1, meaning that the relative attractiveness of an area has increased over time, more people would want to migrate in to that area as they otherwise would. As such, when the relative attractiveness of an area relative to initial increases from 1 to 2, the effect of relative attractiveness area on net migration will increase decreasingly from 1 to 1.5 - the higher the relative attractiveness of an area relative to initial becomes, small changes will make less of a difference. There is a limit to the amount of people who will want to migrate in to an area.

The effect is calibrated based on population data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).

Fraction of total effect on attractiveness distant areas for outer area
Equation 2/3 **Unit** dmnl **Documentation** Distant areas are areas located further away from the central area. As such, the ring area is a more distant area than the central area, and the outer area is a more distant area than the ring area. The total effect on relative attractiveness distant areas is therefore distributed between the ring and the outer area. However, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of the ring and outer areas increases, the relative attractiveness of the central area has to decrease, and the other way around. The variable fraction of total effect on attractiveness distant areas for outer area represents the part of the total effect that is distributed to the outer area. It is assumed that, as the outer area is more distant than the ring area, a bigger part of the total effect should be distributed to the outer area compared to the ring area. As such, the value for fraction of total effect on attractiveness distant areas for outer area is assumed to be 2/3.
Fraction of total effect on attractiveness distant areas for ring area
Equation 1-fraction_of_total_effect_on_attractiveness_distant_areas_for_outer_area **Unit** dmnl **Documentation** Distant areas are areas located further away from the central area. As such, the ring area is a more distant area than the central area, and the outer area is a more distant area than the ring area. The total effect on relative attractiveness distant areas is therefore distributed between the ring and the outer area. However, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of the ring and outer areas increases, the relative attractiveness of the central area has to decrease, and the other way around. The variable fraction of total effect on attractiveness distant areas for ring area represents the part of the total effect that is distributed to the ring area. As the total effect on relative attractiveness distant areas is distributed between the ring and the outer area, the equation for this variable equals 1 subtracted by the fraction of total effect on attractiveness distant areas for outer area. As the latter fraction has a constant value of 2/3, the fraction of total effect on attractiveness distant areas for ring area also has a constant value of 1/3.
Indicated relative attractiveness area
Equation [CENTRAL] initial_relative_attractiveness_area+(initial_relative_attractiveness_area*effect_change_for_attractiveness_central_area) [RING] initial_relative_attractiveness_area+(initial_relative_attractiveness_area*effect_change_for_attractiveness_ring_area) [OUTER] initial_relative_attractiveness_area+(initial_relative_attractiveness_area*effect_change_for_attractiveness_outer_area) **Unit** dmnl **Documentation** The arrayed variable indicated relative attractiveness area represents an indicative measure for the relative attractiveness area (see model documentation for the stock relative attractiveness area for an explanation of what the stock represents).

The stock relative attractiveness area is adjusted (increased or depleted) towards the indicated relative attractiveness of the area (central, ring, outer). The equation for indicated relative attractiveness area is the same for each area, however as the variables effect change for the attractiveness of a specific area (central, ring, outer) are modeled separately, the equation cannot apply to all. The equation equals the sum of the initial relative attractiveness area with the product of the initial relative attractiveness area by the effect change for attractiveness of the area (the latter variable thus being either the effect change for the attractiveness of the central, ring, or outer area corresponding to the array dimension element in the equation for the indicated relative attractiveness area). When the effect change for the attractiveness of an area equals 0, the indicated relative attractiveness area will equal the initial relative attractiveness area. When the effect change for the attractiveness of an area is positive (higher than 0), the indicated relative attractiveness area will be higher than the initial relative attractiveness area. When the effect change for the attractiveness of an area is negative (lower than 0), the indicated relative attractiveness area will be lower than the initial relative attractiveness area.
Initial relative attractiveness area
Equation 1/3 **Unit** dmnl **Documentation** The arrayed stock relative attractiveness area represents a measure of how the attractiveness of an area (central, ring, outer) has changed relative to how the attractiveness of the other areas has changed. Note that it is not representing how attractive an area actually is, merely that over time the attractiveness of the area has increased, decreased or not changed. For example, when the relative attractiveness of the outer area has increased over time and the relative attractiveness of the central area has decreased over time, this does not mean that the outer area is necessarily more attractive than the central area, rather it shows that the outer area has become more attractive than it initially was where the central area has become less attractive than it initially was. These changes in the attractiveness of an area influence the net migration rate of the area. As the arrayed stock relative attractiveness area does not capture the actual attractiveness of an area, but rather how the attractiveness has changed over time, the initial value for each area (central, ring, outer) is given the same value. Again, this does not mean that all areas are equally attractive at the outset of the simulation. Of interest is how the relative attractiveness of the area has changed over time compared to that initial value, and not the specific value itself. Furthermore, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of one area increases, the relative attractiveness of another area has to decrease. As there are three elements (central, ring, outer) in the array dimension area the initial value for each area is set to be the total relative attractiveness region divided by the amount of elements in the array dimension, thus the initial relative attractiveness area is set to be equal to a dimensionless value of 1/3.

Relative attractiveness area
Equation relative_attractiveness_area[area](t - dt) + (change_in_relative_attractiveness_area[area]) * dt **Properties** INIT relative_attractiveness_area[area] = initial_relative_attractiveness_area **Unit** dmnl **Documentation** The arrayed stock relative attractiveness area represents a measure of how the attractiveness of an area (central, ring, outer) has changed relative to how the attractiveness of the other areas has changed. Note that it is not representing how attractive an area actually is, merely that over time the attractiveness of the area has increased, decreased or not changed. For example, when the relative attractiveness of the outer area has increased over time and the relative attractiveness of the central area has decreased over time, this does not mean that the outer area is necessarily more attractive than the central area, rather it shows that the outer area has become more attractive than it initially was where the central area has become less attractive than it initially was. These changes in the attractiveness of an area influence the net migration rate of the area. The stock is adjusted (increased or depleted) by the flow change in relative attractiveness area. The relative attractiveness of an area is adjusted towards the indicated relative attractiveness of that area which is influenced by various effects. As this arrayed stock does not capture the actual attractiveness of an area, but rather how the attractiveness has changed over time, the initial value for each area (central, ring, outer) is given the same value. Of interest is how the relative attractiveness of the area has changed over time compared to that initial value, and not the specific value itself. Furthermore, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of one area increases, the relative attractiveness of another area has to decrease. As there are three elements (central, ring, outer) in the array dimension area the initial value for each area is set to be the total relative attractiveness region divided by the amount of elements in the array dimension, thus the initial relative attractiveness area is set to be equal to a dimensionless value of 1/3. In order to say something about how attractive an area actually is relative to another area more qualitative research would be necessary into the attractiveness of areas to better quantify the constructs representing the attractiveness in a model.
Relative attractiveness area relative to initial
Equation relative_attractiveness_area/INIT(relative_attractiveness_area) **Unit** dmnl **Documentation** The arrayed stock relative attractiveness area represents a measure of how the attractiveness of an area (central, ring, outer) has changed relative to how the attractiveness of the other areas has changed. Note that it is not representing how attractive an area actually is, merely that over time the attractiveness of the area has increased, decreased or not changed. For example, when the relative attractiveness of the outer area has increased over time and the relative attractiveness of the central area has decreased over time, this does not mean that the outer area is necessarily more attractive than the central area, rather it shows that the outer area has become more attractive than it initially was where the central area has become less attractive than it initially was.

As such, the input to the effect of relative attractiveness area on net migration is the relative attractiveness of the area relative to its initial value showing how the attractiveness of the area has changed, and not to a perceived value representing the actual attractiveness of an area.

The equation for this variable is the same for each arrayed area and equals the division of the current stock value for relative attractiveness area by the initial stock value for relative attractiveness area.

Time to change relative attractiveness area

Equation 5
Unit year
Documentation The variable time to change relative attractiveness area represents the time it takes for the relative attractiveness of an area to be adjusted. Even though the stock is not representing how attractive an area actually is (merely that over time the attractiveness of the area has increased, decreased or not changed), it does take time to perceive changes in the attractiveness of an area. As such, it is assumed that the time to adjust the relative attractiveness of an area equals approximately 5 years.

Total effect on relative attractiveness distant areas

Equation effect_of_travel_time_on_attractiveness_distant_areas*
effect_of_housing_availability_on_attractiveness_distant_areas*
effect_of_car_attractiveness_on_relative_attractiveness_distant_areas*
effect_of_road_network_on_attractiveness_distant_areas
Unit dmnl
Documentation The variable total effect on relative attractiveness distant areas represents the combined effects of road network, housing availability, relative congested travel time, and car attractiveness on the relative attractiveness of distant areas.

Note that there is no effect of jobs on relative attractiveness distant areas as it is assumed that the fraction of total jobs in the region per area remains equal throughout the time horizon of this model, meaning that the distribution of jobs across the region does not change. Even when there is a growth in jobs, this growth would be applicable to all areas. As such, any effect of jobs on the relative attractiveness of an area would be canceled out. Therefore jobs do not influence the relative attractiveness of distant areas in this model.

The equation for total effect on relative attractiveness distant areas equals the multiplication of the various effects. As such, the equation equals the product of the effect of road network on attractiveness distant areas, by the effect of housing availability on attractiveness distant areas, by the effect of travel time on attractiveness distant areas, and by the effect of car attractiveness on relative attractiveness distant areas.

Distant areas are areas located further away from the central area. As such, the ring area is a more distant area than the central area, and the outer area is a more distant area than the ring area. The total effect on relative attractiveness distant areas is therefore distributed between the ring and the outer area. However, it is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of the ring and outer area increases, the relative attractiveness of the central area has to decrease, and the other way around.

Total relative attractiveness region
Summing converter **Equation** SUM(relative_attractiveness_area[*]) **Unit** dmnl **Documentation** The variable total relative attractiveness region represents the attractiveness of the areas (central, ring, outer) together and thus represents the attractiveness of the The Hague region as a whole. It is assumed that the attractiveness of the The Hague region does not change over time and thus the sum of the relative attractiveness of all three areas (central, ring, outer) should always equal 1, meaning 100%. As such, when the relative attractiveness of one area increases, the relative attractiveness of another area has to decrease, otherwise the total relative attractiveness region would increase above or decrease below 1. The equation for total relative attractiveness region equals the sum of the relative attractiveness area of all three elements in the array dimension area, being central, ring and outer.
COMMUTING SECTOR
Average car attractiveness
Equation ((car_attractiveness[central]*labor_force_participants_commuting_by_car[central]) +(car_attractiveness[ring]*labor_force_participants_commuting_by_car[ring]) +(car_attractiveness[outer]*labor_force_participants_commuting_by_car[outer]))/ total_labor_force_participants_commuting_by_car **Unit** dmnl **Documentation** The variable average car attractiveness represents an average relative measure indicating how attractive the car as a transport mode is compared to taking public transport, solely based on travel time. Other aspects, such as the impact of transport mode on the environment, costs of transport mode, flexibility offered by transport mode, are not taken into consideration. The equation for average car attractiveness equals the sum of the three products of car attractiveness per area by the labor force participants commuting by car in the area (so for each area (central, ring, outer) the product of car attractiveness and the labor force participants commuting by car is determined and these three values are summed together). The resulting value is then divided by the total labor force participants commuting by car. By calculating the average car attractiveness this way the relative contribution of each area to the average car attractiveness is taken into account. This is important as the relative shares of labor force participants traveling by car are not equal across the arrayed areas.
Average congested travel time by car per trip
Equation average_normal_travel_time_by_car_per_trip*effect_of_relative_congestion_on_travel_time **Unit** minutes/trip **Documentation** The arrayed variable average congested travel time by car per trip represents the average time it takes in minutes per trip to travel from the current location to the destination (the home or work location) by car for each area while taking congestion into account.

The equation for average congested travel time by car per trip is the same for each of the arrayed areas and equals the product of the average normal travel time by car per trip, by the effect of relative congestion on travel time. As the effect of relative congestion on travel time will not return a value lower than 1, the travel time will not decrease below the average normal travel time by car per trip. Due to this a MAX function is not required here to ensure that the travel time will not become too low as even when there is no congestion, it will take some time to travel from the current location to the destination.
Average normal travel time by car per trip
Equation [CENTRAL] 7 [RING] 15 [OUTER] 30 **Unit** minutes/trip **Documentation** The arrayed variable average normal travel time by car per trip represents the average time it takes in minutes per trip to travel from the current location to the destination (the home or work location) by car for each area. The value for each area (central, ring, outer) is determined based on the average indicated travel time by Google Maps when opting for transport by car. For each area (central, ring, outer), multiple points of departure with the destination of central The Hague were explored in Google Maps and an average travel time by car value is calculated based on the travel times indicated by Google Maps. When measuring the traffic situation was not congested, as such the values for the average normal travel time by car per trip can be considered to be relative to 2001.
Average normal travel time by public transport
Equation average_travel_time_by_public_transport_per_trip **Unit** minutes/trip **Documentation** The arrayed variable average normal travel time by public transport per trip represents the average time it takes in minutes per trip to travel from the current location to the destination (the home or work location) by public transport for each area. The equation for average normal travel time by public transport per trip is the same for each area and equals the value of the stock average travel time by public transport per trip, the initial value of which for each area (central, ring, outer) is determined based on the average indicated travel time by Google Maps when opting for public transport. For each area (central, ring, outer), multiple points of departure with the destination of central The Hague were explored in Google Maps and an average travel time by public transport value is calculated based on the travel times indicated by Google Maps. When the public transport policy is not switched on, or the policy status is inactive, this value will not change.
Car attractiveness
Equation average_normal_travel_time_by_public_transport_per_trip/ average_congested_travel_time_by_car_per_trip **Unit** dmnl **Documentation** The arrayed variable car attractiveness represents a relative measure indicating how attractive the car as a transport mode is compared to taking public transport, solely based on travel time, for each area. Other aspects, such as the impact of transport

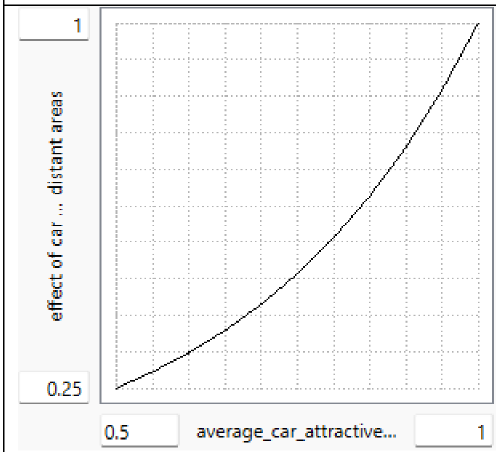
mode on the environment, costs of transport mode, flexibility offered by transport mode, are not taken into consideration.

The equation for car attractiveness is the same for each of the arrayed areas and equals the division of the average normal travel time by public transport per trip by the average congested travel time by car per trip.

When the average normal travel time by public transport per trip equals the average congested travel time by car per trip, then the car attractiveness will equal 1. Both transport modes are equally attractive based solely on travel time.
When the average normal travel time by public transport per trip is lower than the average congested travel time by car per trip, then the car attractiveness will equal a value lower than 1. Public transport will be considered as a more attractive transport mode than car based solely on travel time, and through an effect will influence the fraction of the labor force opting for either transport mode.
When the average normal travel time by public transport per trip is higher than the average congested travel time by car per trip, then the car attractiveness will equal a value higher than 1. The car will be considered as a more attractive transport mode than public transport based solely on travel time, and through an effect will influence the fraction of the labor force opting for either transport mode.

Of course, when the car is considered to be more attractive, more people will opt for the car as transport mode.

Effect of car attractiveness on relative attractiveness distant areas

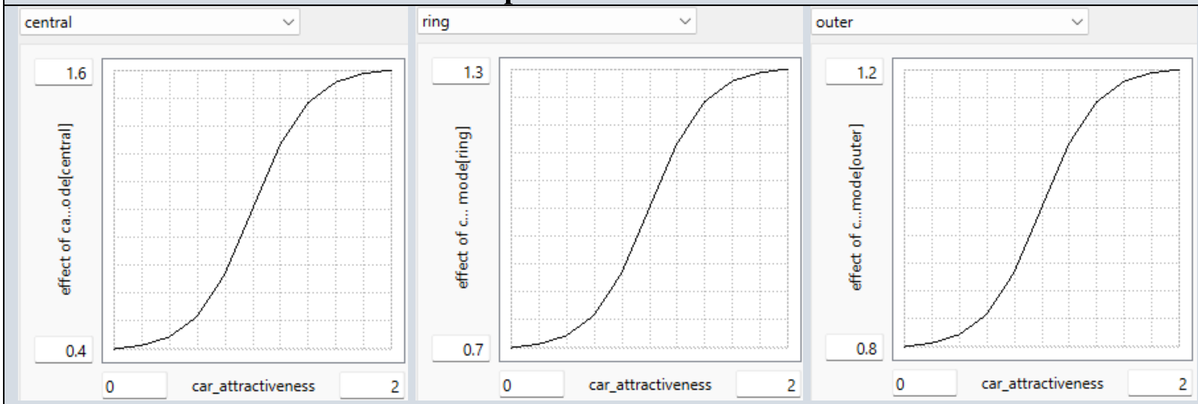


Equation GRAPH(average_car_attractiveness) Points: (0.5000, 0.2500), (0.5500, 0.2835), (0.6000, 0.3227), (0.6500, 0.3685), (0.7000, 0.4222), (0.7500, 0.4849), (0.8000, 0.5584), (0.8500, 0.6443), (0.9000, 0.7448), (0.9500, 0.8624), (1.0000, 1.0000)
Unit dmnl
Documentation This graphical function represents the effect of car attractiveness on the relative attractiveness of distant areas. As it is predominantly the expanding road network that facilitates people to locate themselves further away from places of interest (OECD, 2021) it is assumed that when car attractiveness increases above 1, the attractiveness of distant areas does not necessarily increase too. When the car as a transport mode was relatively new, increasing car attractiveness might have aided the expanding road network in working to increase the attractiveness of distant areas. However, as the starting point of this simulation is the year 2001 where the car as a transport mode was already heavily engrained in our commuting behavior, increasing car attractiveness is not expected to make

much of a difference in aiding the effect expanding road network has on the attractiveness of distant areas.

However, when car attractiveness decreases below 1, meaning that public transport is a more attractive option compared to the car, the attractiveness of distant areas is assumed to decrease as well as public transport is usually easier accessible in central areas compared to outer areas (OECD, 2018). As the car attractiveness decreases from 1 to 0.5, the effect of car attractiveness on relative attractiveness distant areas decreases from 1 to 0.25. The lower the car attractiveness becomes, the less attractive distant areas become as well. It is assumed that when the car attractiveness decreases from 1 to 0.5, initially the effect of car attractiveness on the relative attractiveness of distant areas decreases faster. However, the lower the car attractiveness becomes, small changes will make less of a difference. The effect is not assumed to decrease to 0, as there is public transport available in distant areas (even though this might be less accessible compared to the central area).

Effect of car attractiveness on transport mode



Equation
[CENTRAL] GRAPH(car_attractiveness) Points: (0.000, 0.400), (0.200, 0.4152), (0.400, 0.4521), (0.600, 0.5398), (0.800, 0.7211), (1.000, 1.000), (1.200, 1.279), (1.400, 1.460), (1.600, 1.548), (1.800, 1.585), (2.000, 1.600)
[RING] GRAPH(car_attractiveness) Points: (0.000, 0.7000), (0.200, 0.7076), (0.400, 0.7260), (0.600, 0.7699), (0.800, 0.8606), (1.000, 1.0000), (1.200, 1.1390), (1.400, 1.2300), (1.600, 1.2740), (1.800, 1.2920), (2.000, 1.3000)
[OUTER] GRAPH(car_attractiveness) Points: (0.000, 0.8000), (0.200, 0.8051), (0.400, 0.8174), (0.600, 0.8466), (0.800, 0.9070), (1.000, 1.0000), (1.200, 1.0930), (1.400, 1.1530), (1.600, 1.1830), (1.800, 1.1950), (2.000, 1.2000)
Unit dmnl
Documentation This arrayed graphical function represents the effect of car attractiveness on transport mode. The shape of the graphical function is the same for each of the arrayed areas, however the upper and lower bounds of the graphical function is different for each of the arrayed areas as they are adjusted to the normal fraction of the labor force commuting by car. This is done because that fraction should not be able to become higher than 100% subtracted by the percentage of labor force participants commuting by other means than car or public transport.

Furthermore, as public transport is usually easier accessible in central areas compared to outer areas (OECD, 2018), it is assumed that the difference between the upper and lower bound of the graphical function can be bigger for the central area compared to the ring area and in turn compared to the outer area, as a higher accessibility of the transport modes public transport and car makes it easier to actually change the transport mode when one becomes more attractive compared to the other.

When car attractiveness equals 1, the effect of car attractiveness on transport mode will also equal 1 and the fraction of labor force commuting by car will take its normal value.
When car attractiveness is lower than 1, which would indicate that public transport is a more attractive mode of transport based on travel time compared to the car, the fraction of labor force commuting by car should take on a value for each of the arrayed areas lower than the normal value. As such, when car attractiveness decreases from 1 to 0, the effect of car attractiveness on transport mode decreases decreasingly. The values varying for the three arrayed areas (central, ring, outer). The lower the car attractiveness becomes, small changes will make less of a difference. Also, the lower bounds will not reach 0 as there will always be a fraction of the labor force that chooses to commute by car.
When car attractiveness is higher than 1, which would indicate that the car is a more attractive mode of transport based on travel time compared to public transport, the fraction of labor force commuting by car should take on a value for each of the arrayed areas higher than the normal value. As such, when car attractiveness increases from 1 to 2, the effect of car attractiveness on transport mode increases decreasingly. The values varying for the three arrayed areas (central, ring, outer). The higher the car attractiveness becomes, small changes will make less of a difference. Also, the upper bounds are chosen so that there will always be a fraction of the labor force that chooses to commute by public transport.

Fraction of labor force commuting by car

Delay converter
Equation DELAYN(normal_fraction_of_labor_force_commuting_by_car*
effect_of_car_attractiveness_on_transport_mode, time_to_change_transport_mode,
1,
initial_fraction_of_labor_force_commuting_by_car)
Unit dmnl
Documentation The arrayed variable fraction of labor force commuting by car represents the fraction of the labor force per area (central, ring, outer) that commutes by car.

As the destinations generally have a closer proximity for people living in the central area compared to the ring area, and in turn for people living in the ring area compared to the outer area, the fraction of labor force commuting by car is much higher for the outer area compared to the ring area and in turn compared to the central area.

The equation for this variable contains a DELAY function. A delay was chosen instead of a smooth as the fraction represents a part of the regional labor force population per area, and bluntly distinguished people are more like material as they are tangible than they are like intangible information. The DELAY function was necessary to implement in order to solve the circularity error which would arise if the equation was merely stated as the product of the normal fraction of labor force commuting by car, by the effect of car attractiveness on transport mode. Nevertheless, the DELAY function is also applicable as it takes time to change the transport mode used for commuting and the fraction can thus be seen as a stock variable. However, the time to change the transport mode is quite small when taking the entire simulation duration into account.

Due to the same circularity issue, the initial fraction of labor force commuting by car had to be written exogenous instead of the product of the normal fraction of labor force commuting by car, by the effect of car attractiveness on transport mode. However, as the normal fraction illustrates the situation where car and public transport are equally attractive, which is not the case in the initial situation, the effect of car attractiveness relative to public transport has to be taken into account in the initialization of the fraction of the labor force commuting by car.

Fraction of labor force commuting by other means

Equation
[CENTRAL] 0.65
[RING] 0.5
[OUTER] 0.05
Unit dmnl
Documentation The arrayed variable fraction of labor force commuting by other means represents the fraction of the labor force per area (central, ring, outer) that commutes by other means than by public transport or by car, other means transport modes include for example cycling and walking.

As the destinations generally have a closer proximity for people living in the central area compared to the ring area, and in turn for people living in the ring area compared to the outer area, it is no surprise that the fraction of labor force commuting by other means is much higher for the central area compared to the ring area and in turn compared to the outer area. The value of fraction of labor force commuting by other means for each area (central, ring, outer) is derived of data from Den Haag (2022).

For simplification purposes the model assumes that this fraction will not change. As such, changes in transport mode only happen in the distribution between the fraction of labor force commuting by public transport and the fraction of labor force commuting by car.

Fraction of labor force commuting by public transport

Equation MIN(1-fraction_of_labor_force_commuting_by_other_means, MAX(0, 1-fraction_of_labor_force_commuting_by_other_means-fraction_of_labor_force_commuting_by_car))
Unit dmnl
Documentation The arrayed variable fraction of labor force commuting by public transport represents the fraction of the labor force per area (central, ring, outer) that commutes by public transport.

The equation for fraction of labor force commuting by public transport is the same for each of the arrayed areas and contains both a MIN and MAX function.

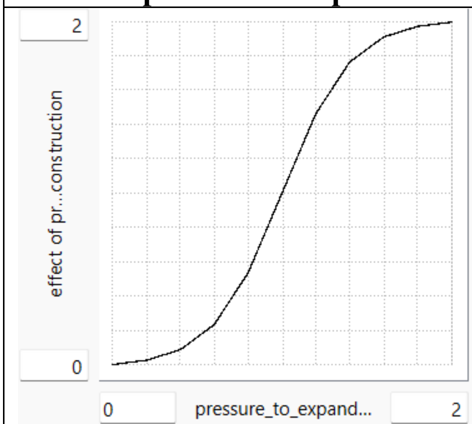
The MIN and MAX functions ensure that the total fraction transport modes will always equal 1, which it should, and that the fraction of labor force commuting by public transport does not go over its upper or lower bound. The MIN function ensures that the fraction of labor force commuting by public transport is equal to either 1 subtracted by the fraction of the labor force commuting by other means (which is constant in this model), or the result of the MAX function. It will return the value which is lowest, as such ensuring the fraction will not go over the upper bound. The MAX function ensures that the fraction of labor force commuting by public transport is equal to either 0, or equal to 1 subtracted by the fraction of the labor force commuting by other means and subtracted by the fraction of the labor force commuting by car. It will return the value which is highest, as such ensuring the fraction will not go under the lower bound.

