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Modelling Urban Carrying Capacity and Measuring Quality of Life using System Dynamics

An examination of the dynamics of urban growth, capacity constraints, and impact on people's quality of life

CONTENTS

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Introduction

An outcome of urban growth is concentration of population and businesses. As the population of an urban area increases, so do diverse concerns and problems including issues of servicing large number of people with existing, limited resources. Environmental problems, particularly pollution and water scarcity, have become more prominent and worrisome in recent times and are central issues for urban planners and decision makers. To address these complex problems, practical approaches that incorporate the concept of carrying capacity into managing urban development are needed. This paper presents a system dynamics (SD) model highlighting the drivers of urbanization, its impact on carrying capacity, and the consequent multiple feedbacks that impacts urbanization's growth.

Carrying Capacity

Urban areas are entities that have great potential of exceeding the local carrying capacity because they require enormous concentrations of food, water, energy, and material in a small area. The concentration requirements may go far beyond the level provided by the local carrying capacity. Also, this high degree of consumption is associated with huge quantity of waste production and consequent environmental pollution in the concentrated region, which may not get properly assimilated within the local carrying capacity.

The concept of carrying capacity was pioneered by Thomas Malthus in the year 1798. (E. Rees) In simple terms, the carrying capacity of an area can be defined as the maximum number of people that can be supported by the environment there through optimum utilization of the available resources. This concept holds a crucial position in determining the quality and state of an ecosystem with respect to the pressures meted out by the demands of the dwelling population. It is basically an ecological concept that also embraces socioeconomic parameters. If this limit is crossed, then nature reacts by imposing pressures that resist the abrupt growth and development (IIT Guwahati). For the purpose of our study, carrying capacity has been defined as:

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Anthropocentric Dynamic Carrying Capacity: The degree of human activity that the environment and ecosystems within an area can support without degrading or damaging quality of life of its people.

Research Approach

The current model is based upon the structures of Urban Dynamics (Forrester 1969), WORLD2 (Forrester 1971), WORLD3 (Meadows *et al.* 1974) models. The model is populated using data of Surat as a sample city.

This study is not intended to provide a forecast or prediction but to demonstrate the need for a planning tool where complex interactions could be better understood and policies tested using simulations. The model works as a template that can be customized for any urban area, to gain insights about its future possibilities.

The paper presents the model description, simulation results, and highlights insights generated from them. It also makes a case for measuring and monitoring the quality of life (QoL) as a lead indicator for holistic management of a city and well-being of its people. This gains policy relevance in light of the growing focus on the development of smart cities and the emphasis being given to QoL.

Research Methodology

Urban systems are complex and composed of various sectors, such as population, businesses, environmental resources, waste generation, and pollution. These are interconnected, interrelated, interdependent of each other, and closely related by multiple cause and effect relationships and feedbacks. Such complex systems may be best understood using dynamic simulation techniques (Casti 1997). SD is one such approach, suited to understand the non-linear behaviour of complex systems over time using stocks and flows, internal feedback loops, and time delays (MIT n.d.). Pioneered by Jay W Forrester at MIT in the late 1950s (Forrester 1961), SD is able to unveil the counterintuitive nature of complex systems and uncover relationships between variables that are responsible for behaviour of the system. Further, being transparent, it provides the reader with an opportunity to go through the model structure and study the linkages (Gallati & Wiesmann 2011).

Model Description

A brief description of the model structure is given in this section. The detailed model structure and equations can be found here.

The model uses the principle of attractiveness (Forrester 1969) to govern the flows of stocks of population and active businesses. As long as an area is attractive, inflows would remain high while if the region loses its attractiveness or becomes unattractive, inflows would fall while outflows would increase. In this model, there are five attractiveness factors.

Attractiveness Factors

1 **Labour force-to-jobs ratio:** This is the ratio of employable population against jobs available.
2 **Pollution density:** This is the level of environmental pollution against a base value (taken at the 2010 levels).
3 **Ratio of water available against water required per capita:** This is the ratio between how much water is available per capita and how much water is required (kept at current supply per capita).
4 **Ratio of water consumed to water requirement per capita:** This is the ratio between the actual water consumption per capita and how much water is required (kept at current supply per capita).
5 **Ratio of available against required land per capita:** This is a ratio between available open land and open land required per capita.