Due to how the variable effect of car attractiveness on transport mode is formulated, this fraction will always return 1 subtracted by the fraction of the labor force commuting by other means and subtracted by the fraction of the labor force commuting by car. Nevertheless, in extreme conditions the MIN and MAX formulations are necessary. Even though the value for this variable is determined by an equation, the value it returns (initially) corresponds with data from Den Haag (2022).
Initial fraction of labor force commuting by car
Equation [CENTRAL] 0.22 [RING] 0.39 [OUTER] 0.9 **Unit** dmnl **Documentation** The arrayed variable initial fraction of labor force commuting by car is constructed to solve the circularity error when initializing the fraction of labor force commuting by car in its normal value multiplied by the effect of car attractiveness. The normal fraction illustrates the situation where car and public transport are equally attractive, however in the initial situation this is not the case. As such, the effect of car attractiveness relative to public transport has to be taken into account. An indication for the value for the initial fraction of the labor force commuting by car is derived of data from Den Haag (2022) for each area and then calibrated to data for the relative congested travel time (Loop & Hamersma, 2018; Tomtom, 2023).
Labor force participants commuting by car
Equation regional_labor_force_per_area*fraction_of_labor_force_commuting_by_car **Unit** person **Documentation** The arrayed variable labor force participants commuting by car represents the amount of labor force participants per area (central, ring, outer) that are commuting by the transport mode car. Thus it is the amount of people per area who generally travel to and from work by car. The equation for labor force participants commuting by car is the same for each of the arrayed areas and equals the product of the regional labor force per area by the fraction of the labor force commuting by car.
Labor force participants commuting by car per vehicle
Equation labor_force_participants_per_vehicle **Unit** person/vehicle **Documentation** The variable labor force participants commuting by car per vehicle represents the average amount of people commuting in one vehicle. In The Netherlands almost all labor force participants who commute by car, commute alone (Geuze, 2017). The value for labor force participants commuting by car per vehicle equals the value of the stock labor force participants per vehicle, the initial value of which equals 1 person per vehicle. When the carpooling policy is not switched on, or the policy status is inactive, this value will not change.
Normal fraction of labor force commuting by car
Equation [CENTRAL] 0.15 [RING] 0.3 [OUTER] 0.75

Unit dmnl **Documentation** The arrayed variable normal fraction of labor force commuting by car represents the fraction of the labor force per area commuting by car in the situation where car and public transport are equally attractive based on travel time. An indication of the value for the normal fraction of the labor force commuting by car is derived of data from Den Haag (2022).
Time to change transport mode
Equation 1 **Unit** year **Documentation** The variable time to change transport mode represents the time it takes for labor force participants to change the transport mode (car or public transport) they use when commuting. For structural behavior change it is assumed that the time to change transport mode equals 1 year.
Total cars used in region for labor commuting
Equation total_labor_force_participants_commuting_by_car/ labor_force_participants_commuting_by_car_per_vehicle **Unit** vehicle **Documentation** The variable total cars used in region for labor commuting represents the total amount of cars that are used by labor force participants who travel by car to commute to and from work. The equation for total cars used in region for labor commuting equals the division of the total labor force participants commuting by car by the labor force participants commuting by car per vehicle. Thus it equals the total labor force participants commuting by car divided by the average amount of people commuting in one vehicle.
Total fraction transport modes
Summing converter **Equation** fraction_of_labor_force_commuting_by_other_means + fraction_of_labor_force_commuting_by_public_transport + fraction_of_labor_force_commuting_by_car **Unit** dmnl **Documentation** The arrayed variable total fraction transport modes represents the total fraction of transport modes used per area by labor force participants when commuting. As this model differentiates three transport modes, being car, public transport and other means, the total fraction of transport modes should equal 1 - meaning 100% - for each of the areas (central, ring, outer). As such, all labor force participants that commute have chosen a mode of transport. The equation for total fraction transport modes is the same for each of the arrayed areas and equals the sum of the fraction of labor force commuting by other means, fraction of labor force commuting by public transport, and the fraction of labor force commuting by car.
Total labor force participants commuting by car
Equation B SUM(labor_force_participants_commuting_by_car) **Unit** person **Documentation** The variable total labor force participants commuting by car represents the total amount of labor force participants that are commuting by the transport mode car. Thus it is the total amount of people who generally travel to and from work by car.

The equation for total labor force participants commuting by car equals the sum of the labor force participants commuting by car in all three areas being The Hague central, ring and outer.
CONGESTION SECTOR
Acceptable congested speed
Equation average_speed_limit/acceptable_relative_congestion_measure **Unit** km/hour **Documentation** As it is unrealistic to never have congestion, some congestion is regarded acceptable. The arrayed variable acceptable congested speed represents the average speed in kilometers per hour which is still acceptable to obtain. When this average speed can be obtained, even though there is some congestion in reality, the traffic situation will not be perceived as congested as it is within the acceptable congestion range (Rijkswaterstaat, 2022). The equation for acceptable congested speed is the same for each of the arrayed areas and equals the division of the average speed limit by the acceptable relative congestion measure.
Acceptable relative congestion measure
Equation 1.75 **Unit** dmnl **Documentation** As it is unrealistic to never have congestion, some congestion is regarded acceptable. According to the Structuurvisie Infrastructuur en Ruimte an acceptable average congested travel time on connecting highways (national roads) is a maximum of 1.5 times the average uncongested travel time where a safe distance between consecutive vehicles can be maintained (Rijkswaterstaat, 2022). As such, if the speed limit is 100 km/hour, a speed of 66 km/hour in a congested situation is still acceptable. For urban roads (provincial roads and local roads) an average congested travel time of maximum 2 times the average uncongested travel time where a safe distance between consecutive vehicles can be maintained is considered as acceptable (Rijkswaterstaat, 2022). As such, if the speed limit is 100 km/hour, a speed of 50 km/hour in a congested situation is still acceptable. Based on roads data (CBS, 2022e) approximately half of the roads in the The Hague region are connecting highways and half are urban roads. As such the maximum acceptable measures for both type of roads (1.5 and 2) can be averaged to determine the average acceptable relative congestion measure, which thus is a dimensionless value of 1.75.
Actual vehicle density on road
Equation total_cars_used_in_region_for_labor_commuting/roads **Unit** vehicle/kilometer **Documentation** The variable actual vehicle density on road represents the vehicle density of actual vehicles on the road. The equation for actual vehicle density on road equals the division of the total cars used in the The Hague region for labor commuting by the amount of roads in kilometers in the region. This will result in a measure with the units vehicles per kilometer.
Actual vehicle density relative to maximum acceptable
Equation actual_vehicle_density_on_road/maximum_acceptable_vehicle_density_on_road **Unit** dmnl **Documentation** B The variable actual vehicle density relative to maximum acceptable represents a congestion measure.

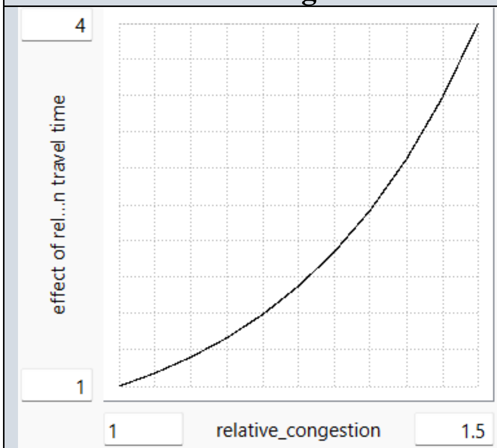
The equation for actual vehicle density relative to maximum acceptable is equal to the division of the actual vehicle density on road by the maximum acceptable vehicle density on road. When the actual vehicle density on road is equal to the maximum acceptable vehicle density on road, then this variable will return a value of 1. The traffic situation will not be perceived as congested as it is within the acceptable congestion range (Rijkswaterstaat, 2022). When the actual vehicle density on road is lower than the maximum acceptable vehicle density on road, then this variable will return a value lower than 1. The traffic situation will not be perceived as congested as it is within the acceptable congestion range (Rijkswaterstaat, 2022). When the actual vehicle density on road is higher than the maximum acceptable vehicle density on road, then this variable will return a value higher than 1. The traffic situation will be perceived as congested as it is not within the acceptable congestion range (Rijkswaterstaat, 2022).
Average distancing
Equation ((distancing_between_consecutive_vehicles[central]*labor_force_participants_commuting_by_car[central])+ (distancing_between_consecutive_vehicles[ring]*labor_force_participants_commuting_by_car[ring])+ (distancing_between_consecutive_vehicles[outer]*labor_force_participants_commuting_by_car[outer]))/ total_labor_force_participants_commuting_by_car **Unit** meter/vehicle **Documentation** The variable average distancing represents the minimum acceptable average distance between consecutive vehicles in meter per vehicle. The equation for average distancing equals the sum of the three products of distancing between consecutive vehicles per area by the labor force participants commuting by car in the area (so for each area (central, ring, outer) the product of the distancing between consecutive vehicles and the labor force participants commuting by car is determined and these three values are summed together). The resulting value is then divided by the total labor force participants commuting by car. By calculating the average distancing this way the relative contribution of each area to the average distancing is taken into account. This is important as the relative shares of labor force participants traveling by car are not equal across the arrayed areas.
Average length car
Equation 4 **Unit** meter/vehicle **Documentation** The average length of a normal car is approximately 4 meters per vehicle (TDnieuws, n.d.).
Average speed limit
Equation [CENTRAL] 30 [RING] 45 [OUTER] 60 **Unit** km/hour

Documentation The arrayed variable average speed limit represents the average speed limit by car per area. Based on the type of roads in the area, the values for average speed limit for each area is estimated. Three types of roads are generally distinguished in The Netherlands (with the exclusion of waterways) being national roads, provincial roads and local roads (Rijksoverheid, n.d.). The speed limit on national roads is higher compared to provincial roads, and the speed limit on provincial roads is higher compared to local roads. As the outer area contains more national roads compared to the ring area, and the ring area contains more provincial roads compared to the central area, the average speed limit for the outer area is estimated to be higher compared to the ring area, and the average speed limit for the ring area is estimated to be higher compared to the central area.
Congestion deflator to 2001 level
Equation HISTORY(actual_vehicle_density_relative_to_maximum_acceptable, 2001) **Unit** dmnl **Documentation** As the reference mode for relative travel time derived from Loop & Hamersma (2018) and Tomtom (2023) represents a relative value where the year 2001 equals 100%, the congestion as determined by the model has to be made relative to the year 2001 as well. When determining the real GDP based on the nominal GDP, a GDP deflator is used. For determining the relative congestion (relative to what is acceptable and relative to the 2001 level), the same deflator principle is applied, but the congestion deflator value will not change over time as a GDP deflator does. This variable congestion deflator to 2001 level represents the congestion deflator. The equation is a HISTORY function and equals the value that the actual vehicle density relative to the maximum acceptable has in the year 2001.
Distancing between consecutive vehicles
Equation acceptable_congested_speed*minimum_distancing_measure **Unit** meter/vehicle **Documentation** The arrayed variable distancing between consecutive vehicles represents the minimum acceptable average distance between consecutive vehicles in meter per vehicle per area (central, ring, outer). As a general rule the minimum distance between two driving vehicles equals approximately half the driving speed where the minimum distance is measured in meters and the driving speed in km/hour (Suzuki, 2017). The equation for distancing between consecutive vehicles is the same for each of the arrayed areas and equals the product of the acceptable congested speed by the minimum distancing measure.
Effect of pressure to expand roads on road construction


Equation GRAPH(pressure_to_expand_roads) Points: (0.000, 0.000), (0.200, 0.02526), (0.400, 0.08682), (0.600, 0.2331), (0.800, 0.5352), (1.000, 1.000), (1.200, 1.465), (1.400, 1.767), (1.600, 1.913), (1.800, 1.975), (2.000, 2.000)
Unit dmnl
Documentation This graphical function represents the effect of pressure to expand roads on road construction. The graphical function is s-shaped. It is assumed that when the pressure to expand roads is decreases from 1 to 0, the road construction rate will be decreased decreasingly towards 0 as well, the flow road construction would then work only to repair the existing road network but new road network will not be constructed.

However, when the pressure to expand roads is higher than 1, this effect will return a value higher than 1 as well and the road construction will be higher than it would normally be without taking the effect of land occupied into account. As the pressure to expand roads increases from 1 to 2, this effect increases decreasingly from 1 to 2. The higher the pressure to expand roads becomes, the more road construction will be expanded. It is assumed that when the pressure to expand roads increases from 1 to 2, initially the effect of pressure to expand roads on road construction increases faster, however the higher the pressure to expand roads becomes the effect increases slower and eventually evens out as there is a limit to how much road construction can be increased per year. The effect is calibrated based on road data from CBS (2022e).

Effect of relative congestion on travel time



Equation GRAPH(relative_congestion) Points: (1.0000, 1.000), (1.0500, 1.108), (1.1000, 1.240), (1.1500, 1.399), (1.2000, 1.593), (1.2500, 1.828), (1.3000, 2.112), (1.3500, 2.457), (1.4000, 2.876), (1.4500, 3.384), (1.5000, 4.000)
Unit dmnl
Documentation This graphical function represents the effect of relative congestion on travel time. According to Asten (2019), travel time will increase exponentially when congestion increases. Asten (2019) further mentions that an increase of approximately 12% in congestion leads to an increase of approximately 25%-30% travel time. The effect is calibrated with this reference point in mind and based on the reference mode for relative travel time derived from Loop and Hamersma (2018) and Tomtom (2023).

The effect of relative congestion on travel time will not return a value lower than 1. When there is no congestion and commuters can reach the speed limit, the travel time will not decrease below the minimum travel time needed to commute from the current location to one's destination.

Effect of travel time on attractiveness distant areas
Equation 1+sensitivity_of_attractiveness_distant_areas_to_congested_travel_time*(relative_congested_travel_time_relative_to_perceived-1) **Unit** dmnl **Documentation** The variable effect of travel time on attractiveness distant areas represents how the attractiveness of distant areas relative to the central The Hague area would change depending on changes in the relative congested travel time relative to perceived. The higher the relative congested travel time relative to perceived, the more people find the distant areas less attractive compared to the central area as it would take a longer time than expected to travel from distant locations to one's destination and back. The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function. When the relative congested travel time relative to perceived equals 1, the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1. When the relative congested travel time relative to perceived equals a value lower than 1 meaning that the relative congested travel time is shorter than perceived, the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1. When the relative congested travel time relative to perceived equals a value higher than 1 meaning that the relative congested travel time is longer than perceived, the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).
Initial perceived relative congested travel time
Equation HISTORY(relative_congested_travel_time, 2001)*0.95 **Unit** dmnl **Documentation** The variable initial perceived relative congested travel time represents a measure for the initial perceived relative travel time in a congested situation. Given the reference mode of behavior showing exponential growth for relative travel time it is assumed likely that before the year 2001 the relative congested travel time was lower than compared to the 2001 level. As it takes time to perceive the relative congested travel time, the initial value for the perceived relative congested travel time is assumed to be approximately 0.95 times the value of the relative congested travel time in 2001 as the perceived value would be closer to the relative congested travel time before the year 2001.

Maximum acceptable vehicle density on road
Equation meters_per_kilometer/space_needed_per_car_on_road **Unit** vehicle/kilometer **Documentation** The variable maximum acceptable vehicle density on road represents the maximum vehicle density of vehicles on the road that is acceptable. As it is unrealistic the never have congestion, some congestion is regarded acceptable. When the vehicle density is equal or lower than the maximum acceptable value, the traffic situation will not be perceived as congested as it is within the acceptable congestion range, even though there is some congestion in reality (Rijkswaterstaat, 2022). When the vehicle density is higher than the maximum acceptable value, the traffic situation will be perceived as congested as it is not within the acceptable congestion range. The equation for maximum acceptable vehicle density on road equals the division of meters per kilometer by the space (in metes per vehicle) needed per car on the road. This will result in a measure with the units vehicles per kilometer, and gives the maximum acceptable vehicle density on the road.
Meters per kilometer
Equation 1000 **Unit** meter/kilometer **Documentation** 1 kilometer equals 1000 meters.
Minimum distancing measure
Equation 0.5 **Unit** (meter/(km/hour))/vehicle **Documentation** As a general rule the minimum distance between two driving vehicles equals approximately half the driving speed where the minimum distance is measured in meters and the driving speed in km/hour (Suzuki, 2017). Each vehicle should maintain this minimum driving distance. For example if all driving vehicles on a road have a speed of 120 km/hour, each vehicle should maintain a minimum distance of 60 meters from the one driving in front. For a speed of 10 km/hour a distance of 5 meters in between all consecutive vehicles should be maintained. As such, the minimum distancing measure can be determined as 0.5 meter per km/hour of speed for each vehicle.
Perceived relative congested travel time
Delay converter **Equation** SMTHN(relative_congested_travel_time, time_to_perceive_relative_congested_travel_time, 1, initial_perceived_relative_congested_travel_time) **Unit** dmnl **Documentation** The variable perceived relative congested travel time represents the perception of the measure for the relative travel time in a congested situation. The measure holds a double relative as the it is relative to what is acceptable and relative to the 2001 level. As it takes time to update one's perception of something the perceived relative congested travel time runs behind the relative congested travel time. The equation for this variable contains a SMTH function. A smooth was chosen instead of a delay as a perception relates to information rather than material.

Pressure to expand roads
Delay converter **Equation** SMTHN(actual_vehicle_density_relative_to_maximum_acceptable, time_to_change_pressure_to_expand_roads, 1, actual_vehicle_density_relative_to_maximum_acceptable) **Unit** dmnl **Documentation** The variable pressure to expand roads represents pressure as perceived by decision makers to extend the road network to accommodate the commuters by car. As congestion increases, pressure on decision makers to expand the road network builds so that congestion might decrease again as there is more road available when the road network is increased (OECD, 2021; Sterman, 2000). The equation for this variable contains a SMTH function. A smooth was chosen instead of a delay as the pressure as perceived by decision makers to extend the road network relates to information rather than material. It is assumed that the pressure builds equal to the congestion as represented by the actual vehicle density relative to the maximum acceptable, however this value is delayed as it takes time to build pressure.
Relative congested travel time
Equation effect_of_relative_congestion_on_travel_time **Unit** dmnl **Documentation** The variable relative congested travel time represents a measure for the relative travel time in a congested situation. The measure holds a double relative as it is relative to what is acceptable and relative to the 2001 level. Note that this is not a measure of travel time in minutes, rather a relative travel time which values have a dimensionless unit. If for example in one year the relative congested travel time has a value of 1.1, this would mean that when compared to the 2001 level, the travel time is now 1.1 times as much due to congestion. So if the travel time in 2001 was 30 minutes per trip, it would now be 33 minutes per trip due to congestion. The equation for relative congested travel time equals the effect of relative congestion on travel time as the normal relative congested travel time would be equal to a dimensionless value of 1 since the model is made relative to the 2001 level. As such a product equation of the effect of relative congestion on travel time by the normal relative congested travel time would be redundant.
Relative congested travel time relative to perceived
Equation relative_congested_travel_time/ perceived_relative_congested_travel_time **Unit** dmnl **Documentation** The variable relative congested travel time relative to perceived represents the ratio between what is perceived to be the relative congested travel time, and what the relative congested travel time actually is currently. This variable is constructed as it is unrealistic to assume that, as the time in the simulation progresses, people compare the actual situation to the initial situation in 2001 - which can be up to 50 years ago as the simulation runs for 50 years. By doing so, the effect of travel

time on the attractiveness of distant areas is based on the actual situation for relative congested travel time relative to the perceived situation. The equation equals the division of the relative congested travel time by the perceived relative congested travel time.
Relative congestion
Equation actual_vehicle_density_relative_to_maximum_acceptable/ congestion_deflator_to_2001_level **Unit** dmnl **Documentation** The variable relative congestion represents a measure of the the actual congestion relative to what is considered acceptable - as determined by the actual vehicle density relative to maximum acceptable - and relative to the 2001 level - due to the congestion deflator. The equation for relative congestion equals the division of the actual vehicle density relative to the maximum acceptable vehicle density by the congestion deflator which is set to the 2001 level. When the relative congestion equals 1, the current congestion is equal to the 2001 level. When the relative congestion is lower than 1, traffic is less congested as it was in 2001. When the relative congestion is higher than 1, traffic is more congested as it was in 2001.
Sensitivity of attractiveness distant areas to congested travel time
Equation -0.4 **Unit** dmnl **Documentation** The variable sensitivity of attractiveness distant areas to congested travel time represents the direction and slope of the effect of travel time on attractiveness distant areas. Thus, it determines how the relative attractiveness of an area changes based on changes in relative congested travel time. The sensitivity has a negative value as it is assumed that the higher the relative congested travel time relative to perceived, the more people find the distant areas less attractive compared to the central areas as it would take a longer time than expected to travel from distant locations to one's destination and back. Due to how the attractiveness areas sector is modeled, this sensitivity variable does not have to be arrayed per area. The value for sensitivity of attractiveness distant areas to congested travel time is calibrated based on population data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022), and on the reference mode for relative travel time derived from Loop and Hamersma (2018) and Tomtom (2023).
Space needed per car on road
Equation average_distancing+average_length_car **Unit** meter/vehicle **Documentation** The variable space needed per car on road represents the minimum space needed on the road in meters per car in an acceptable congested situation (congestion is either equal or lower than what is considered to be acceptable). Each car takes up space on the road and needs to have space to practice safe distancing on vehicles in front of it. As such, the equation for space needed per car on road equals the sum of the average distancing and the average length of a car.
Time to change pressure to expand roads
Equation 5 **Unit** year

Documentation The variable time to change pressure to expand roads represents the time it takes for the pressure to expand roads to build. As it takes time for the population to start exerting pressure, but also for decision makers to feel the pressure that is exerted by the population and to accept it (it takes time for them to distinguish whether it is a structural problem or whether the pressure will decrease on its own), it is assumed that the time to change the pressure to expand roads is approximately 5 years.
Time to perceive relative congested travel time
Equation 5 **Unit** year **Documentation** The variable time to perceive relative congested travel time represents the time it takes for the relative congested travel time to be perceived. As it takes time to determine whether changes in travel time are structural or whether they will go back to a prior situation, it is assumed that the time to perceive relative congested travel time is equal to the time to change pressure to expand roads and thus equals approximately 5 years.
HOUSEHOLDS AND HOUSING SECTOR
Average home lifetime
Equation 100 **Unit** year **Documentation** The average home lifetime is approximately 100 years (Eskinasi, 2014).
Average household to homes ratio for distant areas
Equation (households[outer]+households[ring])/(homes[outer]+homes[ring]) **Unit** household/home **Documentation** The variable average households to homes ratio for distant areas represents the average housing availability for areas outside of central The Hague. Included are the areas ring and outer The Hague. The equation for this variable equals the division of the sum of households for the ring and outer area by the sum of homes in the ring and outer area.
Desired households to homes ratio
Equation 1 **Unit** household/home **Documentation** The desired households to homes ratio represents the desired amount of households per home in the area. Thus it represents the desired housing availability. What is desirable is a matter of perspective. For people looking for a home, it might be more desirable to have a lower than 1 households to homes ratio implying a higher housing availability as it will be easier for them to find a new home. For people selling their home, it might be more desirable to have a higher than 1 households to homes ratio implying a lower housing availability as it will be easier for them to sell their home. As such, the model opts for a middle ground and assumes a desired households to homes ratio of 1 household/home so that in theory there would be a home for each household and there will be no housing shortage or surplus. This is under the assumption that the amount of households per home and homes per household both equal one.
Effect of housing availability on attractiveness distant areas
Equation 1+sensitivity_of_attractiveness_distant_areas_to_housing_availability*(housing_availability_distant_areas_relative_to_central-1) **Unit** dmnl **Documentation** The variable effect of housing availability on attractiveness distant areas represents how the attractiveness of distant areas relative to the central The Hague area

would change depending on changes in the housing availability of distant areas relative to the central area. The higher the housing availability of distant areas relative to the central The Hague area, the more people find the distant areas more attractive compared to the central area as it would be relatively easier for them to find a new home there. This is applicable as The Hague is a thriving region, the opposite would be the case for regions that are emptying too much and becoming a ghost town for example.

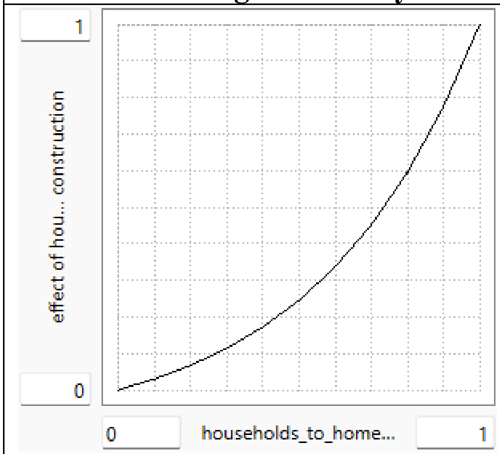
The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function.

When the housing availability of distant areas relative to the central area equals 1, the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1.

When the housing availability of distant areas relative to the central area equals a value lower than 1 meaning that housing is relatively more available in the central area compared to distant areas, the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1.

When the housing availability of distant areas relative to the central area equals a value higher than 1 meaning that housing is relatively more available in distant areas compared to the central area, the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).

Effect of housing availability on home construction



Equation GRAPH(households_to_homes_ratio) Points: (0.000, 0.000), (0.100, 0.02973), (0.200, 0.06696), (0.300, 0.1136), (0.400, 0.172), (0.500, 0.2451), (0.600, 0.3367), (0.700, 0.4513), (0.800, 0.5949), (0.900, 0.7748), (1.000, 1.000)

Unit dmnl
Documentation This graphical function represents the effect of housing availability on home construction and is the same for each of the arrayed areas. In general the housing availability in The Netherlands is considered too low by the Dutch population since the second world war. As such, the construction rate is usually determined by the maximum construction rate possible. However, in areas with a higher housing availability construction of new homes might be somewhat reduced and not meet the maximum construction rate.

Therefore, when the household to homes ratio is higher than 1 - meaning there is a lesser housing availability - this effect will return a value of 1 and the construction rate will equal the maximum construction rate without taking the effect of occupied land into account. This will also be the case when the household to homes ratio is equal to 1.
However, when the household to homes ratio is lower than 1 - meaning there is a higher housing availability - this effect will return a value lower than 1 and the construction rate will be smaller than the maximum construction rate. As the households to homes ratio decreases from 1 to 0, this effect decreases decreasingly from 1 to 0. The smaller the households to homes ratio becomes - and thus the higher housing availability becomes - the less need there is for more homes. It is assumed that when the households to homes ratio decreases from 1 to 0, initially the effect of housing availability on construction decreases faster as construction projects (and its crew) will be implemented in other neighboring areas with a higher need for more homes, however the lower the households to homes ratio becomes, small changes will make less of a difference. The effect is calibrated based on home data from CBS (2023b), DHIC (2023), DIC (2023), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023).

Effect of housing availability on net migration

Equation 1+sensitivity_of_net_migration_to_housing_availability*(households_to_homes_ratio/desired_households_to_homes_ratio-1)
Unit dmnl
Documentation The arrayed variable effect of housing availability on net migration represents how the normal net migration of the area would change depending on changes in housing availability. The higher the housing availability (thus the lower the households to homes ratio), the more people want to migrate in to the area.

The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function.

When the households to homes ratio equals the desired households to homes ratio (and thus equals 1), the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1.

When the households to homes ratio is lower than the desired households to homes ratio (and thus equals a value lower than 1), the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1.

When the households to homes ratio is higher than the desired households to homes ratio (and thus equals a value higher than 1), the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).

Fraction of multifamily homes

Equation
[CENTRAL] 0.85
[RING] 0.65
[OUTER] 0.35
Unit dmnl
Documentation Not all homes are single family homes. This does not mean that multiple families live together in one home, however it does mean that a dwelling can consist of multiple homes for multiple families. For example, an apartment building is a multifamily home while a typical terraced house is a single family home. It is important to make this distinction as in multifamily homes, the homes are built on top of each other and do not take up as much space as they would do if they were all built on ground floor level.

As such, the arrayed variable fraction multifamily homes represents the fraction of the total homes in a specific area that are part of a multifamily home building. The values for each area (central, ring, outer) are derived from AlleCijfers (2023) and DHIC (2023).

In the central The Hague area there are far more multifamily homes than there are single family homes. In the ring The Hague area there are also more multifamily homes than there are single family homes, however the difference between the two fractions (multifamily versus single family) is smaller. In the outer The Hague area there are less multifamily homes than there are single family homes.

Home construction

Equation homes*home_construction_rate
Unit home/year
Documentation The arrayed flow home construction represents the homes that are being constructed per year for each area (central, ring, outer). It is the rate at which the stock homes increases per year.

The equation for this flow is the same for each arrayed area and equals the product of the homes in the area by the construction rate.

Home construction rate

Equation maximum_home_construction_rate*
effect_of_land_fraction_occupied_on_home_construction*
effect_of_housing_availability_on_home_construction
Unit dmnl/year
Documentation The arrayed variable construction rate represents the actual amount of homes per home in the area (central, ring, outer) that will be constructed each year. The units thus being home/home/year, which is the same as dmnl/year. The construction rate will equal the maximum construction rate when the effects of land occupied and housing availability do not limit the construction and both effects equal 1.

When there is enough housing availability, then there is less need for construction. And when there is not enough land left to construct new homes on, then there is less opportunity for construction. As such, both effects can limit - but not increase - the construction rate.

The equation for construction rate is the same for each of the arrayed areas and equals the product of the maximum construction rate by the effect of land fraction occupied on home construction and by the effect of housing availability on home construction.

Home demolition

Equation homes/average_home_lifetime
Unit home/year
Documentation The arrayed flow home demolition represents the homes that are being demolished per year for each area (central, ring, outer). It is the rate at which the stock homes decreases per year.

The equation for this flow is the same for each arrayed area and equals the division of the homes in the area by the average home lifetime.

Homes

Equation homes[area](t - dt) + (home_construction[area] - home_demolition[area]) * dt
Properties INIT homes[area] = initial_homes
Unit home
Documentation The arrayed stock homes represents the amount of homes for a specific area. The stock is arrayed by the dimension area with the elements The Hague central area, The Hague ring area and The Hague outer area.

The stock is increased by the flow home construction and depleted by the flow home demolition. When home construction is equal to home demolition, the stock homes will not change. When home construction is higher than home demolition, the stock homes will increase. When home construction is lower than home demolition, the stock homes will decrease.

The initial value of homes for each area (central, ring, outer) is calibrated based on data of CBS (2023b), DHIC (2023), DIC (2023), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023).

Homes occupying land area

Equation multifamily_homes_occupying_land_area+single_family_homes
Unit home
Documentation The arrayed variable homes occupying land area represents the total amount of homes that actually occupy land in the area (central, ring, outer). This variable takes both horizontally distributed homes (for example terraced homes) and vertically distributed homes (for example apartments) into account.

The equation for this variable is the same for each arrayed area and equals the sum of the single family homes and the multifamily homes occupying land area.

Homes per multifamily home

Equation
[CENTRAL] 4
[RING] 3
[OUTER] 2
Unit home/home
Documentation The arrayed variable homes per multifamily home represents the average

amount of homes that are built on top of each other but on ground floor level take up the space of one home. Thus, it represents the floors per building for multifamily homes. A value of four home/home for example means that four homes (for example apartments) are stacked on top of each other, and that the building would consist of four floors where each home occupies one floor. In that case four homes would only take up the space of one home as they are stacked vertically and not distributed horizontally. As such, the land area occupied needs to be corrected for vertically built multifamily homes. The multifamily homes in the central area are assumed to be higher when compared to the ring area, and in its turn the outer area (for example a high rise flat versus an upstairs/downstairs apartment).
Households
Equation population/persons_per_household **Unit** household **Documentation** The arrayed variable households represents the amount of households residing in an area (central, ring, outer). The equation for this variable is the same for each arrayed area and equals the division of the population of the area by the average amount of people per household in that area.
Households to homes ratio
Equation households/homes **Unit** household/home **Documentation** The arrayed variable households to homes ratio represents the housing availability for each of the arrayed areas. The equation for this variable is the same for each arrayed area and equals the division of the households in the area by the homes in that area. When the households to homes ratio equals 1, then the amount of households in the area (central, ring, outer) equals the amount of homes there are available for households to live in. When the households to homes ratio is lower than 1, then there are less households in the area than there are homes. This would mean that there is a "surplus" of homes. Finding a new home can be easier for households as it otherwise would be. There is more housing availability. Furthermore, as homes are considered to be available, construction of new homes can be decreased. When the households to homes ratio is higher than 1, then there are more households in the area than there are homes. This would mean that there is a "shortage" of homes. Finding a new home can be more difficult for households as it otherwise would be. There is less housing availability. Furthermore, as homes are considered to be less available, construction of new homes should equal the maximum construction rate. This is under the assumption that the amount of households per home and homes per household both equal one.
Housing availability distant areas relative to central
Equation households_to_homes_ratio[central]/ average_household_to_homes_ratio_for_distant_areas **Unit** dmnl **Documentation** The variable housing availability distant areas relative to central represents

the housing availability in more distant areas including ring and outer The Hague in comparison to the housing availability in central The Hague. The equation for this variable equals the division of the households to homes ratio for the central The Hague area by the average households to homes ratio for distant areas. When the households to homes ratio for central The Hague equals the average households to homes ratio for distant areas, then the housing availability in the areas is the same and this variable will return a value of 1. When the households to homes ratio for central The Hague is lower than the average households to homes ratio for distant areas, then there is a higher housing availability in the central area compared to the distant areas and this variable will return a value lower than 1. It would be relatively easier to find a home in the central The Hague area compared to more distant areas. When the households to homes ratio for central The Hague is higher than the average households to homes ratio for distant areas, then there is a lower housing availability in the central area compared to the distant areas and this variable will return a value higher than 1. It would be relatively easier to find a home in the more distant The Hague areas compared to the central area.
Initial homes
Equation [CENTRAL] 45500 [RING] 235000 [OUTER] 132500 **Unit** home **Documentation** The initial value of the arrayed stock homes for each area (central, ring, outer) is calibrated based on data of CBS (2023b), DHIC (2023), DIC (2023), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023).
Maximum home construction rate
Equation maximum_normal_home_construction_rate* effect_of_road_network_on_home_construction **Unit** dmnl/year **Documentation** The arrayed variable maximum construction rate represents the maximum amount of homes per home in the area (central, ring, outer) that can be constructed each year. The unit thus being home/home/year, which is the same as dmnl/year. This maximum construction rate equals the maximum normal construction rate with construction opportunities created or lost due to changes in the road network taken into account. The equation for maximum construction rate is the same for each of the arrayed areas and equals the product of the maximum normal construction rate by the effect of road network on home construction.
Maximum normal home construction rate
Equation [CENTRAL] 0.016 [RING] 0.016 [OUTER] 0.02 **Unit** dmnl/year **Documentation** The arrayed variable maximum normal home construction rate represents the maximum normal amount of homes per home in the area (central, ring, outer) that can be constructed each year. The unit thus being home/home/year, which is the same as

dmnl/year. This maximum normal home construction rate equals the maximum construction rate as long as the road network remains unchanged and does not create or loose opportunities for construction.

The higher this value, the more homes are being constructed per home in the area each year and the more the stock homes will increase (without taking changes in homes by home demolition into account). The values for the maximum normal construction rate are calibrated based on home data from CBS (2023b), DHIC (2023), DIC (2023), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023). It is further assumed that the maximum normal home construction rate does not change throughout the time horizon of this model.

Multifamily homes

Equation homes*fraction_of_multifamily_homes
Unit home
Documentation The arrayed variable multifamily homes represents the amount of homes per area (central, ring, outer) that are part of a multifamily home building. For example an apartment is a multifamily home as multiple apartments are usually constructed in one apartment building. Note that in that case this variable represents the amount of apartments, and not the amount of apartment buildings.

The equation for this variable is the same for each arrayed area and equals the product of the amount of homes in the area by the fraction of multifamily homes in that area.

Multifamily homes occupying land area

Equation multifamily_homes/homes_per_multifamily_home
Unit home
Documentation The arrayed variable multifamily homes occupying land area represent the amount of ground floor multifamily homes that actually take up space and occupy the land area. Other multifamily homes are built on top of the ground floor multifamily homes, and thus do not take up more space. Thus, this variable takes vertical building into account.

The equation for this variable is the same for each arrayed area and equals the division of the amount of multifamily homes in the area by the amount of homes per multifamily home in that area. Thus for example, the amount of apartments divided by the amount of floors an apartment building has.

Persons per household

Equation
[CENTRAL] 1.95
[RING] 2
[OUTER] 2.6
Unit person/household
Documentation The arrayed variable persons per household represents the amount of people of which a household consists on average. The values for the arrayed areas are derived from data of AlleCijfers (2023), CBS (2022a, 2022b, 2023a), DHIC (2023), DIC (2023), EersteKamer (2022), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023). It is assumed that that the persons per household do not change throughout the time horizon of this model.

Sensitivity of attractiveness distant areas to housing availability

Equation 0.5
Unit dmnl
Documentation The variable sensitivity of attractiveness distant areas to housing availability represents the direction and slope of the effect of housing availability on the

attractiveness of distant areas. Thus, it determines how the relative attractiveness of an area changes based on changes in housing availability.

The sensitivity has a positive value as it is assumed that the higher the housing availability of distant areas relative to the central The Hague area, the more people find the distant areas more attractive compared to the central area as it would be relatively easier for them to find a new home there. This is applicable as The Hague is a thriving region, the opposite would be the case for regions that are emptying too much and becoming a ghost town for example.

Due to how the attractiveness areas sector is modeled, this sensitivity variable does not have to be arrayed per area. The value for sensitivity of attractiveness distant areas to housing availability is calibrated based on population data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022), and on the reference mode for relative travel time derived from Loop and Hamersma (2018) and Tomtom (2023).

Sensitivity of net migration to housing availability

Equation
[CENTRAL] -4
[RING] -2
[OUTER] -1
Unit dmnl
Documentation The arrayed variable sensitivity of net migration to housing availability represents the direction and slope of the effect of housing availability on net migration. Thus, it determines how net migration changes based on changes in housing availability.

The sensitivity has a negative value for all areas as it is assumed that a higher housing availability will lead to more people wanting to migrate towards that area. However as housing availability is modeled as the households to homes ratio, a higher than 1 value in households to homes ratio means that there are more households than homes which would imply a lower housing availability. As such, the negative value is necessary to align the direction of the linear effect function with reality.

The value for the central area is assumed to be higher [higher means a bigger, more negative value] compared to the ring area, and the value for the ring area is assumed to be higher [higher means a bigger, more negative value] compared to the outer area as homes are usually less affordable in the central area and more affordable in the ring and in turn the outer area. As such, net migration is expected to react more strongly to changes in housing availability for the central area compared to the ring and in turn the outer area. When the housing availability decreases, home prices are expected to increase much more in the central area compared to the ring and in turn the outer area (expectation based on changes in housing prices over time for the areas included in this model (AlleCijfers (2023)), which should thus limit migration in to the central area more so than it will limit migration in to the ring and in turn the outer area. As such, changes in housing availability will have a bigger impact on net migration for the central The Hague area compared to the ring area, and in its turn compared to the outer area. The values for the sensitivity of net migration to housing availability are calibrated based on population data for each area (central, ring, outer) from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).

Single family homes

Equation homes*(1-fraction_of_multifamily_homes)
Unit home
Documentation The arrayed variable single family homes represents the amount of homes

per area (central, ring, outer) that are not part of a multifamily home building. Single family homes are distributed horizontally and are not built on top of each other, as such each single family home takes up the space of one home.

The equation for this variable is the same for each arrayed area and equals the product of the amount of homes in the area by 1 minus the fraction of multifamily homes in that area. The latter part of the equation, 1 minus the fraction of multifamily homes, equals the fraction of single family homes out of the total homes in the area.

JOBS AND LABOR FORCE SECTOR

Change in jobs

Equation jobs_in_region*normal_job_growth_rate*
effect_of_labor_force_availability_on_change_in_jobs*
effect_of_land_fraction_occupied_on_change_in_jobs
Unit job/year
Documentation The flow change in jobs represents the adjustment of jobs in the The Hague region by new job creation per year. It is the rate at which the amount of jobs in the The Hague region increases or decreases per year. However, the model is operating under the assumption that the jobs in the region will not decrease (for more information see model documentation for variable effect of labor force availability on change in jobs), as such this flow acts as an inflow only working to maintain or increase the jobs in region stock.

The equation for this flow equals the product of the jobs in the The Hague region by the normal job growth rate by the effects of labor force availability and land fraction occupied on the change in jobs.

Desired jobs per labor force participant

Equation 1
Unit job/person
Documentation The desired jobs per labor force participant represents the desired amount of jobs in the region per person participating in the labor force of the region.

What is desirable is a matter of perspective. For people looking for a job, it might be more desirable to have a higher than 1 job availability as it will be easier for them to find a job. However, this might also indicate a higher workload (as companies have a hard time finding new good employees). For companies looking for new employees, it might be more desirable to have a lower than 1 job availability as it will be easier for them to find new employees. However, less people than normal might want to migrate towards the region due to the competitive nature of the labor market in the region.

As such, the model opts for a middle ground and assumes a desired jobs per labor force participant of 1 job per person so that in theory there would be a job for each labor force participant and there will be no job shortage or surplus. This is under the assumption that the amount of jobs per person and the amount of people per job both equal one.

Effect of job availability on net migration

Equation 1+sensitivity_of_net_migration_to_job_availability*
(jobs_per_labor_force_participant/desired_jobs_per_labor_force_participant-1)
Unit dmnl
Documentation The arrayed variable effect of job availability on net migration represents how the normal net migration of the area would change depending on changes in job availability. The higher the job availability, the more people want to migrate in to the area.

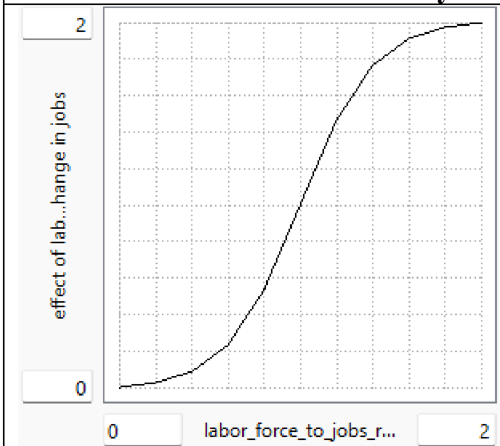
The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function.

When the jobs per labor force participant equals the desired jobs per labor force participant (and thus equals 1), the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1.

When the jobs per labor force participant is lower than the desired jobs per labor force participant (and thus equals a value lower than 1), the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1.

When the jobs per labor force participant is higher than the desired jobs per labor force participant (and thus equals a value higher than 1), the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).

Effect of labor force availability on change in jobs



Equation GRAPH(labor_force_to_jobs_ratio) Points: (0.000, 0.000), (0.200, 0.02526), (0.400, 0.08682), (0.600, 0.2331), (0.800, 0.5352), (1.000, 1.000), (1.200, 1.465), (1.400, 1.767), (1.600, 1.913), (1.800, 1.975), (2.000, 2.000)

Unit dmnl

Documentation This assumed effect of labor force availability on change in jobs is a limitation to the model because the literature reports on effects between unemployment, labor force participation and economic growth in an ambiguous way (Chen, Hsu & Lai, 2016). Nevertheless, there does seem to be a relation between the labor force and job growth which tends towards an enhancement of growth when the labor force increases. As such, the effect as used by Grimeland (2022) is copied into this model and calibrated based on data from CBS (2022c).

When the labor force to jobs ratio equals 1, the effect of labor force availability on change in jobs will also equal 1 and the change in jobs will follow the normal job growth rate (without taking the effect of occupied land into account).
When the labor force to jobs ratio is lower than 1, which would indicate a "shortage" of labor force, new employees are hard to come by which makes it more difficult for businesses to grow. As such, when the labor force to jobs ratio decreases from 1 to 0, the effect of labor force availability on change in jobs decreases decreasingly from 1 to 0 - the lower the labor force to jobs ratio becomes, small changes will make less of a difference.
When the labor force to jobs ratio is higher than 1, which would indicate a "surplus" of labor force, new employees are easier to come by which makes it easier for business to grow. As such, when the labor force to jobs ratio increases from 1 to 2, the effect of labor force availability on change in jobs increases decreasingly from 1 to 2 - the higher the labor force to jobs ratio becomes, small changes will make less of a difference. There is a limit to the growth in jobs.

Furthermore, the model is operating under the assumption that the jobs in the region will not decrease. As The Hague is a thriving region hosting approximately 6% of all jobs in The Netherlands (CBS, 2022c) [while it only holds approximately 0.7% of the total land] and due to the important political nature of the region, the effect of labor force availability on change in jobs ranges from 0 to 2 and will only work to limit the normal job growth when there is a lower than 1 labor force availability but will not go negative (where a negative effect would work to decrease the jobs in the region). As such, without changing the normal job growth rate to a negative value, the jobs in the region will either remain equal or will increase, but not decrease.

Fraction of labor force participating in regional labor force

Equation
[CENTRAL] 0.53
[RING] 0.53
[OUTER] 0.73
Unit dmnl
Documentation The arrayed variable fraction of labor force participating in regional labor force represents the fraction of the labor force which actually participates as a laborer in the The Hague region. This is a very interesting variable. The Netherlands is a country where commuting to your job is more of a rule than an exception. On average in the whole of The Netherlands approximately 50% of the jobs are occupied by people not living in the same municipality where they work (Lewis, 2013). For the The Hague region this percentage is even higher, as approximately 58% of the jobs are occupied by commuters from outside The Hague and only 42% of the jobs are occupied by people living in the municipality (Den Haag, 2022). Note that the outer The Hague area is not part of the The Hague municipality.

Of the working population in central The Hague and its ring, 53% works in the The Hague region and can be considered as part of the regional labor force (Den Haag, 2022). Assuming that approximately half of the remaining jobs are occupied by people from the outer The Hague area, and the rest by people living even further away in municipalities outside of this model boundary, this means that approximately 73% of the working population of the outer area can be included in the regional labor force.

How is this calculated? The sum of the initial The Hague central and ring population equals approximately 568000 people. Of that population, 60% can be included in the labor force, and 53% of that population can be included in the regional labor force, being approximately

180600 people. Those people occupy 42% of the jobs, meaning that approximately 4300 people will occupy 1% of the jobs. Under the assumption that approximately 50% of the remaining 58% jobs is occupied by people from the outer The Hague area, this would mean approximately 125000 people which is approximately 73% of the working population for the outer The Hague area.
Fraction of population included in labor force
Equation 0.6 **Unit** dmnl **Documentation** The variable fraction of population included in labor force represents the fraction of the total population which is included in the labor force. Only the civilian adult population fit to work should be included in the labor force (between 18 and 68 years of age approximately) as children, elderly and adults unfit to work are not participating in the labor force. This fraction is assumed to be 0.6 meaning that 60% of the population is assumed to be included in the labor force. This assumption is based on the national labor force participation rate as estimated by TWB (2023) of approximately 64%, the value in the model is assumed to be a little lower than the national average as some groups of people who are unfit to work [homeless people, heavy drug users, etc.] often reside in the Dutch major cities including The Hague as opposed to smaller towns. It is further assumed that this fraction does not change throughout the time horizon of this model.
Initial jobs in region
Equation 440000 **Unit** job **Documentation** The initial value for the stock jobs in region is calibrated based on data from CBS (2022c).
Jobs in region
Equation jobs_in_region(t - dt) + (change_in_jobs) * dt **Properties** INIT jobs_in_region = initial_jobs_in_region **Unit** job **Documentation** The stock jobs in region represents the amount of jobs in the The Hague region. The stock is adjusted (increased or depleted) by the flow change in jobs. However, the model is operating under the assumption that the jobs in the region will not decrease (for more information see model documentation for variable effect of labor force availability on change in jobs), as such the flow change in jobs acts as an inflow only working to maintain or increase the jobs in region stock. The initial value for the stock jobs in region is calibrated based on data from CBS (2022c).
Jobs per labor force participant
Equation jobs_in_region/regional_labor_force **Unit** job/person **Documentation** The variable jobs per labor force participant represents the job availability in the The Hague region. The equation for this variable is the division of the jobs in the region by the regional labor force. When the jobs per labor force participant equals 1, then the amount of jobs there are available for people equals the amount of people participating in the regional labor force.

When the jobs per labor force participant is lower than 1, then there are less jobs available for people than the amount of people participating in the regional labor force. This would mean that there is a "shortage" in jobs. Finding a job is more difficult in such a situation. When the jobs per labor force participant is higher than 1, then there are more jobs available for people than the amount of people participating in the regional labor force. This would mean that there is a "surplus" in jobs. Finding a job is easier in such a situation. This is under the assumption that the amount of jobs per person and the amount of people per job both equal one.
Labor force to jobs ratio
Equation regional_labor_force/jobs_in_region **Unit** person/job **Documentation** The variable labor force to jobs ratio represents the labor force availability in the The Hague region. The equation for this variable is the division of the regional labor force by the jobs in the region. When the labor force to jobs ratio equals 1, then the amount of people participating in the regional labor force equals the amount of jobs there are available. When the labor force to jobs ratio is lower than 1, then there are less people participating in the regional labor force than there are jobs available. This would mean that there is a "shortage" of labor force. New employees are hard to come by which makes it more difficult for businesses to grow. When the labor force to jobs ratio is higher than 1, then there are more people participating in the regional labor force than there are jobs available. This would mean that there is a "surplus" of labor force. New employees are easy to come by which makes it easier for businesses to grow. This is under the assumption that the amount of jobs per person and the amount of people per job both equal one.
Normal job growth rate
Equation 0.01 **Unit** dmnl/year **Documentation** The variable normal job growth rate represents the amount of jobs that are created each year per job in the The Hague region. The units thus being job/job/year, which is the same as dmnl/year. The higher this value, the more jobs will be created each year per job in the region and the more the amount of jobs in the region will increase (without taking the effects of labor force availability and occupied land into account). The value for this variable is calibrated based on data from CBS (2022c). It is further assumed, that the normal job growth rate does not change throughout the time horizon of this model.
Regional labor force
Equation SUM(regional_labor_force_per_area) **Unit** person **Documentation** The variable regional labor force represents the total amount of people who participate in the labor force in the The Hague region as included in this model and also live in one of the areas being central, ring and outer The Hague. It is equal to the sum of all three of the regional labor forces per subarea.