The model consists of eight sectors: Population, Business, Land, Water, Solid Waste, Energy and Emissions, Environmental Pollution, and QoL. These are detailed below.

Population Sector

This sector consists of the stock of population living in the urban area. The stock changes through flows of births, deaths, in-migration, and out-migration. These flows have normal flow rates, which are multiplied by functions of the various attractiveness factors giving rise to dynamic flow rates during simulation. For example, the flow for in-migration in a year would be Population stock × Normal migration rate × Function of labour force to job-based attractiveness × Function of pollution-based attractiveness × Function of water-based attractiveness × Function of open land-based attractiveness; considering a product with all the relevant functions. A similar equation is used for the business sector described later. These attractiveness functions are described below:

- **Impact of jobs on in-migration:** When the labour force-to-jobs ratio has a value of 1, this function has no impact on in-migration. It increases when the labour force-to-jobs ratio falls (signifying availability of employment) and reduces when the ratio increases (signifying excess employable population and fewer jobs).
- **Impact of jobs on out-migration:** This function increases when the labour force-to-jobs ratio increases above 1 (signifying excess employable population and

fewer jobs) and reduces when the ratio falls below it (signifying availability of jobs).

- **Impact of available open land on in-migration:** This function falls when the ratio of available and required land falls below 1, resulting in a fall in in-migration. It signifies the impact of crowding and lack of open spaces for people.
- **Impact of environmental pollution on in-migration:** This function decreases when the pollution density increases, signifying the negative impact of increasing environmental pollution on in-migration.
- **Impact of environmental pollution on out-migration:** This function increases when the pollution level increases, causing increase in out-migration.
- **Impact of environmental pollution on deaths:** This function increases with increasing pollution due to the various negative health impacts of increased pollution.
- **Impact of water availability on in-migration:** This function falls when the ratio of per capita water availability and water requirement falls below 1; signifying a negative impact of diminishing water availability on the in-migration flow.
- **Impact of water availability on out-migration**: This function rises as the ratio of water consumed to water required per capita falls below 1, signifying an increased out-migration in times of acute water shortage.
- **Impact of water consumption on deaths**: This function rises as the ratio of water consumed to water required per capita falls below 1, signifying an increase in deaths in times of acute water shortage.

Business Sector

This sector consists of the stock of active businesses and flows of opening and closing of businesses. The normal closing and opening rates of businesses are dynamically impacted by functions of the various attractiveness factors. These are described below:

- **Impact of land availability on opening of new businesses:** Signifying the importance and attractiveness of open land for new businesses, this function increases when the ratio of available to required open land is greater than 1 and falls when it is less than 1.
- **Impact of water availability on opening of new businesses:** This function decreases when the ratio of available water to water required falls below 1; signifying the negative impact poor water availability would have on opening of new businesses.
- **Impact of water availability on closing of businesses:** This function increases in value when the ratio of water consumed to water required per unit of business falls below 1, to reflect an increase in businesses shutting down due to water scarcity.
- **Impact of workforce availability on opening of new businesses:** This function decreases in value when labour force-to-job ratio falls below 1, and vice versa. This reflects the positive impact of availability of an employable work force when launching new business ventures, and negative impact of the converse.
- **Impact of workforce availability on closing of businesses:** This function increases in value when the labour force-to-jobs ratio falls below 1, signifying an increased closing of businesses due to lack of employable work force. Further, when the ratio increases above 1, this function again increases, denoting an increased closing of businesses due to a reduced demand for goods and services of a largely unemployed population.

Land Sector

This sector consists of the stocks of Usable Open Land and Total Constructed Land. The former has no inflows as the stock of Usable Open Land for urban growth is taken to be limited (although sufficiently large). Its outflow is construction, due to which the level of this stock reduces and flows into the stock of constructed land. Growth in population (new births and in-migration) as well as opening of new businesses is taken to be the drivers for construction flow. The land requirement for business reduces over time denoting vertical growth of the city.

Fresh Water Sector

This sector has one composite stock of the fresh water resources available (comprising of groundwater as well as water coming in from surface flows) and a stock of consumed fresh water. Fresh water recharge (its inflow) takes places through recharge on the available open land as well as surface flows from rivers. It is consumed (outflow) by the active businesses and population. What is left in the city as untreated water contributes to environment pollution.