People who work in The Hague but do not live in one of the areas as included in this model are outside of this model boundary and thus not included in this variable.
Regional labor force per area
Equation population* fraction_of_labor_force_participating_in_regional_labor_force* fraction_of_population_included_in_labor_force **Unit** person **Documentation** The arrayed variable regional labor force per area represents the amount of people participating in the labor force in the The Hague region for each area of interest (central, ring, outer) while also being an inhabitant of that area. Thus it is the amount of people per area who hold a job in the The Hague region as included in this model. The equation for regional labor force per area is the same for each of the arrayed areas and equals the product of the population of that area by the fraction of that population actually included in the labor force, by the fraction of the labor force which practices their job in the The Hague region. People who work in The Hague but do not live in one of the areas as included in this model are outside of this model boundary and thus not included in this variable.
Sensitivity of net migration to job availability
Equation [CENTRAL] 1 [RING] 0.5 [OUTER] 0.25 **Unit** dmnl **Documentation** The arrayed variable sensitivity of net migration to job availability represents the direction and slope of the effect of job availability on net migration. Thus, it determines how net migration changes based on changes in job availability. The sensitivity has a positive value for all areas as it is assumed that a higher job availability will lead to more people wanting to migrate towards that area. The value for the central area is assumed to be higher compared to the ring area, and the value for the ring area is assumed to be higher compared to the outer area as the central The Hague area is identified with more significant career opportunities compared to the ring area, and in its turn compared to the outer area. As such, changes in job availability will have a bigger impact on net migration for the central The Hague area compared to the ring area, and in its turn compared to the outer area. Nevertheless, as The Netherlands is a country of commuters (Lewis, 2013) the slope of the effect is not expected to be very steep. The values of sensitivity of net migration to job availability are calibrated based on population data for each area (central, ring, outer) from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).
LAND SECTOR
Average size home
Equation [CENTRAL] 80 [RING] 100 [OUTER] 130 **Unit** square meter/home **Documentation** The arrayed variable average size home represents the average size of a home per area (central, ring, outer) in square meter. Homes are generally larger in the outer area compared to the ring area, and in turn compared to the central area as generally central

areas are more densely populated compared to ring areas, and in turn outer areas. The values for the average size of a home, including both single family and multifamily homes, for each area are derived from CBS (2022d), LVIC (2023), PNIC (2023), RIC (2023). It is further assumed that the average size of homes does not change throughout the time horizon of this model.

Average width road per area

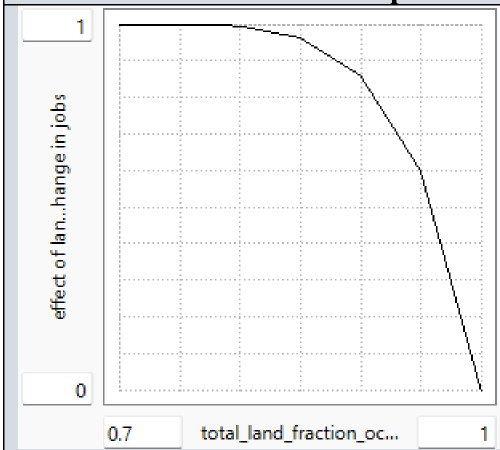
Equation
[CENTRAL] 8
[RING] 16
[OUTER] 20
Unit meter
Documentation Three types of roads are generally distinguished in The Netherlands (with the exclusion of waterways) being national roads, provincial roads and local roads (Rijksoverheid, n.d.). The average width of national roads is broader compared to provincial roads, and the average width of provincial roads is broader compared to local roads.

As the outer area contains more national roads compared to the ring area, and the ring area contains more provincial roads compared to the central area, the average road width for the outer area is estimated to be broader compared to the ring area, and the average road width for the ring area is estimated to be broader compared to the central area.

The value for average width road per area represents the average width of a road per area in meters including space necessary at the sides of roads for safety, and is based on DBI (2012).

It is assumed that the average width of the road per area does not change throughout the time horizon of this model.

Effect of land fraction occupied on change in jobs



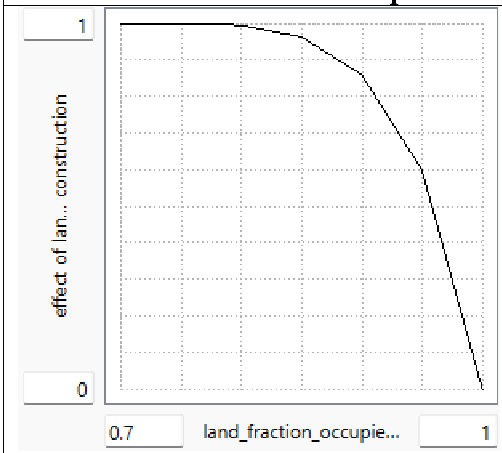
Equation GRAPH(total_land_fraction_occupied) Points: (0.7000, 1.000), (0.7500, 1.000), (0.8000, 0.995), (0.8500, 0.963), (0.9000, 0.860), (0.9500, 0.600), (1.0000, 0.000)
Unit dmnl
Documentation This graphical function represents the effect of total land fraction occupied on change in jobs in the The Hague region.

As long as there is enough land available in the The Hague region to increase the amount of jobs, change in jobs will not be limited by the effect of land fraction occupied. As such, when the total land fraction occupied is smaller than or equal to 0.75 - meaning less than or equal to 75% of all available land for homes, jobs and roads is currently occupied - then this effect will return a value of 1 and the change in jobs flow will not be decreased due to this effect.

However, when the total land fraction occupied is higher than 0.75 - meaning more than 75% of all available land for homes, jobs and roads is currently occupied - then the effect of land fraction occupied on change in jobs will start to decrease. When the total land fraction occupied increases from 0.75 to 1, the effect of land fraction occupied on change in jobs will decrease increasingly from 1 to 0. The effect of land fraction occupied will work to decrease the jobs growth rate so that the change in jobs flow is lower than it otherwise would be. It is assumed that the higher the land fraction occupied becomes, where small changes make a big difference as there is only a limited amount of space available, the effect will decrease faster and faster. When the land fraction occupied equals 1 - meaning that all available land in the The Hague region for homes, jobs and roads is occupied - no growth in jobs can take place anymore and as such the effect of land fraction occupied on change in jobs will return a value of 0 to nullify the jobs growth rate and thereby the change in jobs flow.

As the stock jobs in region is not arrayed but applies to the The Hague region, the effect of land fraction occupied on change in jobs is based on the total land fraction occupied. The effect is similar in shape and values to the effect of land fraction occupied on road construction and the effect of land fraction occupied on home construction, although the latter is arrayed per area.

Effect of land fraction occupied on home construction



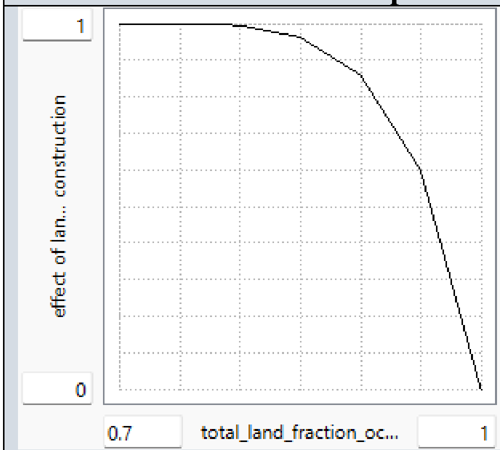
Equation GRAPH(land_fraction_occupied_per_area) Points: (0.7000, 1.000), (0.7500, 1.000), (0.8000, 0.995), (0.8500, 0.963), (0.9000, 0.860), (0.9500, 0.600), (1.0000, 0.000)
Unit dmnl
Documentation This graphical function represents the effect of land fraction occupied per area on the home construction per area. The graphical function is the same for each of the arrayed areas (central, ring, outer).

As long as there is enough land available per area to construct new homes, home construction will not be limited by the effect of land fraction occupied. As such, when the land fraction occupied per area is smaller than or equal to 0.75 - meaning less than or equal to 75% of all available land per area for homes, jobs and roads is currently occupied - then this effect will return a value of 1 and the home construction rate will not be decreased due to this effect.

However, when the land fraction occupied per area is higher than 0.75 - meaning more than 75% of all available land per area for homes, jobs and roads is currently occupied - then the effect of land fraction occupied on home construction will start to decrease. When the land fraction occupied per area increases from 0.75 to 1, the effect of land fraction occupied on home construction will decrease increasingly from 1 to 0. The effect of land fraction occupied will work to decrease the home construction rate so that it is lower than it otherwise would be. It is assumed that the higher the land fraction occupied per area becomes, where small changes make a big difference as there is only a limited amount of space available, the effect will decrease faster and faster. When the land fraction occupied per area equals 1 - meaning that all available land per area for homes, jobs and roads is occupied - no home construction can take place anymore and as such the effect of land fraction occupied on home construction will return a value of 0 to nullify the home construction rate.

As the stock homes is arrayed, the effect of land fraction occupied on home construction is based on the land fraction occupied per area. Nevertheless, the effect is similar in shape and values to the effect of land fraction occupied on road construction and the effect of land fraction occupied on change in jobs.

Effect of land fraction occupied on road construction



Equation GRAPH(total_land_fraction_occupied) Points: (0.7000, 1.000), (0.7500, 1.000), (0.8000, 0.995), (0.8500, 0.963), (0.9000, 0.860), (0.9500, 0.600), (1.0000, 0.000)
Unit dmnl
Documentation This graphical function represents the effect of total land fraction occupied on road construction in the The Hague region.

As long as there is enough land available in the The Hague region to construct roads, road construction will not be limited by the effect of land fraction occupied. As such, when the total land fraction occupied is smaller than or equal to 0.75 - meaning less than or equal to 75% of all available land for homes, jobs and roads is currently occupied - then this effect will return a value of 1 and the road construction flow will not be decreased due to this effect.

However, when the total land fraction occupied is higher than 0.75 - meaning more than 75% of all available land for homes, jobs and roads is currently occupied - then the effect of land fraction occupied on road construction will start to decrease. When the total land fraction occupied increases from 0.75 to 1, the effect of land fraction occupied on road construction will decrease increasingly from 1 to 0. The effect of land fraction occupied will work to decrease the road construction flow so that it is lower than it otherwise would

be. It is assumed that the higher the land fraction occupied becomes, where small changes make a big difference as there is only a limited amount of space available, the effect will decrease faster and faster. When the land fraction occupied equals 1 - meaning that all available land in the The Hague region for homes, jobs and roads is occupied - no road construction can take place anymore and as such the effect of land fraction occupied on road construction will return a value of 0 to nullify the road construction flow. As the stock roads is not arrayed but applies to the The Hague region, the effect of land fraction occupied on road construction is based on the total land fraction occupied. The effect is similar in shape and values to the effect of land fraction occupied on change in jobs and the effect of land fraction occupied on home construction, although the latter is arrayed per area.
Fraction of total jobs per area
Equation [CENTRAL] 0.4 [RING] 0.3 [OUTER] 0.3 **Unit** dmnl **Documentation** The arrayed variable fraction of total jobs per area represents the fraction of the total amount of jobs in the The Hague region per area (central, ring, outer). The fraction of total jobs for the central and ring area combined and the fraction of total jobs for the outer area are derived from jobs data (CBS, 2022c). However, an assumption is made for the distribution of jobs between the central and ring area as more detailed data could not be found. As such it is assumed that for the The Hague city (which includes the entire central The Hague area, but only a part the ring area) approximately 65% of all jobs in The Hague city are practiced in central The Hague, and the remaining 35% of all jobs in The Hague city are practiced in the ring area. This assumption in combination with the jobs data (CBS, 2022c) gives a distribution of jobs of 40% of all jobs in the The Hague region are practiced in the central The Hague area, and 30% of all jobs in the The Hague region are practiced in the ring area, and 30% of all jobs in the The Hague region are practiced in the outer area. It is further assumed that the fraction of total jobs per area does not change throughout the time horizon of this model. This assumption had to be made in order to be able to determine the land fraction occupied per area which influences home construction per area through an effect.
Fraction of total roads per area
Equation [CENTRAL] 0.04 [RING] 0.5 [OUTER] 0.46 **Unit** dmnl **Documentation** The arrayed variable fraction of total roads per area represents the fraction of the total road network in the The Hague region per area (central, ring, outer). The fraction of total roads for the central and ring area combined and the fraction of total roads for the outer area are derived from roads data (CBS, 2022e). However, an assumption is made for distribution of the road network between the central and ring area as more detailed data could not be found. The assumption regarding the distribution of the road network between the central and ring area is based on the land area of the arrayed areas. It is further assumed that the fraction of total roads per area does not change throughout the time

horizon of this model. This assumption had to be made in order to be able to determine the land fraction occupied per area which influences home construction per area through an effect.

Ha per km2

Equation 100
Unit ha/square kilometer
Documentation 1 square kilometer equals 100 hectares.

Land area in ha

Equation
[CENTRAL] 763
[RING] 12140
[OUTER] 14723
Unit ha
Documentation The arrayed variable land area in ha represents the amount of land in hectares per area (central, ring, outer). Water area is not included. The values for each of the arrayed areas are derived from AlleCijfers (2023).

Land area in km2

Equation land_area_in_ha/ha_per_km2
Unit square kilometer
Documentation The arrayed variable land area in km2 represents the amount of land in square kilometers for each area (central, ring, outer). Water area is not included.

The equation for this variable is the same for each area and equals the land area in hectares divided by the amount of hectares per square kilometer.

Land area not eligible for homes, jobs or roads

Equation land_fraction_not_eligible_for_homes_jobs_or_roads*land_area_in_km2
Unit square kilometer
Documentation The arrayed variable land area not eligible for homes, jobs or roads represents the amount of land area in square kilometers for each area that is not eligible for homes, jobs or roads.

The equation for this variable is the same for each area and equals the product of the land area in km2 by the land fraction not eligible for homes, jobs or roads.

Land area occupied by homes

Equation homes_occupying_land_area*(average_size_home/m2_per_km2)
Unit square kilometer
Documentation The arrayed variable land area occupied by homes represents the amount of land area in square kilometer that is occupied by homes per area (central, ring, outer).

The equation for land area occupied by homes is the same for each area and equals the product of the amount of homes that occupy land area by the division of the average size per home in square meters by the amount of square meters per square kilometer.

Land area occupied by jobs

Equation jobs_in_region*fraction_of_total_jobs_per_area*m2_per_job/m2_per_km2
Unit square kilometer
Documentation The arrayed variable land area occupied by jobs represents the amount of land area in square kilometer that is occupied by jobs per area (central, ring, outer).

The equation for land area occupied by jobs is the same for each area and equals the product of jobs in the region by the fraction of total jobs per area, by the division of square meter per job by the amount of square meters per square kilometer.
Land area occupied by roads
Equation roads*fraction_of_total_roads_per_area*average_width_road_per_area/ meters_per_kilometer **Unit** square kilometer **Documentation** The arrayed variable land area occupied by roads represents the amount of land area in square kilometer that is occupied by roads per area (central, ring, outer). The equation for land area occupied by roads is the same for each area and equals the product of roads by the fraction of total roads per area, by the division of the average width of a road per area by the amount of meters per kilometer.
Land fraction not eligible for homes, jobs or roads
Equation [CENTRAL] 0.05 [RING] 0.1 [OUTER] 0.15 **Unit** dmnl **Documentation** Not all available land is eligible for home, business or road construction (homes, jobs or roads). The arrayed variable land fraction not eligible for homes, jobs or roads represents that fraction of the land per area (central, ring, outer). It is assumed that in the outer area, a bigger fraction of the land is not eligible for homes, jobs or roads compared to the ring area, and in its turn compared to the central area. This fraction of land can therefore be viewed as "occupied" as it is not available for homes, jobs or roads.
Land fraction occupied by homes
Equation land_area_occupied_by_homes/land_area_in_km2 **Unit** dmnl **Documentation** The arrayed variable land fraction occupied by homes represents the fraction of land per area (central, ring, outer) which is occupied by homes. The equation for this variable is the same for each area and equals the division of the land area occupied by homes per area by the land area in square kilometers per area.
Land fraction occupied by jobs
Equation land_area_occupied_by_jobs/land_area_in_km2 **Unit** dmnl **Documentation** The arrayed variable land fraction occupied by jobs represents the fraction of land per area (central, ring, outer) which is occupied by jobs. The equation for this variable is the same for each area and equals the division of the land area occupied by jobs per area by the land area in square kilometers per area.
Land fraction occupied by roads
Equation land_area_occupied_by_roads/land_area_in_km2 **Unit** dmnl **Documentation** The arrayed variable land fraction occupied by roads represents the fraction of land per area (central, ring, outer) which is occupied by roads. The equation for this variable is the same for each area and equals the division of the land area occupied by roads per area by the land area in square kilometers per area.

Land fraction occupied per area
Equation land_fraction_not_eligible_for_homes_jobs_or_roads+ land_fraction_occupied_by_homes+ land_fraction_occupied_by_roads+ land_fraction_occupied_by_jobs **Unit** dmnl **Documentation** The arrayed variable land fraction occupied per area represents the fraction of the total land available per area (central, ring, outer) which is being occupied by homes, jobs and roads, or that is not eligible to be occupied by homes, jobs or roads. The higher the land fraction occupied per area, the more land is already build up in the area. The closer the fraction gets to 1, where 1 would mean that all the available land is build up, the less land will be available for additional homes, roads and jobs. As such, when the land fraction occupied per area becomes higher than a certain fraction (in this model this is a fraction of 0.75), then an effect of land fraction occupied will limit the growth of homes, jobs and roads. As such the growth in homes, jobs and roads will be less than it otherwise would be. Eventually, when all available land per area is occupied and the land fraction occupied per area equals 1, then the same effect will ensure that no growth in homes, jobs and roads can take place. The equation for this variable is the same for each area and equals the sum of the land fraction occupied by homes, the land fraction occupied by jobs, the land fraction occupied by roads, and the land fraction not eligible for homes, jobs or roads.
m2 per job
Equation [CENTRAL] 12 [RING] 60 [OUTER] 84 **Unit** square meter/job **Documentation** In the central The Hague area, jobs predominantly consists of office jobs which need less space per job, on average 12m2 (Lansink, 2019). However the type of job which is predominant will differ in the ring and outer areas. In the ring area for example jobs predominantly might consist of industry or shops and in the outer area for example jobs predominantly might consist of farming/working in greenhouses. These types of jobs require more space per job. As such, it is assumed that the space needed per job increases the further away from the central The Hague area. Jobs in the central area require the least amount of space per job, jobs in the outer area require the most amount of space per job, and jobs in the ring area require an amount of space in between those measures (here it is assumed that the ring area requires 5 times the space per job compared to the central area, and the outer area requires 7 times the space per job compared to the central area).
m2 per km2
Equation 1000000 **Unit** square meter/square kilometer **Documentation** 1 square kilometer equals 1 000 000 square meter.
Total land area in km2
Equation SUM(land_area_in_km2) **Unit** square kilometer **Documentation** The variable total land area in km2 represents the amount of land in square kilometers for the The Hague region as included in this model. Water area is not included.

The equation for this variable equals the sum of the land areas in square kilometers for the central, ring and outer area.
Total land area occupied by homes
Equation SUM(land_area_occupied_by_homes) **Unit** square kilometer **Documentation** The variable total land area occupied by homes represents the amount of land area in square kilometer that is occupied by homes in the The Hague region. The equation for total land area occupied by homes equals the sum of the land areas occupied by homes for the central, ring and outer area.
Total land area occupied by jobs
Equation SUM(land_area_occupied_by_jobs) **Unit** square kilometer **Documentation** The variable total land area occupied by jobs represents the amount of land area in square kilometer that is occupied by jobs in the The Hague region. The equation for total land area occupied by jobs equals the sum of the land areas occupied by jobs for the central, ring and outer area.
Total land area occupied by roads
Equation SUM(land_area_occupied_by_roads) **Unit** square kilometer **Documentation** The variable total land area occupied by roads represents the amount of land area in square kilometer that is occupied by roads in the The Hague region. The equation for total land area occupied by roads equals the sum of the land areas occupied by roads for the central, ring and outer area.
Total land fraction not eligible for homes, jobs or roads
Equation (SUM(land_area_not_eligible_for_homes_jobs_or_roads))/ total_land_area_in_km2 **Unit** dmnl **Documentation** The variable total land fraction not eligible for homes, jobs or roads represents the fraction of land for the total The Hague land region which is not eligible for home, business or road construction (homes, jobs or roads). The equation for this variable equals the division of the sum of the land areas not eligible for homes, jobs or roads for the central, ring and outer area, by the total land area in km2.
Total land fraction occupied
Equation total_land_fraction_not_eligible_for_homes_jobs_or_roads+ total_land_fraction_occupied_by_jobs+ total_land_fraction_occupied_by_roads+ total_land_fraction_occupied_by_homes **Unit** dmnl **Documentation** The variable total land fraction occupied represents the fraction of the total land available in the The Hague region which is being occupied by homes, jobs and roads, or that is not eligible to be occupied by homes, jobs or roads. The higher the total land fraction occupied, the more land is already build up in the The Hague region. The closer the fraction gets to 1, where 1 would mean that all the available land is build up, the less land will be available for additional homes, roads and jobs. As such, when the total land fraction occupied becomes higher than a certain fraction (in this model this is a fraction of 0.75), then an effect of land fraction occupied will limit the

growth of homes, jobs and roads. As such the growth in homes, jobs and roads will be less than it otherwise would be. Eventually, when all available land in the The Hague region is occupied and the total land fraction occupied equals 1, then the same effect will ensure that no growth in homes, jobs and roads can take place. The equation for this variable equals the sum of the total land fraction occupied by homes, the total land fraction occupied by jobs, the total land fraction occupied by roads, and the total land fraction not eligible for homes, jobs or roads.
Total land fraction occupied by homes
Equation total_land_area_occupied_by_homes/total_land_area_in_km2 **Unit** dmnl **Documentation** The variable total land fraction occupied by homes represents the fraction of land of the total The Hague region which is occupied by homes. The equation for this variable equals the division of the total land area occupied by homes by the total land area in square kilometers for the The Hague region.
Total land fraction occupied by jobs
Equation total_land_area_occupied_by_jobs/total_land_area_in_km2 **Unit** dmnl **Documentation** The variable total land fraction occupied by jobs represents the fraction of land of the total The Hague region which is occupied by jobs. The equation for this variable equals the division of the total land area occupied by jobs by the total land area in square kilometers for the The Hague region.
Total land fraction occupied by roads
Equation total_land_area_occupied_by_roads/total_land_area_in_km2 **Unit** dmnl **Documentation** The variable total land fraction occupied by roads represents the fraction of land of the total The Hague region which is occupied by roads. The equation for this variable equals the division of the total land area occupied by roads by the total land area in square kilometers for the The Hague region.
POLICIES SECTOR
Average travel time by public transport per trip
Equation average_travel_time_by_public_transport_per_trip[area](t - dt) + (- change_in_average_travel_time_by_public_transport_per_trip[area]) * dt **Properties** INIT average_travel_time_by_public_transport_per_trip[area] = initial_average_travel_time_by_public_transport_per_trip **Unit** minutes/trip **Documentation** The arrayed stock average travel time by public transport per trip represents the average time it takes in minutes per trip to travel from the current location to the destination (the home or work location) by public transport for each area. The public transport policy aims to decrease the average travel time by public transport per trip so that public transport as a transport mode is competitive with the car when looking at travel time. The stock is decreased by the flow change in average travel time by public transport per trip. Through a goal gap formulation over time the stock average travel time by public transport per trip will be decreased downwards to the lower goal of the average congested

travel time by car per trip when the public transport policy is switched on and the policy status is active. The initial value for each area (central, ring, outer) is determined based on the average indicated travel time by Google Maps when opting for public transport. For each area (central, ring, outer), multiple points of departure with the destination of central The Hague were explored in Google Maps and an average travel time by public transport value is calculated based on the travel times indicated by Google Maps.
Carpooling policy adjustment time
Equation MAX(minimum_policy_adjustment_time, (carpooling_policy_deadline-TIME)) **Unit** year **Documentation** The variable carpooling policy adjustment time represents how fast the labor force participants per vehicle are being adjusted towards the goal for the labor force participants per vehicle. A higher adjustment time means a slower adjustment while a lower adjustment time means a faster adjustment. In this variable a changing adjustment time is chosen (to allow for experimentation with a longer time for the carpooling policy to be implemented) to create a smoother adjustment towards the goal. As such the equation contains a MAX function. The MAX function ensures that the carpooling policy adjustment time will not become lower than the minimum policy adjustment time which represents the minimum time needed to implement (parts of) the policy. The equation equals either the difference between the carpooling policy deadline and the current time, or equals the minimum policy adjustment time when the difference between the carpooling policy deadline and the current time becomes smaller than the minimum time needed to implement (parts of) the policy.
Carpooling policy deadline
Equation policy_start_time+time_for_carpooling_policy_to_be_implemented **Unit** year **Documentation** The variable carpooling policy deadline represents the time at which the goal for the carpooling policy should be reached without taking implementation obstacles into account. The equation for this variable equals the sum of the policy start time and the time for the carpooling policy to be implemented.
Change in average travel time by public transport per trip
Equation (gap_in_travel_time_between_car_and_public_transport/ public_transport_policy_adjustment_time)*policy_status* SWITCH_public_transport_policy **Unit** minute/trip/year **Documentation** The arrayed flow change in average travel time by public transport per trip represents the reduction of the travel time in minutes per trip per year for each area (central, ring, outer). It is the rate at which the stock average travel time by public transport per trip decreases per year. The equation for this flow is the same for each arrayed area and equals the division of the gap in travel time between car and public transport by the public transport policy adjustment time. The product of this value by the SWITCH public transport policy and by the policy status ensures that the average travel time by public transport per trip will not be changed when the policy status is inactive or when the public transport policy is not turned on.