Solid Waste Sector

The solid waste sector consists of stocks of generated solid waste as well as collected solid waste. Solid waste is generated by the population, of which a fraction is collected by the municipality. Post collection, some fraction of the waste is treated/recycled, while the rest is dumped contributing to environment pollution.

Energy and Emissions Sector

Energy consumption is a flow consisting of the energy use in the municipal services, domestic uses, businesses, and transportation. Emissions are calculated using the CO_2

emission factor and accumulated in the stock of emissions.

Environmental Pollution Sector

This sector consists of one composite stock of environmental pollution, which has one inflow and one outflow. The inflow is a composite flow: a function of emissions, untreated waste water, as well as uncollected and untreated solid waste. It is a representation of the air, water, and solid waste related environmental pollution. The outflow from the stock depends on the absorptive capacity of the environment (how quickly the environment is able to absorb the pollution and cleanse itself). It has been found (Forrester 1971, Ourdighi *et al*. 2014) that as the value of the pollution stock increases, it creates a feedback that reduces the absorptive capacity and increases the time required for cleaning the amount of pollution.

QoL Sector

QoL sector is a composite index to measure the dynamic QoL of people. It comprises several sector-wise QoLs, measured on a scale of 0 to 5. These are briefly described below.

- **Jobs-based QoL:** Determined from the labour force-to-jobs ratio. The QoL falls when this ratio drops below 1.
- **Open space-based QoL:** Determined from the ratio of available and desired open land per capita. QoL falls when this ratio drops below 1.
- **Water-based QoL:** Determined from the ratio of consumed and required water. QoL falls for ratio values below 1.
- **Environmental pollution based QoL:** Determined from the pollution density ratio. QoL falls when this increases beyond 1.

The Overall QoL is obtained by multiplying the above and appropriately normalizing to a scale of 0 to 5 to give the overall QoL, with 5 denoting the best and 0 the worst QoL.

Simulation Results

The model run shows different phases of growth and correction in the urban region. From 1951 to 2014, the simulation reflects the historical growth of the city. Here, there is plenty of open space, high water availability, and low levels of environmental pollution. This makes the initial city conditions very attractive for new businesses and population to move in resulting in growth of their stocks (refer to Figure 1). As businesses move in, they provide jobs that attract more people and increases labour force. This further attracts more businesses. Due to this positive reinforcement, both stocks witness growth from 1951 till 2014. This growth further continues in the future until around year 2030 when the city faces its first limit to growth. In our model, this limit comes from environmental pollution. As population and businesses grow, the levels of pollution also increase. As pollution levels increase, it creates two feedbacks to the population. One, It impacts people's health through diseases like emphysema, asthma, tuberculosis, etc. (Meadows *et al*. 1974) which results in