Change in labor force participants per vehicle
Equation ((goal_labor_force_participants_per_vehicle-labor_force_participants_per_vehicle)/carpooling_policy_adjustment_time)* policy_status* SWITCH_carpooling_policy **Unit** person/vehicle/year **Documentation** The flow change in labor force participants per vehicle represents the addition of people per vehicle per year. It is the rate at which the stock labor force participants per vehicle increases per year. As the carpooling policy aims to adjust the labor force participants per vehicle upwards to a goal, thus aims to adjust an inflow through which the labor force participants per vehicle can be increased, the part of the equation representing the gap between the actual amount of labor force participants per vehicle and the goal for the amount of labor force participants per vehicle should be formulated as the goal subtracted by the actual value for labor force participants per vehicle (thus goal-actual). The remaining part of the equation for this flow equals the division of the gap in labor force participants per vehicle by the carpooling policy adjustment time. The product of this value by the SWITCH carpooling policy and by the policy status ensures that the labor force participants per vehicle will not be changed when the policy status is inactive or when the carpooling policy is not turned on.
Gap in travel time between car and public transport
Equation MAX(0, average_travel_time_by_public_transport_per_trip-average_congested_travel_time_by_car_per_trip) **Unit** minutes/trip **Documentation** The arrayed variable gap in travel time between car and public transport represents the difference in travel time between commuting by car and commuting by public transport. As the public transport policy aims to adjust the travel time by public transport downwards to a goal, thus aims to adjust an outflow through which the travel time can be decreased, the equation - which is the same for each of the arrayed areas - for the difference between the two transport modes their travel time should be the value of the travel time by public transport subtracted by the goal of the average congested travel time by car per trip (thus actual-goal). Furthermore, as the public transport policy works to reduce the travel time by public transport per trip to match the travel time by car per trip, the travel time by public transport should not be adjusted upwards when the travel time by public transport becomes lower than by car - which can happen as the goal average congested travel time by car per trip is not constant but can change over time. As such, the equation contains a MAX function as well. When the travel time by public transport becomes smaller than by car, and the gap part of the equation would return a negative value, the MAX function ensures that this variable returns a value of 0 which will lead to no further adjustment of the travel time by public transport.
Goal labor force participants per vehicle
Equation 1.5 **Unit** person/vehicle **Documentation** The stock labor force participants per vehicle represents the average

amount of people commuting in one vehicle. In The Netherlands almost all labor force participants who commute by car, commute alone (Geuze, 2017). The carpooling policy aims to increase the average amount of labor force participants that are commuting by car per vehicle. The stock is increased by the flow change in labor force participants towards a goal when the carpooling policy is switched on and the policy status is active. This variable represents the goal labor force participants per vehicle. This policy requires a behavior change in people who are motivated to start carpooling with others. Therefore, the goal is set at only 1.5 person per vehicle as to not set a unrealistic goal (of for example 4 people per vehicle).
Initial average travel time by public transport per trip
Equation [CENTRAL] 10 [RING] 35 [OUTER] 70 **Unit** minutes/trip **Documentation** The arrayed variable initial average travel time by public transport per trip represents the represents the initial average time it takes in minutes per trip to travel from the current location to the destination (the home or work location) by public transport for each area. The initial value for each area (central, ring, outer) is determined based on the average indicated travel time by Google Maps when opting for public transport. For each area (central, ring, outer), multiple points of departure with the destination of central The Hague were explored in Google Maps and an average travel time by public transport value is calculated based on the travel times indicated by Google Maps. When measuring the public transport situation was not delayed (no public transport issues in the region for trams and trains and no traffic congestion for buses).
Initial labor force participants per vehicle
Equation 1 **Unit** person/vehicle **Documentation** The variable initial labor force participants per vehicle represents the initial average amount of people commuting in one vehicle. In The Netherlands almost all labor force participants who commute by car, commute alone (Geuze, 2017). As such, the initial labor force participants per vehicle is set at 1 person per vehicle.
Labor force participants per vehicle
Equation labor_force_participants_per_vehicle(t - dt) + (change_in_labor_force_participants_per_vehicle) * dt **Properties** INIT labor_force_participants_per_vehicle = initial_labor_force_participants_per_vehicle **Unit** person/vehicle **Documentation** The stock labor force participants per vehicle represents the average amount of people commuting in one vehicle. In The Netherlands almost all labor force participants who commute by car, commute alone (Geuze, 2017). The carpooling policy aims to increase the average amount of labor force participants that are commuting by car per vehicle.

The stock is increased by the flow change in labor force participants. Through a goal gap formulation over time the stock labor force participants per vehicle will be increased towards a higher goal for labor force participants per vehicle when the carpooling policy is switched on and the policy status is active. The initial value for this variable is set at 1 person per vehicle (Geuze, 2017).
Minimum policy adjustment time
Equation 1 **Unit** year **Documentation** The variable minimum policy adjustment time represents the minimum time needed to implement (parts of) a policy. The minimum adjustment time is assumed to be 1 year.
Policy start time
Equation 2023 **Unit** year **Documentation** The variable policy start time represents the time at which a policy will start to be implemented, without taking implementation obstacles into account.
Policy status
Equation IF policy_start_time<TIME THEN 1 ELSE 0 **Unit** dmnl **Documentation** The variable policy status represents the status of any policy, meaning whether a policy can be active (1) or inactive (0) at this point in time. The equation for this variable equals an IF THEN ELSE statement. IF the time in the simulation has passed the policy start time, thus if the policy start time is smaller than the current time of the simulation THEN a policy can be active and this variable will return a value of 1, ELSE if the time in the simulation has not yet passed the policy start time then a policy cannot be active and this variable will return a value of 0. Note that in order for a policy to actually be active the policy status needs to be active and the SWITCH for the specific policy that is to be implemented should be turned on. If the policy status is active but the policy SWITCH is not turned on, then the policy will not be active, meaning it will not be implemented.
Public transport policy adjustment time
Equation MAX(minimum_policy_adjustment_time, (public_transport_policy_deadline-TIME)) **Unit** year **Documentation** The arrayed variable public transport policy adjustment time represents how fast the average travel time by public transport per trip is being adjusted towards the goal average congested travel time by car per trip. A higher adjustment time means a slower adjustment while a lower adjustment time means a faster adjustment. In this variable a changing adjustment time is chosen to create a smoother adjustment towards the goal. As such the equation contains a MAX function. The MAX function ensures that the public transport policy adjustment time will not become lower than the minimum policy adjustment time which represents the minimum time needed to implement (parts of) the policy. The equation equals either the difference between the public transport policy deadline and the current time, or equals the minimum policy adjustment time when the difference between the public transport policy deadline and the current time becomes smaller than the minimum time needed to implement (parts of) the policy.

Public transport policy deadline
Equation policy_start_time+time_for_public_transport_policy_to_be_implemented **Unit** year **Documentation** The arrayed variable public transport policy deadline represents the time at which the gap in travel time between car and public transport should be closed and equal 0 without taking implementation obstacles into account. The equation for this variable is the same for each of the arrayed areas and equals the sum of the policy start time and the time for the public transport policy to be implemented.
Road network policies
Equation SWITCH_road_network_policies*policy_status **Unit** dmnl **Documentation** The variable road network policies represents if a policy concerning the road network is active - and thus is being implemented - or not, and when a policy concerning the road network is active, which specific policy is actively being implemented. Both policies can be considered able to be implemented instantaneously with regard to the time horizon of the model. The equation for this variable equals the product of the SWITCH road network policies by the policy status. When the policy status is inactive and returns a value of 0, the road network policies will also equal 0. When the policy status is active and returns a value of 1, but neither of the two road network policies are switched on, the road network policies will equal 0. When the policy status is active and returns a value of 1, and the constant road network policy (SWITCH is switched to 1) is switched on, the road network policies will equal 1. When the policy status is active and returns a value of 1, and the road network reduction policy (SWITCH is switched to 2) is switched on, the road network policies will equal 2.
SWITCH carpooling policy
Equation 0 **Unit** dmnl **Documentation** The variable SWITCH carpooling policy represents whether the carpooling policy will be implemented or not. When the SWITCH is off and equals a value of 0, the policy will not be implemented if the time in the simulation passes the policy start time and the policy status is active. When the SWITCH is on and equals a value of 1, the carpooling policy will be implemented from the moment the time in the simulation passes the policy start time the policy status is active. The carpooling policy works to increase the average amount of labor force participants that are commuting by car per vehicle. By turning the knob of the SWITCH the policy can be switched on. By default the SWITCH is turned off.
SWITCH public transport policy
Equation 0 **Unit** dmnl **Documentation** The variable SWITCH public transport policy represents whether the public transport policy will be implemented or not.

When the SWITCH is off and equals a value of 0, the policy will not be implemented if the time in the simulation passes the policy start time and the policy status is active.
When the SWITCH is on and equals a value of 1, the public transport policy will be implemented from the moment the time in the simulation passes the policy start time the policy status is active. The public transport policy works to reduce the travel time by public transport per trip to match the travel time by car per trip.

By turning the knob of the SWITCH the policy can be switched on. By default the SWITCH is turned off.

SWITCH road network policies

Equation 0
Unit dmnl
Documentation The variable SWITCH road network policies represents whether one of two road network policies will be implemented or not.

When the SWITCH is off and equals a value of 0, neither policy will be implemented if the time in the simulation passes the policy start time and the policy status is active.
When the SWITCH is on and equals a value of 1, the constant road network policy will be implemented from the moment the time in the simulation passes the policy start time the policy status is active.
When the SWITCH is on and equals a value of 2, the road network reduction policy will be implemented from the moment the time in the simulation passes the policy start time the policy status is active.
The two policies cannot be implemented at the same time as one cannot keep the road network constant and at the same time reduce the road network.

By turning the knob of the SWITCH either policy can be switched on. By default the SWITCH is turned off.

Time for carpooling policy to be implemented

Equation 2
Unit year
Documentation As change often takes time and does not always happen instantaneously, the variable time for carpooling policy to be implemented represents the time it may take before which the goal for the carpooling policy should be reached without taking implementation obstacles into account.

Time for public transport policy to be implemented

Equation
[CENTRAL] 2
[RING] 3
[OUTER] 5
Unit year
Documentation As change often takes time and does not always happen instantaneously, the arrayed variable time for public transport policy to be implemented represents the time it may take before which the gap in travel time between car and public transport should be closed without taking implementation obstacles into account.

It is assumed that it is easier to close this gap for the central The Hague area than it is for the ring area, and that it is easier to close this gap for the ring The Hague area than it is for the outer area. As such, the time for the public transport policy to be implemented is shorter for the central area compared to the ring area, and the time for the public transport policy to be implemented is shorter for the ring area compared to the outer area.

POPULATION SECTOR

Carrying capacity

Equation maximum_population_density*land_area_in_km2
Unit person
Documentation The arrayed variable carrying capacity represents the maximum amount of people an area (central, ring, outer) can hold.

The equation for carrying capacity is the same for each of the arrayed areas and equals the product of the maximum population density (measured as people per square kilometer) by the land area in square kilometers.

Effect of population density on net migration

Equation GRAPH(population/carrying_capacity) Points: (0.4000, 1.000), (0.5000, 0.950), (0.6000, 0.890), (0.7000, 0.790), (0.8000, 0.630), (0.9000, 0.380), (1.0000, 0.000), (1.1000, -0.580), (1.2000, -1.500)
Unit dmnl
Documentation This graphical function represents the effect of population density on net migration. Net migration is dependent on the population density, the latter measured as the population divided by the carrying capacity.

When the population of the area is lower than the carrying capacity of the area, but increasing towards that carrying capacity - meaning that the population density ranges in this model between 0.4 and 1 - than the effect of population density decreases increasingly from 1 to 0.
The more densely populated the area becomes, the less people will migrate in to the area, yet as there is enough space (since the carrying capacity is not yet reached) net migration will remain positive without taking other effects into account. However, when the population of the area exceeds the carrying capacity of the area - meaning that the population density is higher than 1 - than the effect of population density decreases below 0 and thus becomes negative meaning that more people will migrate out of the area since it is too crowded. It that case net migration will become negative and people will move away. When more people move out of the area than in to the area, the population of the area will decrease without taking net births into account. As the population decreases towards the carrying capacity again, less people will migrate out of the area until the carrying capacity is reached.

Initial population

Equation
[CENTRAL] 97000 {99173}
[RING] 470907
[OUTER] 282715
Unit person
Documentation The initial value of the arrayed stock population for each area (central, ring, outer) is based on data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).

Maximum population density

Equation
[CENTRAL] 20000
[RING] 12000
[OUTER] 10000
Unit person/square kilometer
Documentation The Hague is the most densely populated city in The Netherlands (Statista, 2022). The variable maximum population density represents the maximum amount of people per square kilometer of land the area (central, ring, outer) can hold.

The values for the maximum population density are based on the most densely populated square kilometers in Europe and current population densities from more dense but comparable cities in neighboring country Belgium (Rae, 2018; Statbel, 2022). This is considered acceptable as the variable considers a maximum value and one of the most densely populated square kilometers in Europe is located in Amsterdam, The Netherlands.

It is assumed that the maximum population density is higher for the The Hague central area than for the ring and outer area, and that the maximum population density is higher for the The Hague ring area than for the outer area. It is further assumed that the maximum population density does not change throughout the time horizon of this model.

Net births

Equation population*normal_net_birth_rate
Unit person/year
Documentation The arrayed flow net births represents the adjustment of population for each area (central, ring, outer) by births and deaths per year. It is the rate at which the population increases or decreases per year excluding changes in population by net migration.

The equation for this flow is the same for each arrayed area and equals the product of the population in the area by the normal net birth rate.

Net migration

Equation population*net_migration_rate*effect_of_population_density_on_net_migration
Unit person/year
Documentation The arrayed flow net migration represents the adjustment of population for each area (central, ring, outer) by people migrating in and out of the area each year. It is the rate at which the population increases or decreases per year excluding changes in population by births and deaths.

As this flow is a net construct, it does not say anything about the amount of people migrating in to the area and the amount of people migrating out of the area separately, but merely says something about the net amount of people migrating in or out of the area.

The equation for this flow is the same for each arrayed area and equals the product of the population in the area by the net migration rate and by the effect of population density on migration. When net migration is positive, more people migrate in to the area than out of it. When net migration is negative, more people migrate out of the area than in to it. When net migration equals zero persons/year, an equal amount of people migrate in to the area and out of the area.
Net migration rate
Equation normal_net_migration_rate*effect_of_housing_availability_on_net_migration* effect_of_job_availability_on_net_migration* effect_of_relative_attractiveness_area_on_net_migration **Unit** dmnl/year **Documentation** The arrayed variable net migration rate represents the amount of people that migrate in to the area per person of the population each year while also taking the amount of people that migrate out of the area per person of the population each year into account. It thus represents the net rate at which the population will change per year based on migration. The equation for net migration rate equals the product of the normal net migration rate by the effect of housing availability on net migration, by the effect of job availability on net migration, and by the effect of relative attractiveness of the area on net migration.
Normal birth rate
Equation 0.011 **Unit** dmnl/year **Documentation** The variable normal birth rate represents the amount of people that are born per person of the population each year. The unit thus being person/person/year, which is the same as dmnl/year. The higher this value, the more people are born per person each year and the more the population will increase (without taking changes in population by deaths or net migration into account). The value for this variable is derived from CBS (2022a). It is further assumed, based on the same data, that the normal birth rate does not change throughout the time horizon of this model.
Normal death rate
Equation 0.008 **Unit** dmnl/year **Documentation** The variable normal death rate represents the amount of people that die per person of the population each year. The unit thus being person/person/year, which is the same as dmnl/year. The higher this value, the more people will die per person each year and the more the population will decrease (without taking changes in population by births or net migration into account). The value for this variable is derived from CBS (2022a). It is further assumed, based on the same data, that the normal death rate does not change throughout the time horizon of this model.
Normal net birth rate
Equation normal_birth_rate-normal_death_rate **Unit** dmnl/year **Documentation** The variable normal net birth rate represents the amount of people that are born per person of the population each year while also taking the amount of people that die per person of the population each year into account. It thus represents the net rate at which the population will change per year based on births and deaths.

As such, the equation equals the difference between the normal birth rate and the normal death rate. When the normal birth rate is higher than the normal death rate, the normal net birth rate will be positive and will work to increase the population. When the normal birth rate is lower than the normal death rate, the normal net birth rate will be negative and will work to decrease the population. When the normal birth rate and normal death rate are equal, the normal net birth rate will equal zero and thus the population will not change through the net births flow.
Normal net migration rate
Equation [CENTRAL] 0.001 [RING] 0.006 [OUTER] 0.006 **Unit** dmnl/year **Documentation** The arrayed variable normal net migration rate represents the net amount of people that migrate in to the area (central, ring, outer) per person of the population per year. The unit thus being person/person/year, which is the same as dmnl/year. As it is a net construct, it takes both migrating in and out of the area into account. A positive value for normal net migration rate means that normally more people per person migrate in to the area than out of the area each year. A negative value for normal net migration rate means that normally more people per person migrate out of the area than in to the area each year. A value of zero means that normally an equal amount of people per person migrate in to and out of the area each year. The values for the normal net migration rate are calibrated based on data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022). It is further assumed that the normal net migration rate does not change throughout the time horizon of this model.
Population
Equation population[area](t - dt) + (net_births[area] + net_migration[area]) * dt **Properties** INIT population[area] = initial_population **Unit** person **Documentation** The arrayed stock population represents the amount of people who live in a specific area. The stock is arrayed by the dimension area with the elements The Hague central area, The Hague ring area and The Hague outer area. The stock is adjusted (increased or depleted) by the flows net births and net migration. The initial value of population for each area (central, ring, outer) is based on data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).
Total population in region
Summing converter **Equation** population[central] + population[outer] + population[ring] **Unit** person **Documentation** The variable total population in region represents the amount of people who live in the The Hague region included in this model. It is equal to the sum of the population in all three areas being The Hague central, ring and outer.

ROADS SECTOR
Average road construction time
Equation 10 **Unit** year **Documentation** The variable average road construction time represents the average time it takes to construct roads either by widening existing roads or by creating new roads where there were none before. This includes time for planning and time for the actual construction work. The average road construction time is assumed to be 10 years.
Average road lifetime
Equation 25 **Unit** year **Documentation** The average road lifetime is approximately 25 years (GWW Totaal, 2022; Rijkswaterstaat., n.d.).
Effect of road network on attractiveness distant areas
Equation 1+sensitivity_of_attractiveness_distant_areas_to_road_network*(roads_relative_to_perceived-1) **Unit** dmnl **Documentation** The variable effect of road network on attractiveness distant areas represents how the attractiveness of distant areas relative to the central The Hague area would change depending on changes in the road network. It is assumed that the higher the roads relative to perceived, the more people find the distant areas more attractive compared to the central area as it is predominantly the expanding road network that facilitates people to locate themselves further away from places of interest (OECD, 2021). The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function. When the roads relative to perceived equals 1 meaning that the road network is equally big as perceived, the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1. When the roads relative to perceived equals a value lower than 1 meaning that the road network is smaller than perceived, the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1. When the roads relative to perceived equals a value higher than 1 meaning that the road network is larger than perceived, the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).

Effect of road network on home construction
Equation 1+sensitivity_of_home_construction_to_road_network*(roads_relative_to_perceived-1) **Unit** dmnl **Documentation** The arrayed variable effect of road network on home construction represents how the maximum normal home construction rate of the area would change depending on changes in road network. It is assumed that a bigger road network creates opportunities for homes to be constructed more easily in places that were less accessible before. The equation for this variable is a normalized linear function (meaning it is a linear function with a 1:1 point). In this linear function the sensitivity determines the direction and the slope of the function. When the roads relative to perceived equals 1 meaning that the road network is equally big as perceived, the part in between parentheses will equal 0. As such, the product of the sensitivity with the part between parentheses will also equal zero, and the entire equation will return a value of 1 as 1+0=1. When the roads relative to perceived equals a value lower than 1 meaning that the road network is smaller than perceived, the part in between parentheses will equal a negative value from 0 down until -1. When the sensitivity has a positive value, the product of the sensitivity with the negative value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity). When the sensitivity has a negative value, the product of the sensitivity with the negative value will equal a positive value. As such, the entire equation will return a value higher than 1. When the roads relative to perceived equals a value higher than 1 meaning that the road network is larger than perceived, the part in between parentheses will equal a positive value up from 0. When the sensitivity has a positive value, the product of the sensitivity with the positive value will equal a positive value. As such, the entire equation will return a value higher than 1. When the sensitivity has a negative value, the product of the sensitivity with the positive value will equal a negative value. As such, the entire equation will return a value lower than 1 (but not necessarily negative, this depends on the value of the sensitivity).
Initial perceived roads
Equation initial_roads-100 **Unit** km **Documentation** The initial value for perceived roads is estimated based on the initial value for the stock roads which is calibrated based on data from CBS (2022e). It is assumed that the initial value for perceived roads is 100 kilometers lower than the initial value for the stock roads.
Initial roads
Equation 2670 **Unit** km **Documentation** The initial value for the stock roads is calibrated based on data from CBS (2022e).

Normal road construction rate
Equation 0.0035 **Unit** dmnl/year **Documentation** The variable normal road construction rate represents the rate at which roads increase per year based on construction. The value for this variable is calibrated based on roads data (CBS, 2022e). It is further assumed that the normal road construction rate does not change throughout the time horizon of this model.
Perceived roads
Delay converter **Equation** SMTHN(roads, time_to_change_perceived_roads, 1, initial_perceived_roads) **Unit** km **Documentation** The variable perceived roads represents the perceived amount of road network in kilometers in the The Hague region. As it takes time to update one's perception of something the perceived roads runs behind the stock roads. The equation for this variable contains a SMTH function. A smooth was chosen instead of a delay as a perception relates to information rather than material.
Road construction
Equation IF road_network_policies=0 THEN DELAYN((normal_road_construction_rate* roads*effect_of_pressure_to_expand_roads_on_road_construction* effect_of_land_fraction_occupied_on_road_construction) + road_degradation, average_road_construction_time, 1, (normal_road_construction_rate*roads* effect_of_land_fraction_occupied_on_road_construction* effect_of_pressure_to_expand_roads_on_road_construction) + road_degradation) ELSE IF road_network_policies=1 THEN road_degradation ELSE road_degradation*0.75 **Unit** km/year **Documentation** The flow road construction represents the kilometers of road that are being constructed each year in the The Hague region. It is the rate at which the stock roads increases per year. The equation for this flow contains a DELAY function. A delay was chosen instead of a smooth as road construction relates to material rather than information. It takes time to construct roads by either widening existing roads or by creating new roads where there were none before, and the road construction process is not instantaneously. As such the input to the DELAY function equals the product of roads by the normal road construction rate and the effects of pressure to expand roads and land fraction occupied on road construction. Furthermore, road degradation is added to this value as this model works under the assumption that The Netherlands, and specifically the The Hague region, takes care for their road network and will repair roads when needed. When the SWITCH road policies is turned off, the model will calculate the road construction based on the above equation. When the SWITCH road policies is turned on and equals the value 1, then the constant road network policy will be implemented from the policy start time onward. In that situation, no new road construction will take place meaning that existing roads will not be widened and new roads will not be created. However, as this model works under the assumption that The

Netherlands, and specifically the The Hague region, takes care for their road network and will repair roads when needed, the road construction flow will equal the road degradation when the constant road network policy is being implemented. When the SWITCH road policies is turned on and equals the value 2, then the road network reduction policy will be implemented from the policy start time onward. In that situation, no new road construction will take place meaning that existing roads will not be widened and new roads will not be created. Furthermore, as the road network degrades not all the road will be repaired. Merely a fraction of 0.75 of the degrading road will be repaired, meaning that 75% of the degrading road will be repaired each year. As such 25% of the degrading road will not be repaired and as such the road network will decrease. As the average road lifetime is approximately 25 years, the road network will decrease by 1% per year when the road network reduction policy is being implemented (for example, if I have 100 km of road network, 4 km of road network per year will degrade, and of that 4 km only 75% equaling 3 km will be repaired in construction, as such the road network decreases by 1 km equaling 1%). The road network reduction policy is a partial road reallocation policy. When road is being reallocated and used for purposes other than private commuting, the road network available to commuters decreases. Roads could be reallocated to more sustainable public transport modes or even to uses beyond transport such as recreational areas (OECD, 2021). While this model is capable of reducing the roads stock in general, it is not capable in its current form to capture the effects of a true road reallocation policy as the model lacks then needed detail and what a road is reallocated in to will influence other aspects in the model as well and the feedback of those effects is not captured in the current model form.
Road degradation
Equation roads/average_road_lifetime **Unit** km/year **Documentation** The flow road degradation represents the kilometers of road that are degrading each year in the The Hague region. It is the rate at which the stock roads decreases per year. The equation for this flow equals the division of the stock roads by the average road lifetime.
Roads
Equation roads(t - dt) + (road_construction - road_degradation) * dt **Properties** INIT roads = initial_roads **Unit** km **Documentation** The stock roads represents the amount of road network in kilometers in the The Hague region. It includes, but not differentiates, three types of roads (with the exclusion of waterways) being national roads, provincial roads and local roads (Rijksoverheid, n.d.). The stock is increased by the flow road construction and depleted by the flow road degradation. When road construction is equal to road degradation, the stock roads will not change. When road construction is higher than road degradation, the stock roads will increase. When road construction is lower than road degradation, the stock roads will decrease. The initial value for the stock roads is calibrated based on data from CBS (2022e).

Roads relative to perceived
Equation roads/perceived_roads **Unit** dmnl **Documentation** The variable roads relative to perceived represents the ratio between the actual current road network and the perceived road network. This variable is constructed as it is unrealistic to assume that, as the time in the simulation progresses, people compare the actual situation to the initial situation in 2001 - which can be up to 50 years ago as the simulation runs for 50 years. By doing so, the effect of road network on the attractiveness of distant areas is based on the actual road network relative to the perceived road network. The equation equals the division of the stock roads by the perceived roads. When roads relative to perceived equals 1, then the current road network is the same as it is perceived. When roads relative to perceived is lower than 1, then the current road network is smaller compared to the perceived road network. When roads relative to perceived is higher than 1, then the current road network is larger compared to the perceived road network.
Sensitivity of attractiveness distant areas to road network
Equation 4 **Unit** dmnl **Documentation** The variable sensitivity of attractiveness distant areas to road network represents the direction and slope of the effect of road network on the attractiveness of distant areas. Thus, it determines how the relative attractiveness of an area changes based on changes in the road network. The sensitivity has a positive value as it is assumed that the higher the roads relative to perceived, the more people find the distant areas more attractive compared to the central area as it is predominantly the expanding road network that facilitates people to locate themselves further away from places of interest (OECD, 2021). Due to how the attractiveness areas sector is modeled, this sensitivity variable does not have to be arrayed per area. The value for sensitivity of attractiveness distant areas to road network is calibrated based on population data from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022), and on the reference mode for relative travel time derived from Loop and Hamersma (2018) and Tomtom (2023).
Sensitivity of home construction to road network
Equation [CENTRAL] 1.5 [RING] 3 [OUTER] 6 **Unit** dmnl **Documentation** The arrayed variable sensitivity of home construction to road network represents the direction and slope of the effect of road network on home construction. Thus, it determines how home construction changes based on changes in the road network. The sensitivity has a positive value for all areas as it is assumed that a bigger road network creates opportunities for homes to be constructed more easily in places that were less accessible before.

The value for the outer area is assumed to be higher compared to the ring area, and the value for the ring area is assumed to be higher compared to the central area as central areas are usually more accessible already when compared to ring areas and in turn outer areas (Grimeland, 2022). As such, changes in the road network are expected to have less of an influence on home construction for the central area compared to the ring area and in turn outer area. The values for the sensitivity of home construction to road network are calibrated based on homes data for each area (central, ring, outer) from CBS (2023b), DHIC (2023), DIC (2023), LVIC (2023), PNIC (2023), RIC (2023) and ZIC (2023).
Time to change perceived roads
Equation 10 **Unit** year **Documentation** The variable time to change perceived roads represents the time it takes for the road network to be perceived. As it takes time to change the perception of the total road network available since people usually travel by the same roads in between places of interest, it is assumed that the time to perceive roads equals approximately 10 years.
THE HAGUE DATA
Data homes central
Equation imported data **Unit** home **Documentation** Homes data for the The Hague central area is derived from DHIC (2023).
Data homes outer
Equation imported data **Unit** home **Documentation** Homes data for the The Hague outer area is derived from CBS (2023b), DIC (2023), PNIC (2023) and ZIC (2023).
Data homes ring
Equation imported data **Unit** home **Documentation** Homes data for the The Hague ring area is derived from DHIC (2023), LVIC (2023) and RIC (2023).
Data jobs
Equation imported data **Unit** job **Documentation** Jobs data for the The Hague region is derived from CBS (2022c).
Data population central
Equation imported data **Unit** person **Documentation** Population data for the The Hague central area is derived from AlleCijfers (2023), CBS (2023a), DHIC (2023), and EersteKamer (2022).
Data population outer
Equation imported data **Unit** person **Documentation** Population data for the The Hague outer area is derived from AlleCijfers (2023), CBS (2023a) and EersteKamer (2022).

Data population ring
Equation imported data **Unit** person **Documentation** Population data for the The Hague ring area is derived from AlleCijfers (2023), CBS (2023a) and EersteKamer (2022).
Data relative travel time
Equation imported data **Unit** dmnl **Documentation** Relative travel time by car data for the The Hague region is derived from Loop & Hamersma (2018) and Tomtom (2023). Note that this reference mode of behavior is in relative terms where the year 2001 equals 100%.
Data road
Equation imported data **Unit** km **Documentation** Roads data for the The Hague region is derived from CBS (2022e).

RUN SPECS	
Start time	2001
Stop time	2050
DT	1/64
Fractional DT	True
Save interval	0.015625
Sim duration	1.5
Time units	Year
Pause interval	0
Integration method	Euler
Keep all variable results	True
Run by	Run
Calculate loop dominance information	True
Exhaustive search threshold	1000

ARRAY INFORMATION		
ARRAY DIMENSION	**INDEXED BY**	**ELEMENTS**
Area	Label (3)	Central Ring Outer

Appendix III – Behavior-sensitivity test

Appendix III reports in detail on the conducted behavior-sensitivity test. The model's sensitivity was tested to values between minus-twenty percent and plus-twenty percent of the model value for all auxiliary parameters which do not have a factual defined value [such as hectares per square kilometer] and to manual distortions for all graphical functions. The results for auxiliary parameters or graphical functions that showed sensitive behavior in the key variables are presented in this section.

Parameter: Initial population [CENTRAL, RING, OUTER]

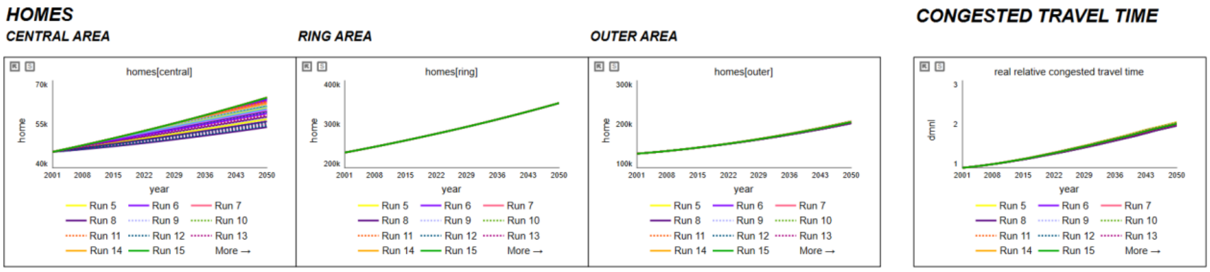
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

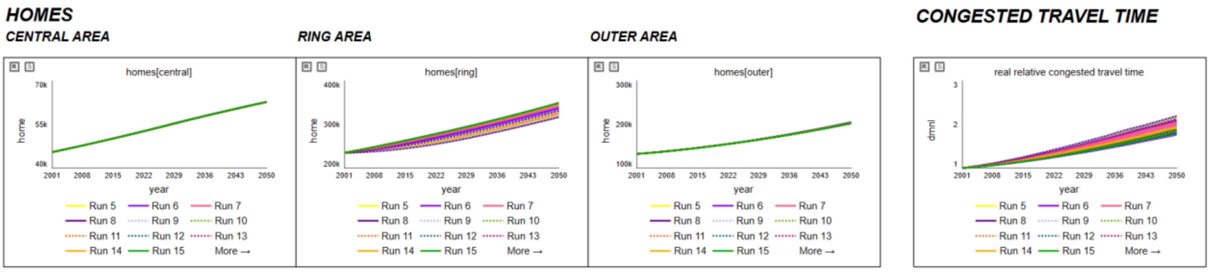
Model value: 97000 [CENTRAL]

Minimum and maximum test values: 77600 – 116400 [CENTRAL]



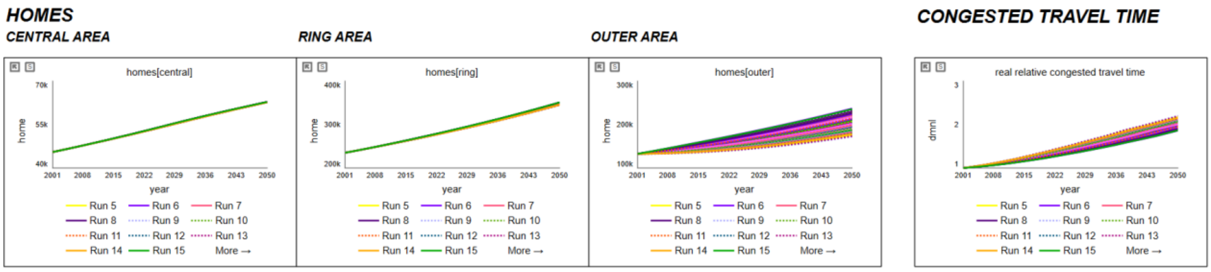
Model value: 470907 [RING]

Minimum and maximum test values: 376725 – 565088 [RING]



Model value: 282715 [OUTER]

Minimum and maximum test values: 226172 – 339258 [OUTER]



Sensitivity to changes in initial population is expected. A bigger initial population results in a lower housing availability which would drive housing construction. The opposite is also applicable. As the congested travel time is a relative measure to the initial value in 2001, one must look at the implications of changes in the population the next time round [as the relative congested travel time in 2001 will always return a value of one]. A bigger initial population results in a bigger increase in population the next time round compared to what it otherwise would have been, this results in a bigger increase in traffic volume which leads to more congestion and in extend a higher relative congested travel time. A smaller initial population results in a smaller increase in population the next time round compared to what it otherwise would have been, this results in a smaller increase in traffic volume which leads to more congestion [but less than it otherwise would have been] and thus a smaller increase in relative congested travel time.

Parameter: Initial homes [CENTRAL, RING, OUTER]

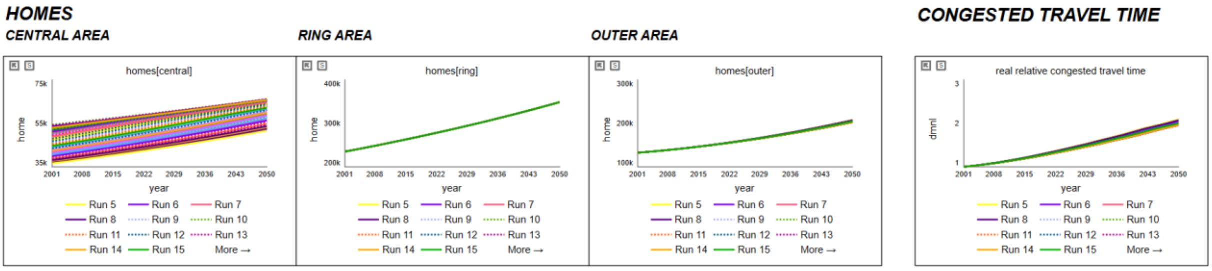
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

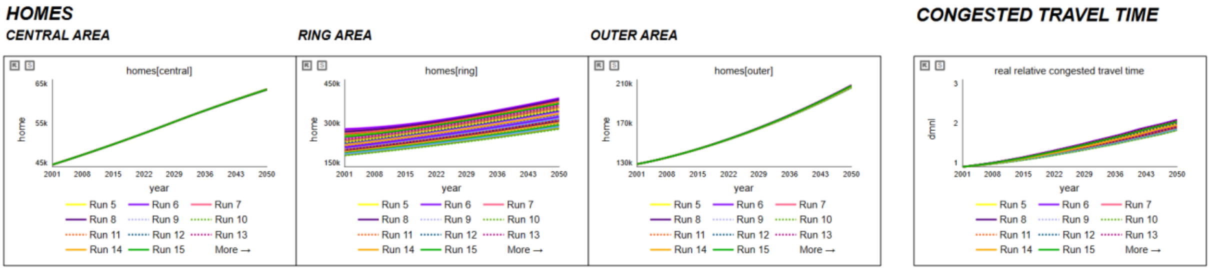
Model value: 45500 [CENTRAL]

Minimum and maximum test values: 36400 – 54600 [CENTRAL]



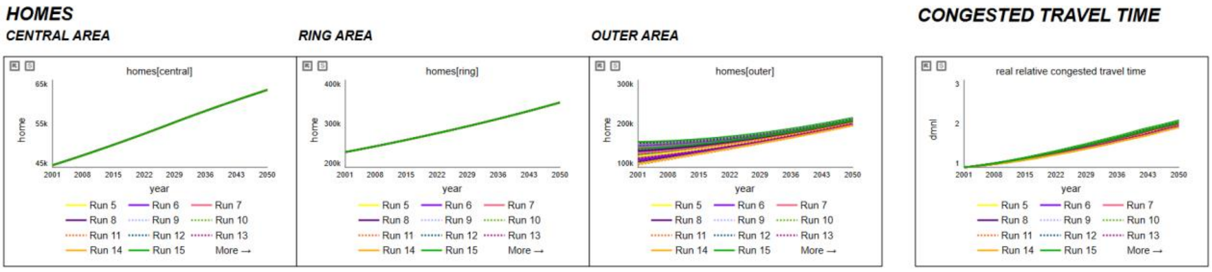
Model value: 235000 [RING]

Minimum and maximum test values: 188000 – 282000 [RING]



Model value: 132500 [OUTER]

Minimum and maximum test values: 106000 – 159000 [OUTER]



Sensitivity to changes in initial homes is expected. Due to variance in housing availability, home construction will sometimes be equal to the maximum construction rate and sometimes be smaller. The housing availability in turn also influences the population for an area which leads to small numerical sensitivity in relative congested travel time.

Parameter: Initial roads

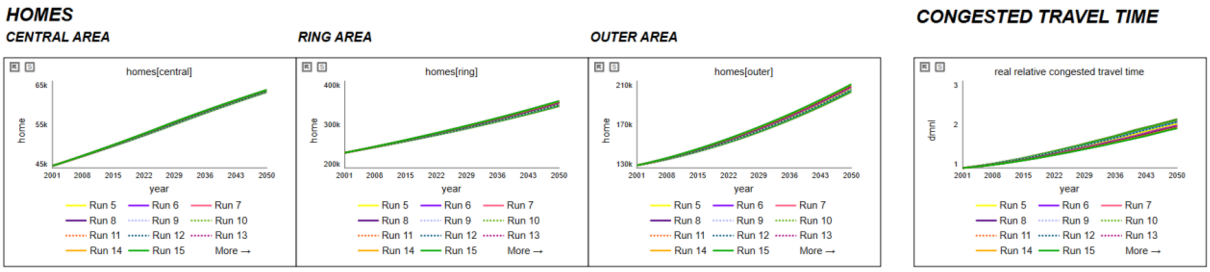
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 2670

Minimum and maximum test values: 2136 – 3204



Slight sensitivity to changes in initial roads is expected. The roads stock influences the flow road construction. The higher the roads stock, the higher road construction will be which works to increase the roads stock. The roads stock in turn influences the maximum home construction rate, where outer areas are more sensitive to changes in the road network. Furthermore, the initial value of the roads stock influences the value of the congestion deflator which thus results in some numerical variance in the relative congested travel time.

Parameter: Initial fraction of labor force commuting by car [RING, OUTER]

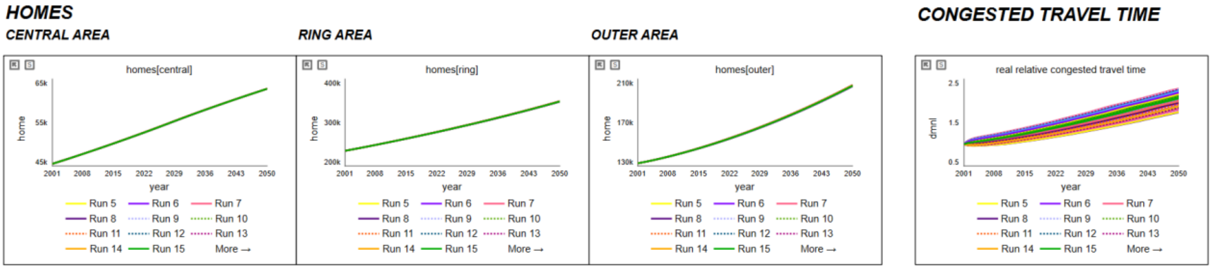
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

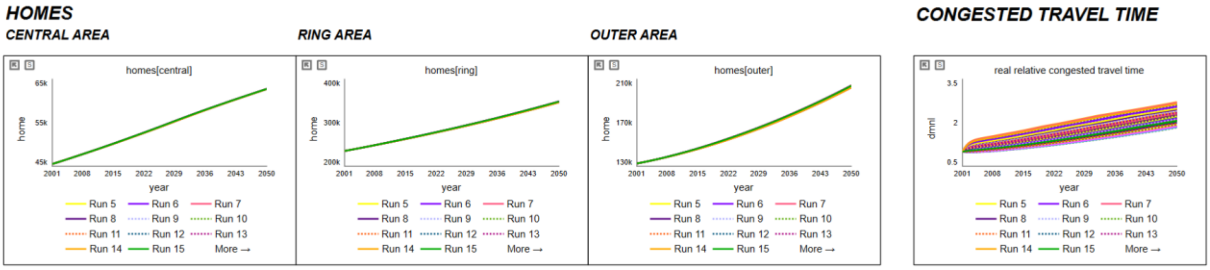
Model value: 0.39 [RING]

Minimum and maximum test values: 0.312 – 0.468 [RING]



Model value: 0.9 [OUTER]

Minimum and maximum test values: 0.72 – 0.95 [OUTER]



Sensitivity to changes in initial fraction of labor force commuting by car is expected for the relative congested travel time for the ring and outer areas as commuters are predominantly from those areas. The key variable homes does not show sensitivity to changes in this variable which is expected as the relative attractiveness of an area responds moderately to changes in the relative congested travel time and as such the population [and in extend housing availability and in turn home construction] does not change as much.

Parameter: Initial average travel time by public transport per trip [RING, OUTER]

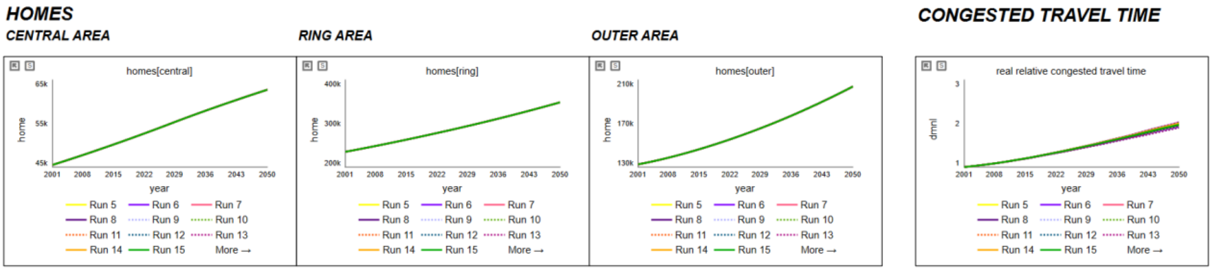
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

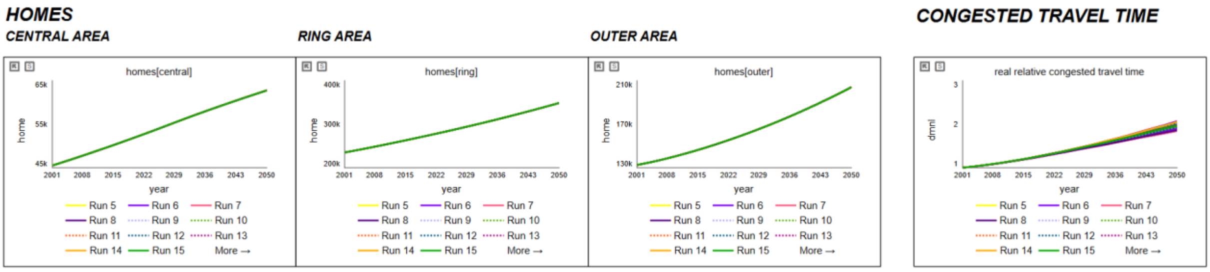
Model value: 35 [RING]

Minimum and maximum test values: 28 – 42 [RING]



Model value: 70 [OUTER]

Minimum and maximum test values: 56 – 84 [OUTER]



Slight sensitivity to changes in initial average travel time by public transport per trip is expected for the relative congested travel time for the ring and outer areas as commuters are predominantly from those areas. When congestion increases significantly enough, a bigger fraction of the population will opt for public transport when commuting instead of the private car to avoid the congested roads. This transition is reached sooner when the travel time by public transport per trip is shorter, which limits further increases in congestion nearing the end of the simulation.

Parameter: Sensitivity of home construction to roads [CENTRAL, RING, OUTER]

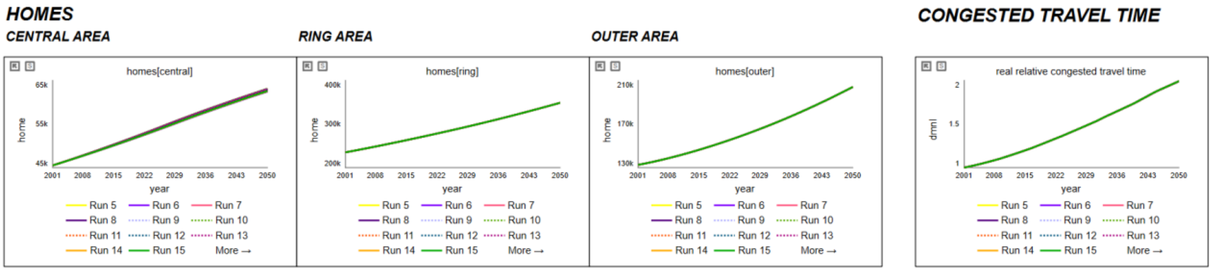
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

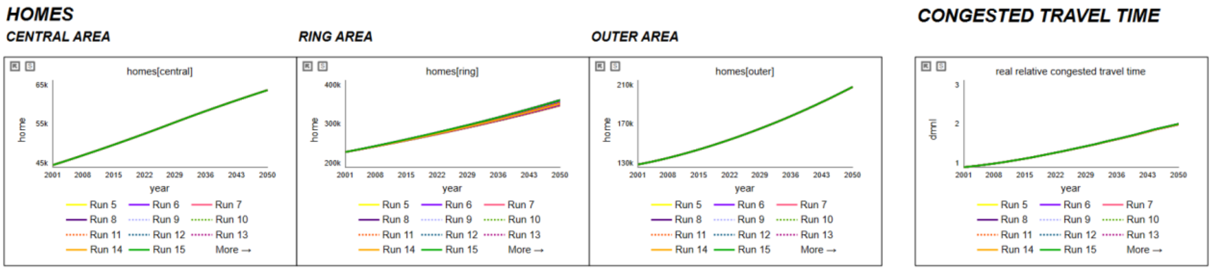
Model value: 1.5 [CENTRAL]

Minimum and maximum test values: 1.2 – 1.8 [CENTRAL]



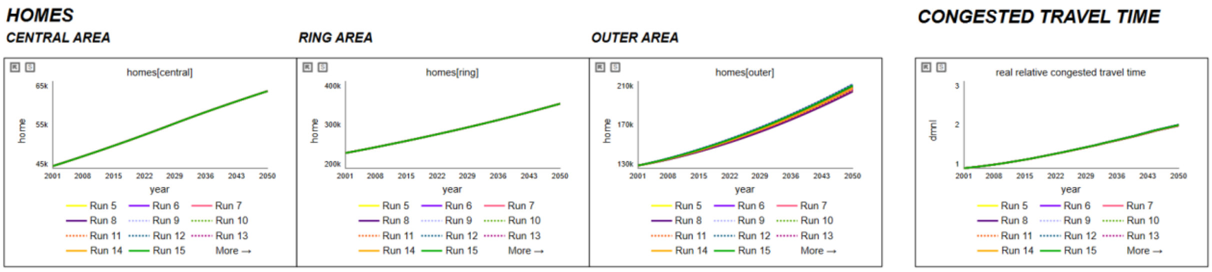
Model value: 3 [RING]

Minimum and maximum test values: 2.4 – 3.6 [RING]



Model value: 6 [OUTER]

Minimum and maximum test values: 4.8 – 7.2 [OUTER]



Slight sensitivity to changes in sensitivity of home construction to roads is expected for homes. The higher this sensitivity, the more the maximum home construction rate will increase when the road network expands, and thus the more homes can be constructed.

Parameter: Normal net migration rate [RING, OUTER]

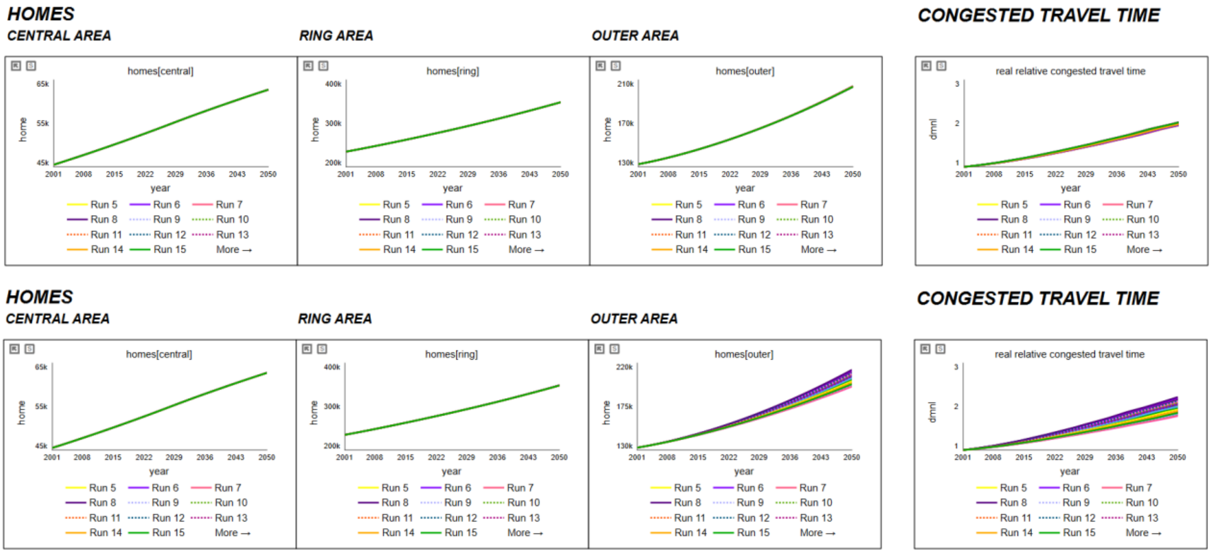
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.006 [RING, OUTER]

Minimum and maximum test values: 0.0048 – 0.0072 [RING, OUTER]



Sensitivity to changes in normal net migration rate is expected for the ring and outer areas [not for the central area as its migration rate is much smaller]. The model however did not prove to be that sensitive to changes in the normal net migration rate for the ring area. The explanation for which is the housing availability. The households to homes ratio for this area is higher than one during the entire simulation, as such home construction is already at its maximum and cannot be increased when housing becomes less available. The behavior of population is numerically sensitive to changes in this variable, but housing availability limits the net migration rate. As population only varies slightly and only a moderate fraction of the population in the ring area commutes by car, the relative congested travel time is only slightly sensitive.

As the households to homes ratio for the outer area is lower than one, and therefore, when housing availability decreases as the population increases due to higher values for the normal net migration rate, the home construction can increase towards its maximum rate. As such homes in the outer area are sensitive to changes in the normal net migration rate. Furthermore, with a higher net migration and more increasing population in the outer area, and most of this population commutes by car, the relative congested travel time is sensitive to changes in the normal net migration rate for the outer area.

Parameter: normal birth rate

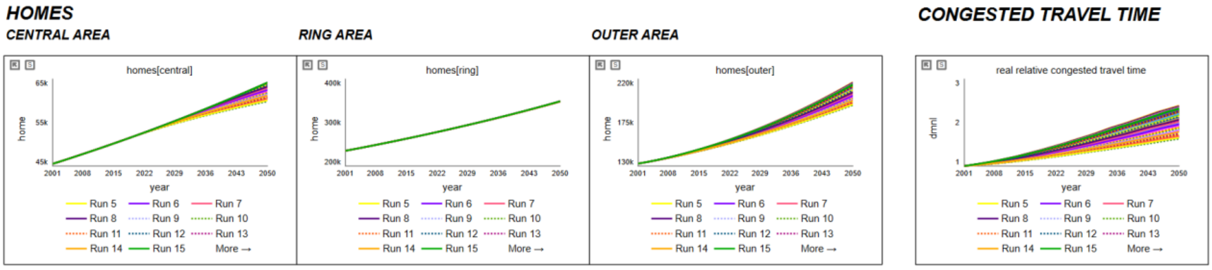
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.011

Minimum and maximum test values: 0.0088 – 0.0132



Sensitivity to changes in normal birth rate is expected. The lower the birth rate, the higher the housing availability will be and as such construction can be limited when the households to homes ratio becomes smaller than one [when home construction catches up to the growth in population]. Furthermore, the smaller the birth rate and the less population increases, the traffic volume will increase less as it otherwise would and thus the relative congested travel time increases more slowly. As the minimum value for normal birth rate in the sensitivity-behavior test is higher than the normal death rate, population will still increase.

Parameter: normal death rate

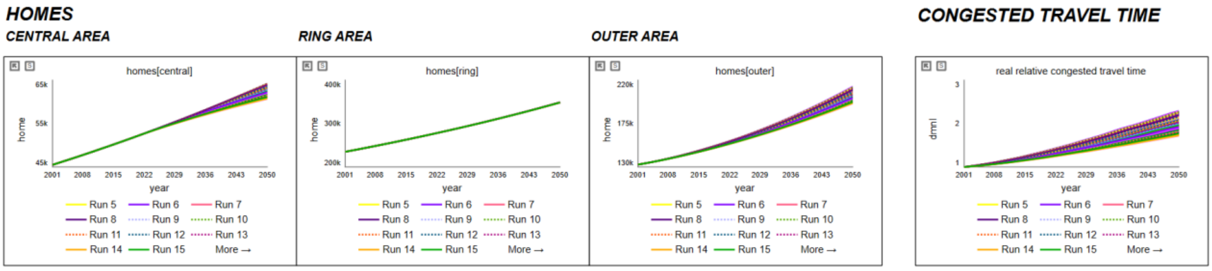
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.008

Minimum and maximum test values: 0.0064 – 0.0096



Sensitivity to changes in normal death rate is expected. The higher the death rate, the higher the housing availability will be and as such construction can be limited when the households to homes ratio becomes smaller than one [when home construction catches up to the growth in population]. Furthermore, the higher the death rate and the less population increases, the traffic volume will increase less as it otherwise would and thus the relative congested travel time increases more slowly. As the maximum value for normal death rate in the sensitivity-behavior test is lower than the normal birth rate, population will still increase.

Parameter: Maximum normal home construction rate [CENTRAL, RING, OUTER]

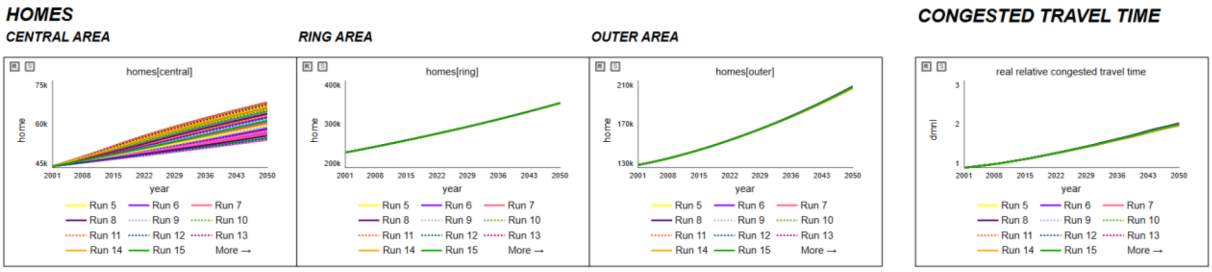
Number of runs: 50

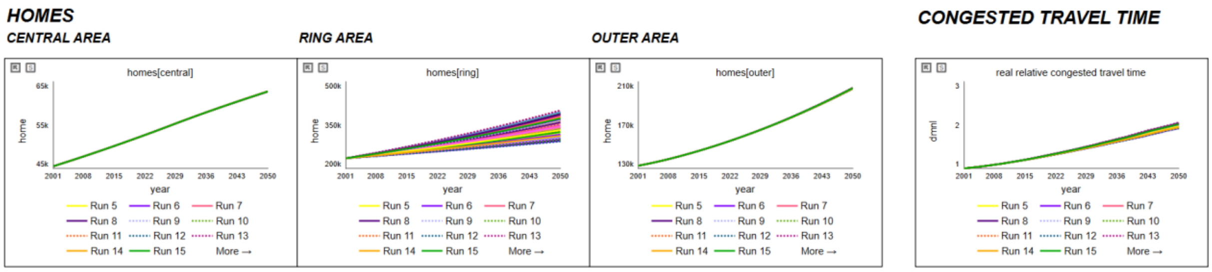
Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.016 [CENTRAL, RING]

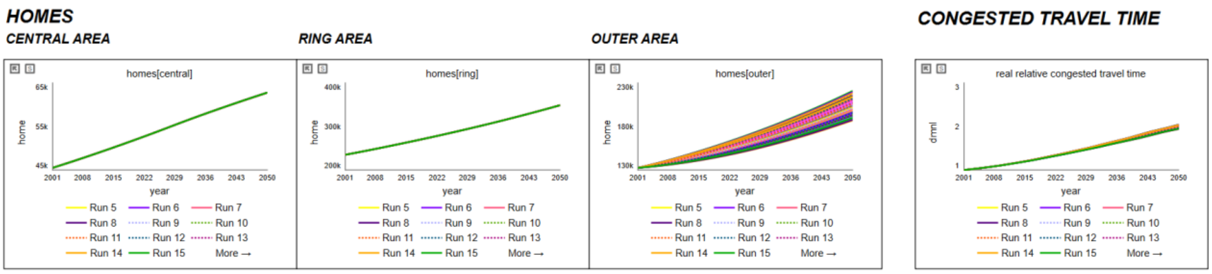
Minimum and maximum test values: 0.0128 – 0.0192 [CENTRAL, RING]





Model value: 0.02 [OUTER]

Minimum and maximum test values: 0.016 – 0.024 [OUTER]



Sensitivity to changes in maximum normal home construction rate is expected for homes. The higher the maximum normal home construction rate, the more homes can be constructed each year increasing the stock homes for each area. By changing the stock homes, the households to homes ratio will change too. For the central area, the households to homes ratio is initially higher than one. For the ring area, the households to homes ratio is initially approximately one. For the outer area, the households to homes ratio is initially lower than one. How the households to homes ratio changes influences home construction.

Parameter: Normal fraction of labor force commuting by car [RING, OUTER]

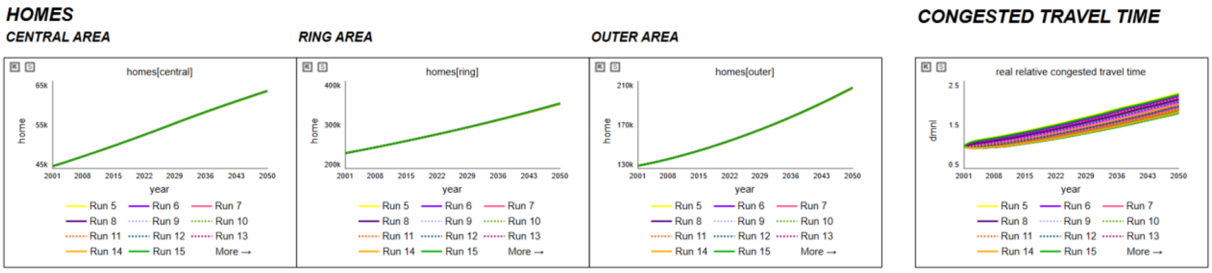
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

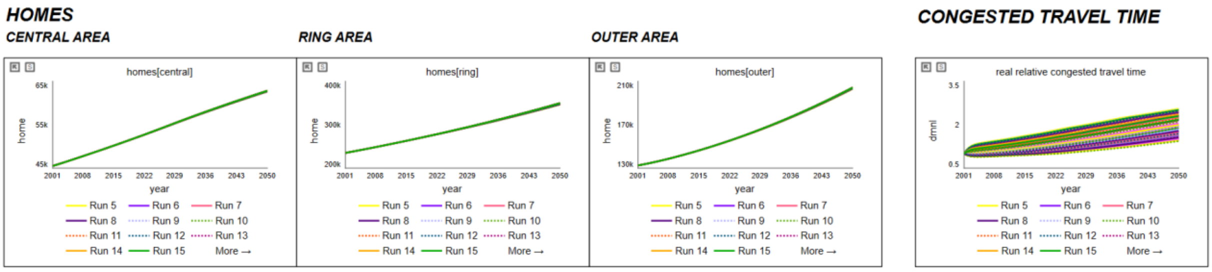
Model value: 0.3 [RING]

Minimum and maximum test values: 0.24 – 0.36 [RING]



Model value: 0.75 [OUTER]

Minimum and maximum test values: 0.6 – 0.9 [OUTER]



Sensitivity to changes in normal fraction of labor force commuting by car is expected for the relative congested travel time for the ring and outer areas as commuters are predominantly from those areas. The key variable homes does not show sensitivity to changes in this variable which is expected as the relative attractiveness of an area responds moderately to changes in the relative congested travel time and as such the population [and in extend housing availability and in turn home construction] does not change as much.

Parameter: Average normal travel time by car per trip [RING, OUTER]

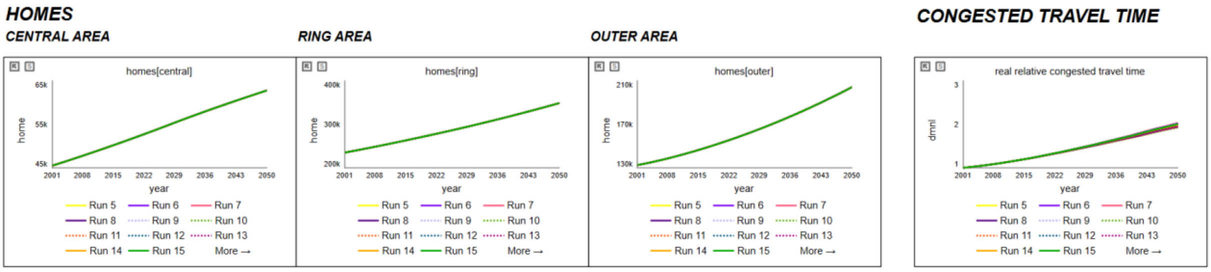
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

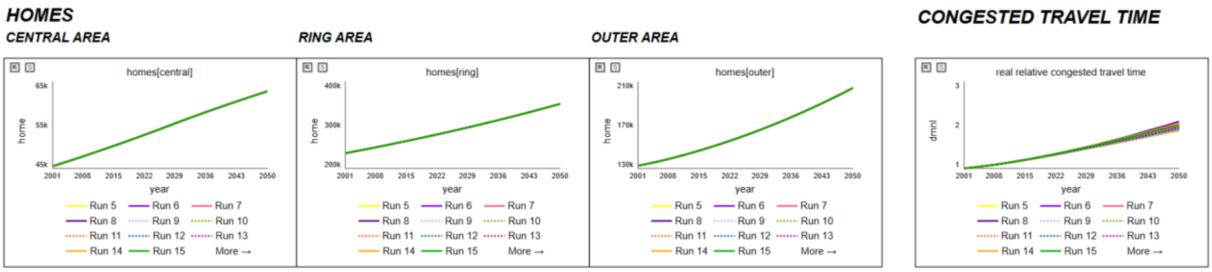
Model value: 15 [RING]

Minimum and maximum test values: 12 – 18 [RING]



Model value: 30 [OUTER]

Minimum and maximum test values: 24 – 36 [OUTER]



Slight sensitivity to changes in average normal travel time by car per trip is expected for the relative congested travel time for the ring and outer areas as commuters are predominantly from those areas. When congestion increases significantly enough, a bigger fraction of the population will opt for public transport when commuting instead of the private car to avoid the congested roads. This transition is reached later when the travel time by car per trip is shorter, and sooner when it is longer. When people change transport mode will influence the relative congested travel time.

Parameter: Normal road construction rate

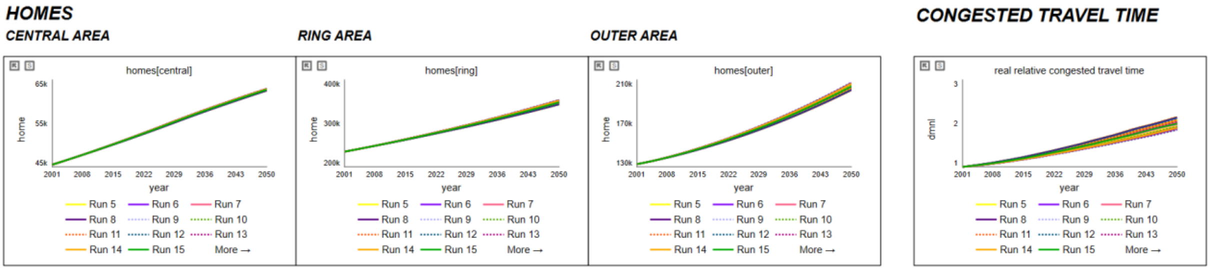
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.0035

Minimum and maximum test values: 0.0028 – 0.0042



Sensitivity to changes in normal road construction rate is expected. More road construction which increases the road network results in higher maximum home construction rates, where more distant areas react more strongly to changes in the road network. Furthermore, more road construction leads to a faster increase in the road network thus limiting congestion and thereby the relative congested travel time does not increase as much.

Parameter: Average home lifetime

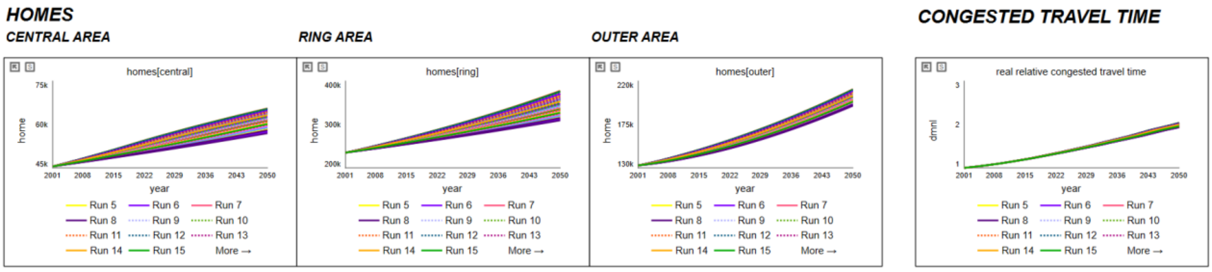
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 100

Minimum and maximum test values: 80 – 120



Sensitivity to changes in average home lifetime is expected for homes. The longer the average home lifetime, the less the stock homes will decrease. This influences home availability which can lead to changes in home construction. For relative congested travel time only slight sensitivity is expected as home availability will influence the attractiveness of areas and net migration to areas. Especially population changes in more distant areas influence the traffic volume and through it, congestion and relative congested travel time.

Parameter: Time to change perceived roads

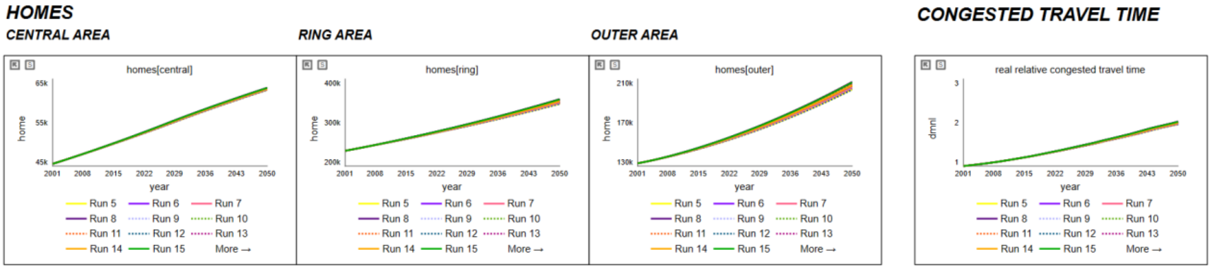
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 10

Minimum and maximum test values: 8 – 12



Slight sensitivity to changes in time to change perceived roads is expected. The longer the time to change perceived roads, the higher the roads relative to perceived will be [with an increasing road network]. However, this ratio will not obtain very high values due to the value for road construction. Nevertheless, the higher the ratio the more the maximum home construction can be increased. This leads to changes in the stock homes, home availability and in extent net migration, traffic volume and thus relative congested travel time.

Parameter: Fraction of population included in labor force

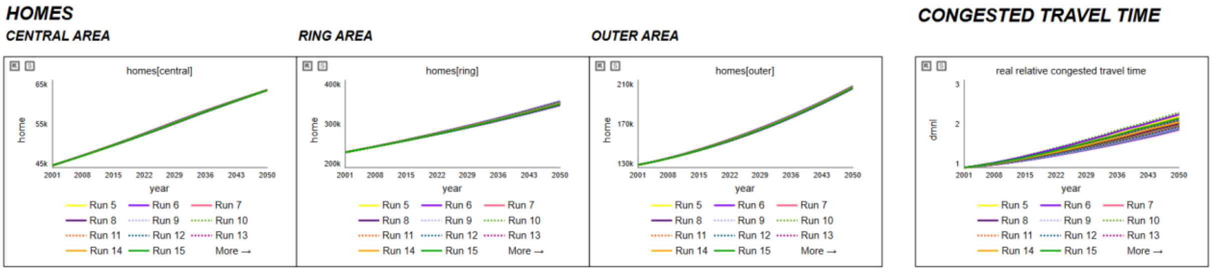
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.6

Minimum and maximum test values: 0.48 – 0.72



Sensitivity to changes in fraction of population included in labor force is expected for relative congested travel time. This fraction influences the traffic volume and thus in extent congestion and relative congested travel time. The higher the fraction of the population included in the labor force, the faster relative congested travel time will increase as the population of an area [especially more distant areas] changes.

Parameter: Fraction of labor force participating in regional labor force [RING, OUTER]

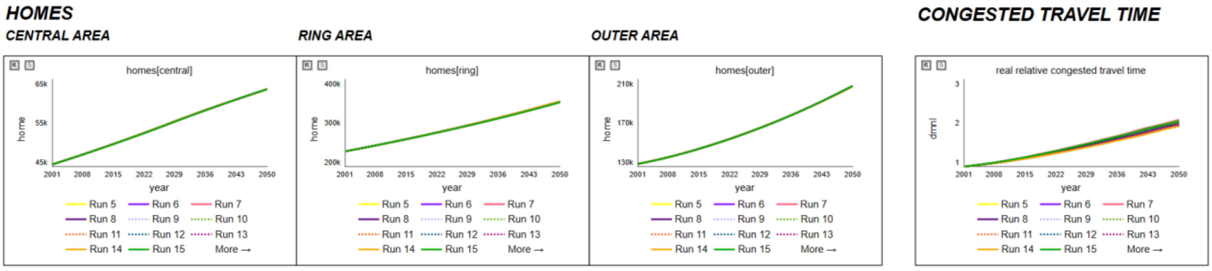
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

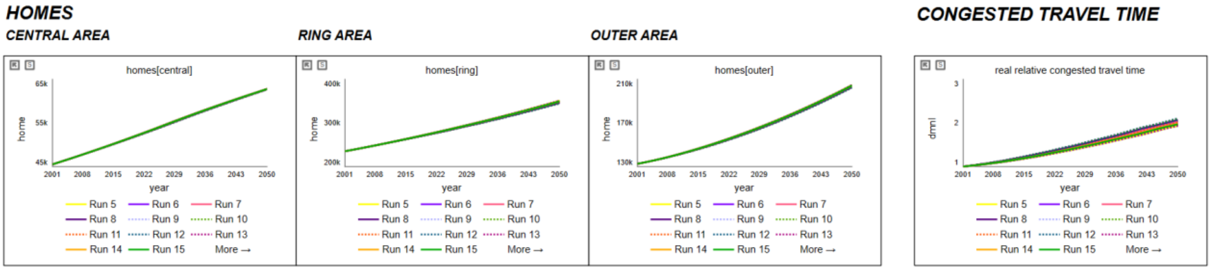
Model value: 0.53 [RING]

Minimum and maximum test values: 0.424 – 0.636 [RING]



Model value: 0.73 [OUTER]

Minimum and maximum test values: 0.584 – 0.876 [OUTER]



Sensitivity to changes in fraction of labor force participating in regional labor force is expected for relative congested travel time. More sensitivity was expected compared to how sensitive the simulation model responds to changes in the fraction. This is due however to the test itself being limited runs Latin Hypercube instead of Sobol Sequencing sampling as only changes in one area are tested, and not in multiple areas simultaneously. Sensitivity is expected as this fraction influences the traffic volume, and thus in extent congestion and relative congested travel time. The higher the fraction of the labor force participating in the regional labor force, the faster relative congested travel time will increase as the population of an area [especially more distant areas] changes.

Parameter: Persons per household [CENTRAL, RING, OUTER]

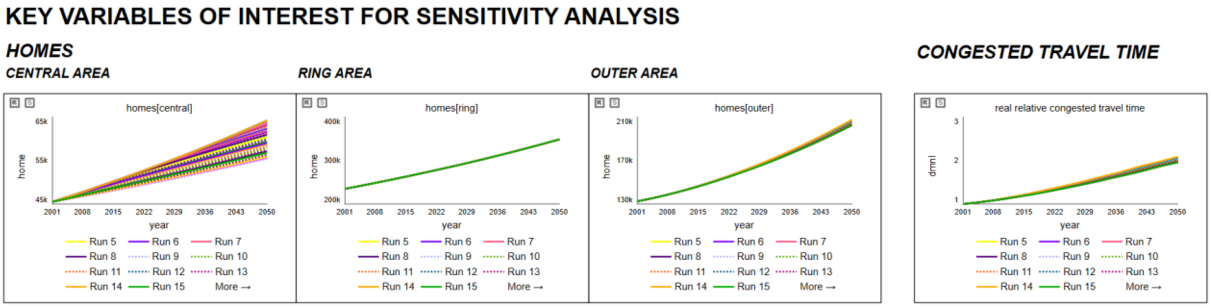
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

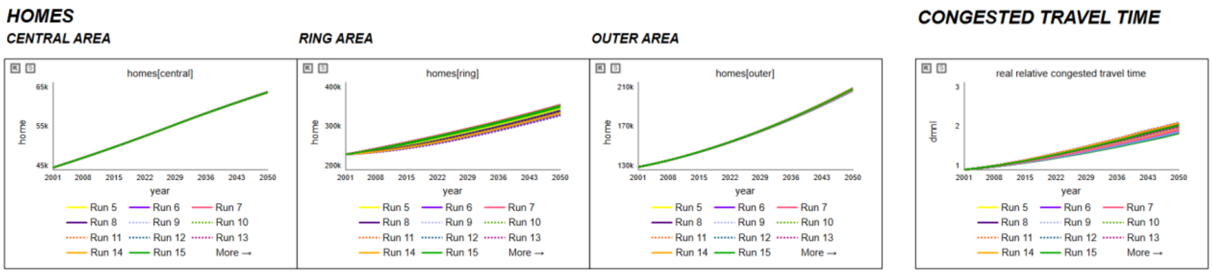
Model value: 1.95 [CENTRAL]

Minimum and maximum test values: 1.56 – 2.34 [CENTRAL]



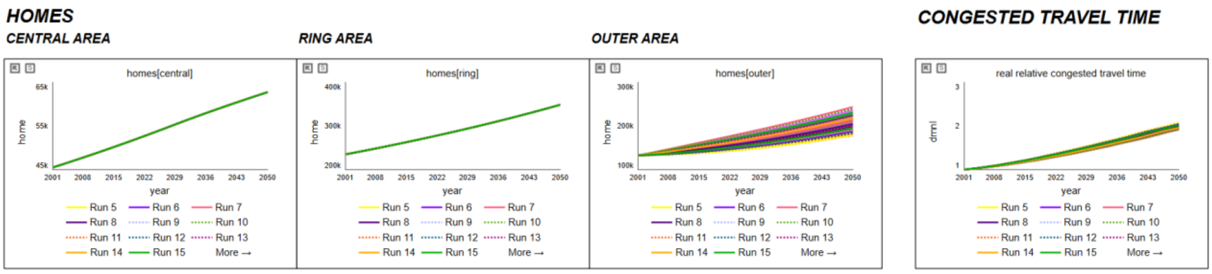
Model value: 2 [RING]

Minimum and maximum test values: 1.6 – 2.4 [RING]



Model value: 2.6 [OUTER]

Minimum and maximum test values: 2.08 – 3.12 [OUTER]



Sensitivity to changes in persons per household is expected. The lower the persons per household is, the less housing availability there is. This will influence home construction, net migration and the attractiveness of more distant areas. For the central area, the households to homes ratio is initially higher than one. For the ring area, the households to homes ratio is initially approximately one. For the outer area, the households to homes ratio is initially lower than one. When changes in the households to homes ratio due to changes in persons per household favor an increase in population in more distant areas, this also affects the traffic volume and in turn congestion and relative congested travel time.

Parameter: Labor force participants commuting by car per vehicle

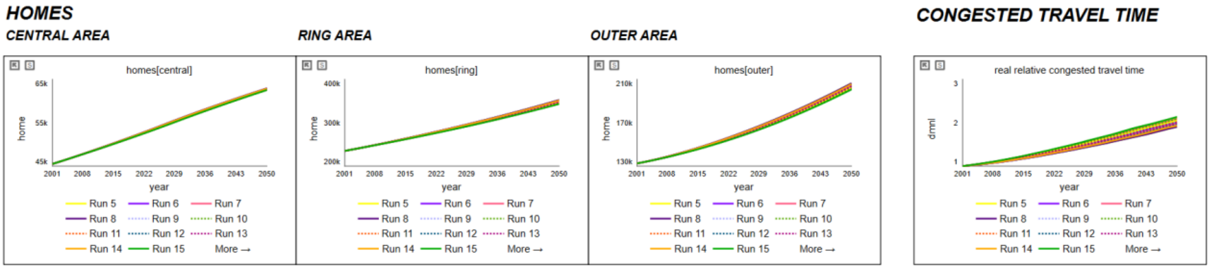
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 1

Minimum and maximum test values: 0.8 – 1.2



Sensitivity to changes in labor force participants commuting by car per vehicle is expected. The more labor force participants share a vehicle when commuting the lower the traffic volume will be. The sensitivity of the model to changes in the labor force participants commuting by car per vehicle is underrepresented due to the way the relative congested travel time is modeled. As it is a relative value where the initial simulation year equals one, whatever value is selected will also be included in the calculation for the relative congested travel time in the initial year. As such, one needs to be mindful of the implications of that model structure.

Parameter: Minimum distancing measure

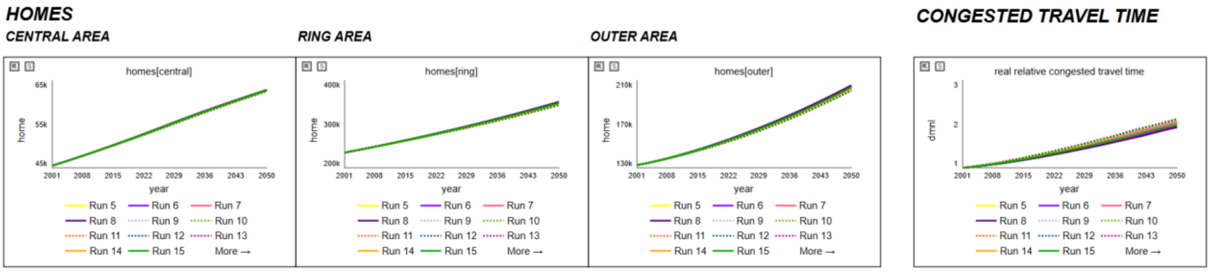
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 0.5

Minimum and maximum test values: 0.4 – 0.6



Slight sensitivity to changes in minimum distancing measure is expected for relative congested travel time. The minimum distancing measure determines, together with other mechanisms, the maximum acceptable vehicle density which influences congestion and in turn relative congested travel time.

Parameter: Acceptable relative congestion measure

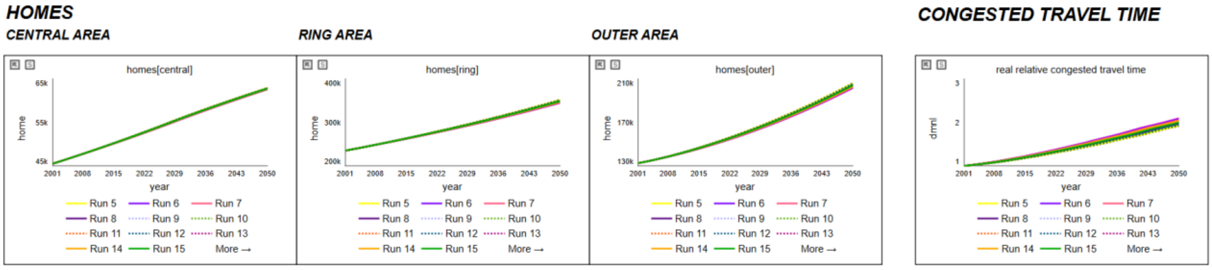
Number of runs: 50

Limited runs (Latin Hypercube sampling)

Distribution: Uniform

Model value: 1.75

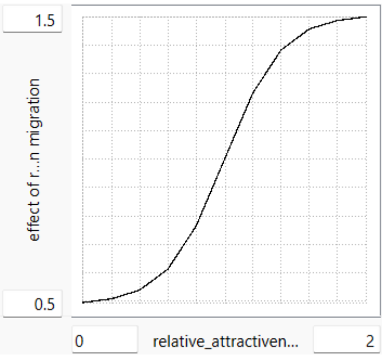
Minimum and maximum test values: 1.4 – 2.1



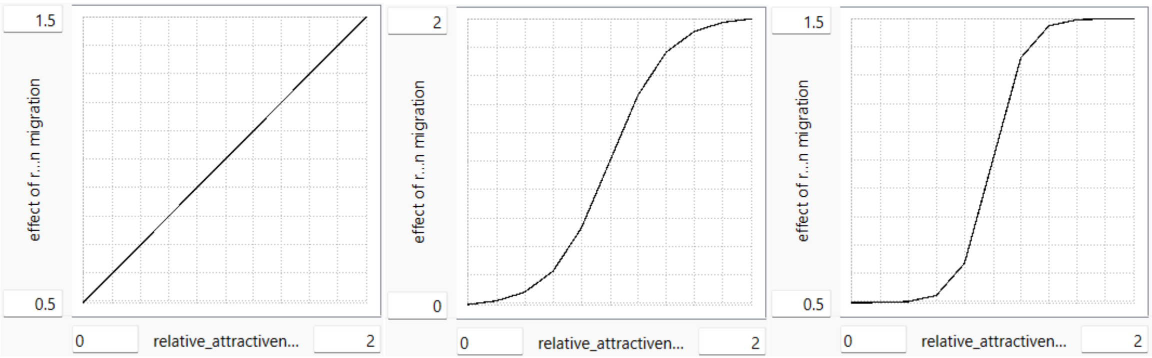
Slight sensitivity to changes in acceptable relative congestion measure is expected for relative congested travel time. The acceptable relative congestion measure determines, together with other mechanisms, the maximum acceptable vehicle density which influences congestion and in turn relative congested travel time.

Graphical function: Effect of relative attractiveness area on net migration [applied to all]

Base function:

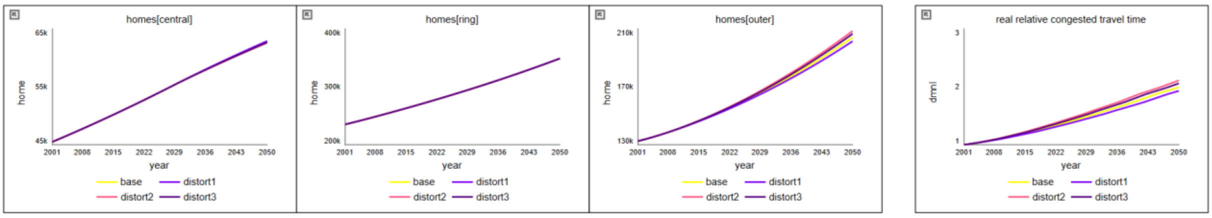


Manual distortions: distort1 distort2 distort3



HOMES

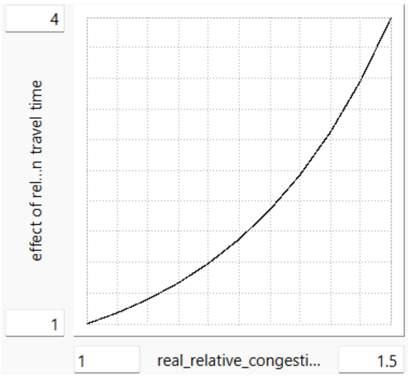
CENTRAL AREA ***RING AREA*** ***OUTER AREA*** ***CONGESTED TRAVEL TIME***



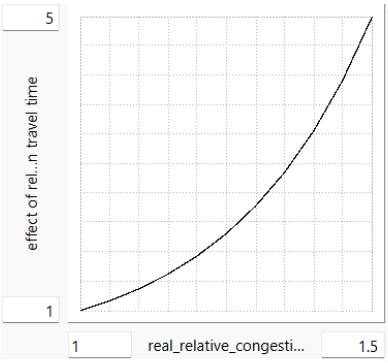
Slight sensitivity to changes in the effect of relative attractiveness area on net migration is expected. As the relative attractiveness of areas does not vary a lot, changes in the effect revolving around the steepness of the effect around the 1:1 part [where it is linear] in the graphical function are expected to affect population [especially in the outer region as changes in the relative attractiveness of more distant areas affect the outer area more so than the inner area]. Population changes influence housing availability and in turn home construction and homes, and traffic volume and in turn congestion and relative congested travel time.

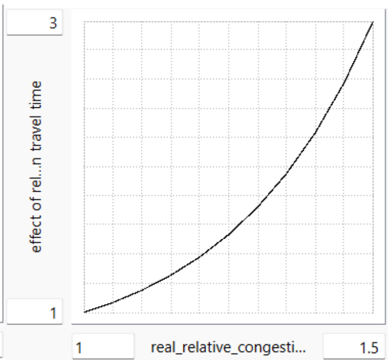
Graphical function: Effect of relative congestion on travel time

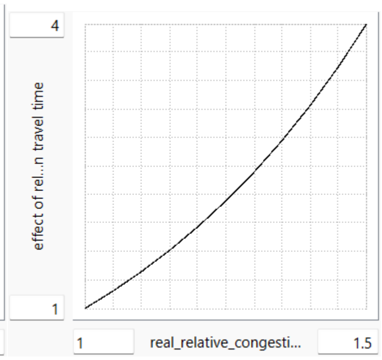
Base function:



Manual distortions: distort1 distort2 distort3

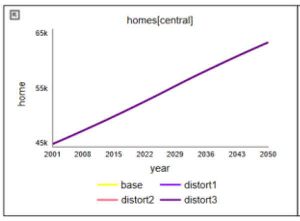




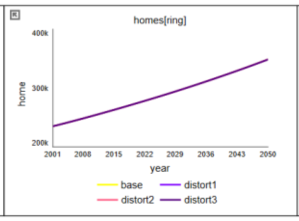


HOMES

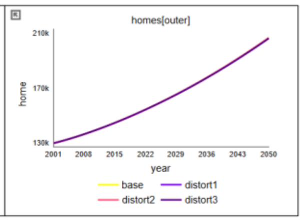
CENTRAL AREA



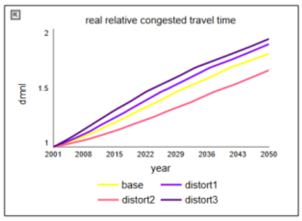
RING AREA



OUTER AREA



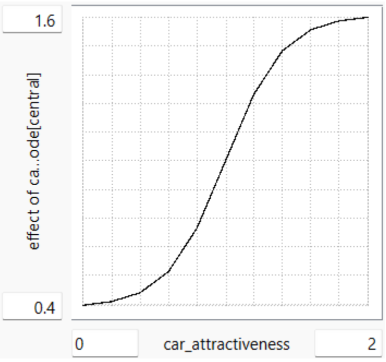
CONGESTED TRAVEL TIME



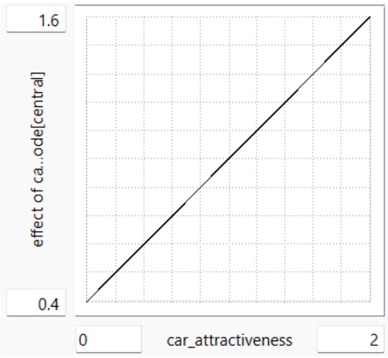
Sensitivity to changes in the effect of relative congestion on travel time is expected for the relative congested travel time. The stronger the effect reacts to changes in its input [the relative congestion] when congestion starts to increase [so going up from a relative congestion value of one to a higher value] the higher travel time becomes. The higher the travel time becomes, the more people will over time opt for an alternative mode of transport to the private vehicle. This influences the numerical output for the relative congested travel time and can slightly influence the behavior mode of relative congested travel time. As Asten (2019) provides the shape of exponential growth and a reference point indication in that shape [an increase of approximately 12% in congestion leads to an increase of approximately 25%-30% travel time] there is confidence in the current shape and bounds of the graphical function.

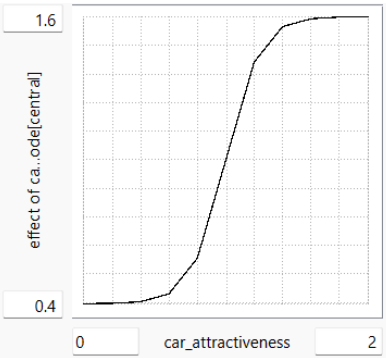
Graphical function: Effect car attractiveness on transport mode [CENTRAL]

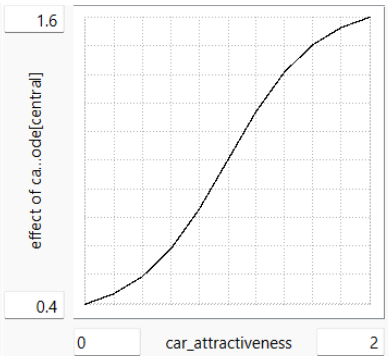
Base function:



Manual distortions: distort1 distort2 distort3

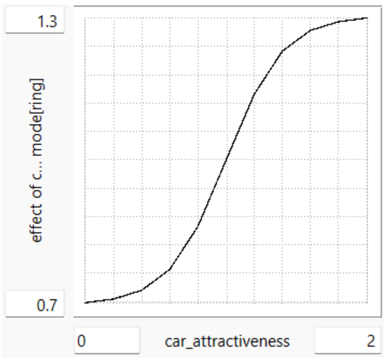




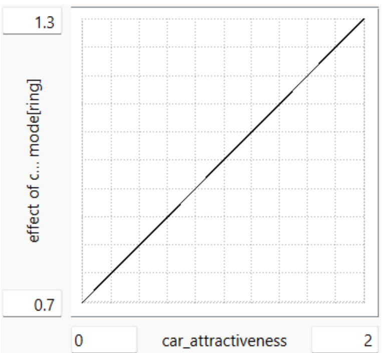


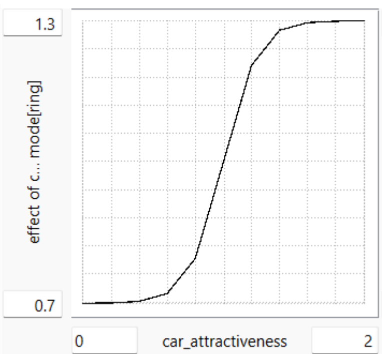
Graphical function: Effect car attractiveness on transport mode [RING]

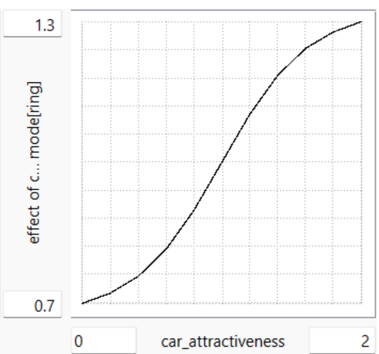
Base function:



Manual distortions: distort1 distort2 distort3

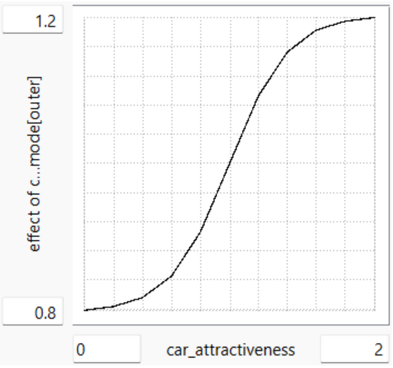




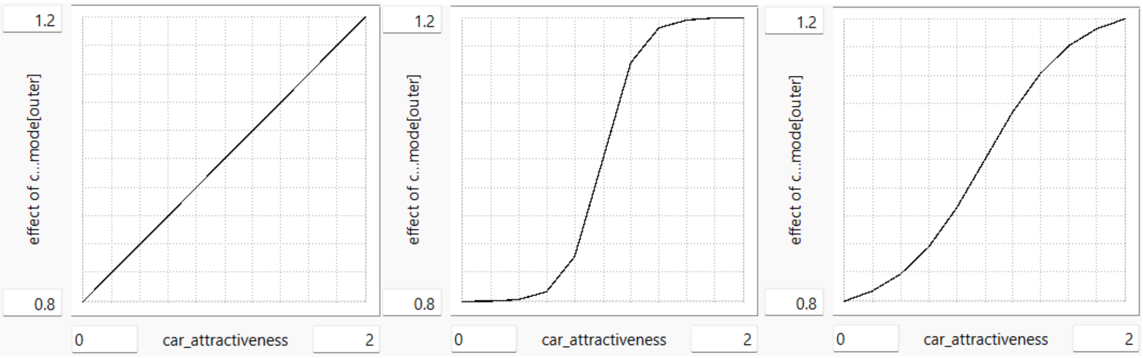


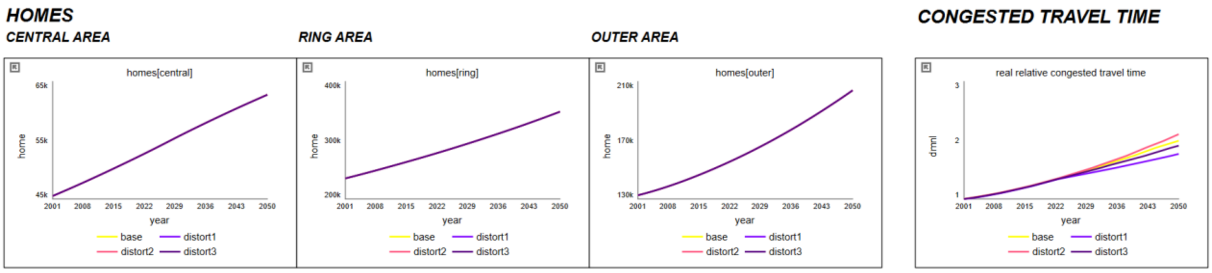
Graphical function: Effect car attractiveness on transport mode [OUTER]

Base function:



Manual distortions: distort1 distort2 distort3

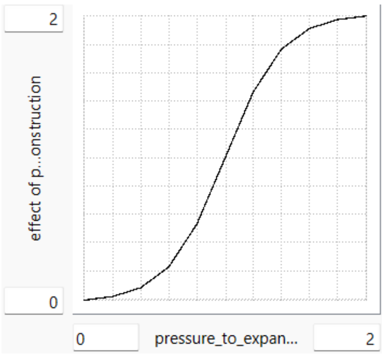




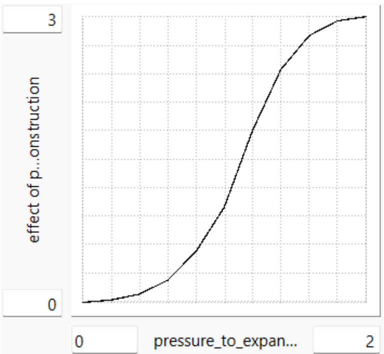
Sensitivity to changes in the effect of car attractiveness on transport mode is expected for the relative congested travel time. This is especially the case for changes in the graphical functions for the ring and outer areas as bigger fractions of the labor force of those areas commute by car. The curvature of the graphical function around the maximum outer bound of the input to the graphical function [car attractiveness] is especially influential. In the ring and outer area car attractiveness is initially higher than two as the travel time by public transport is more than twice the amount of time that a trip would take by car. However, when the road network becomes more congested and the travel time by car increases, car attractiveness decreases. The steeper [less curved] the graphical function is around the maximum outer bound, the more people will over time opt for an alternative mode of transport to the private vehicle. This will limit the increase in congestion.

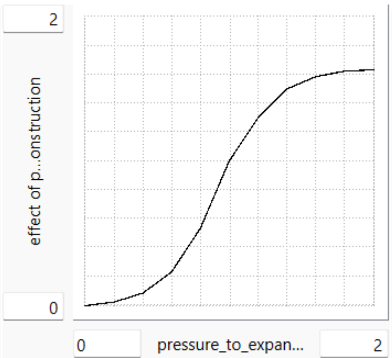
Graphical function: Effect of pressure to expand roads on road construction

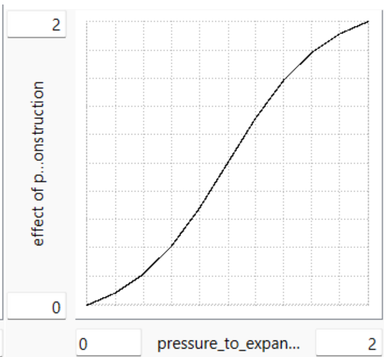
Base function:



Manual distortions: distort1 distort2 distort3

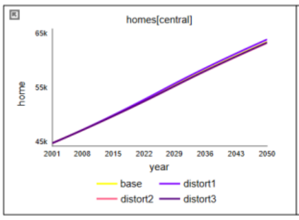




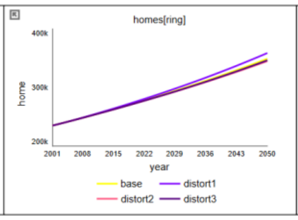


HOMES

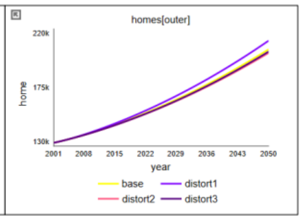
CENTRAL AREA



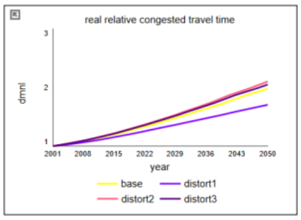
RING AREA



OUTER AREA

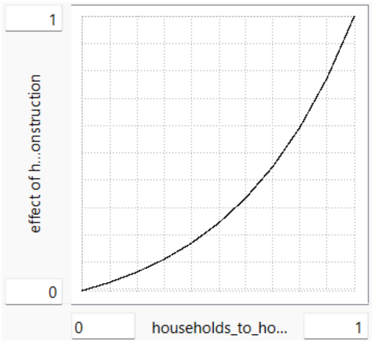


CONGESTED TRAVEL TIME

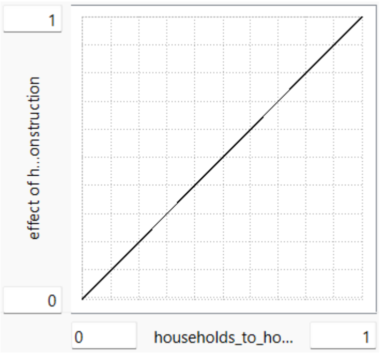


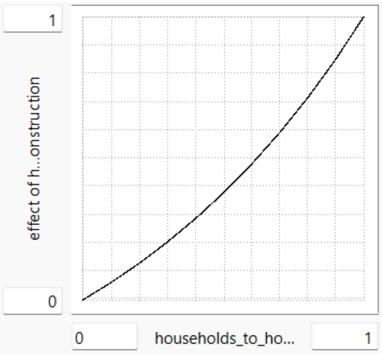
Sensitivity to changes in the effect of pressure to expand roads on road construction is expected. The stronger road construction responds to the pressure to expand roads the more roads will be constructed, and the more the road network increases. On the one hand this will work to reduce the vehicle density on the road network. On the other hand, this will also work through the effect of road network on home construction to increase the maximum construction rate [especially for more distant areas].

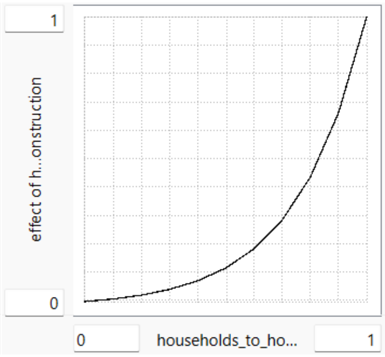
Graphical function: Effect of housing availability on home construction [applied to all]

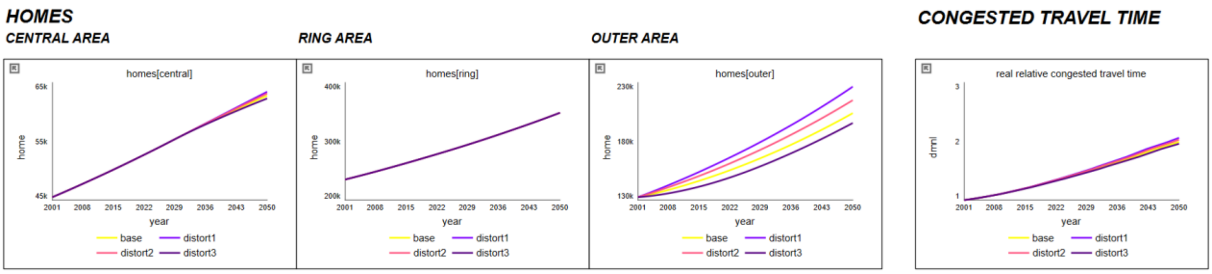
Base function: 

Manual distortions: distort1 distort2 distort3









Sensitivity to changes in the effect of housing availability on home construction is expected, especially for homes in the outer area. For the central area, the households to homes ratio is initially higher than one. This value will decrease over time. For the ring area, the households to homes ratio is initially approximately one. This value will increase over time. For the outer area, the households to homes ratio is initially lower than one. This value will increase over time. As this effect only works to decrease home construction when there is enough housing availability, it will especially influence home construction and thus housing in the outer area, but not in the ring area, and only in the central area when enough housing has become available for the population. The more curved the graphical function is, the less homes will initially be constructed in the outer area. But as housing availability decreases [and households to homes increases towards one], the faster home construction increases. A slight sensitivity in relative congested travel time is also visible. Housing availability influences net migration. The more curved the graphical function for the outer area, the more housing availability decreases as the population increases. This in turn will results in less net migration than there otherwise would be, and as the labor force of the outer area contributes the most to the congestion on the road network, the increase in relative congested travel time will be limited slightly.