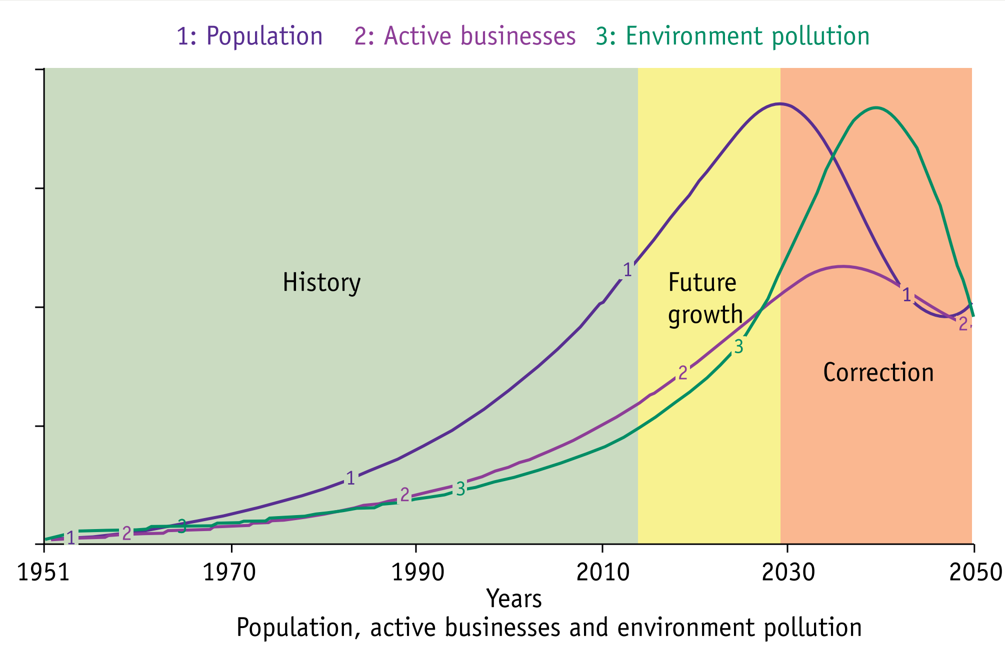

Figure 1: Simulation of population, active businesses, and environment pollution

increase in death rates. Two, the city becomes unattractive due to very high levels of pollution, increasing out-migration rates while reducing in-migration (refer to Figure 2 and 3).

As population stock decreases, it causes a decline in the business stock due to falling availability of labour force (refer to Figure 2). The decrease of the two stocks continues until a situation is reached, where the pollution levels start falling and the city again becomes attractive for people to move in while its impact on death rate reduces. This causes the second growth phase of the city. The system variables continue to repeat this behaviour and move in oscillations in the longer time frames (refer to Figure 4).

Quality of Life

The QoL happens to start falling before a correction in population (refer to Figure 5). This indicates that the peak and fall in QoL happens much before physical impacts of falling resources or increasing pollution levels

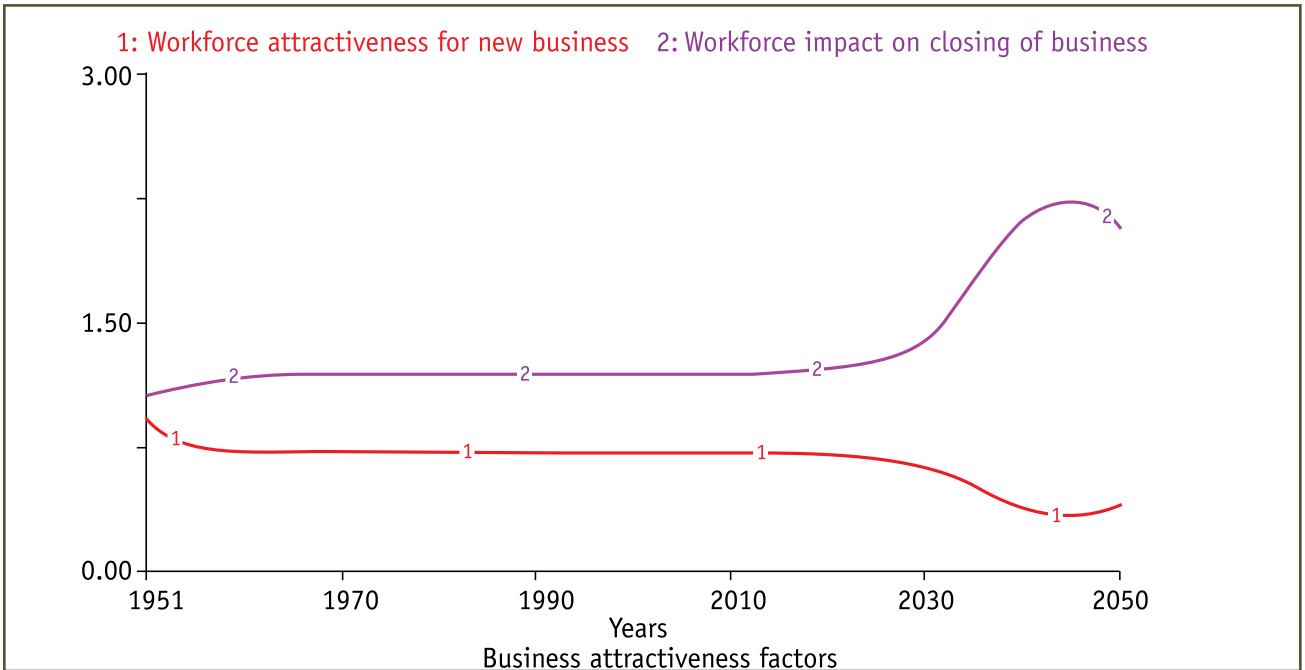

Figure 2: Businesses attractiveness factors

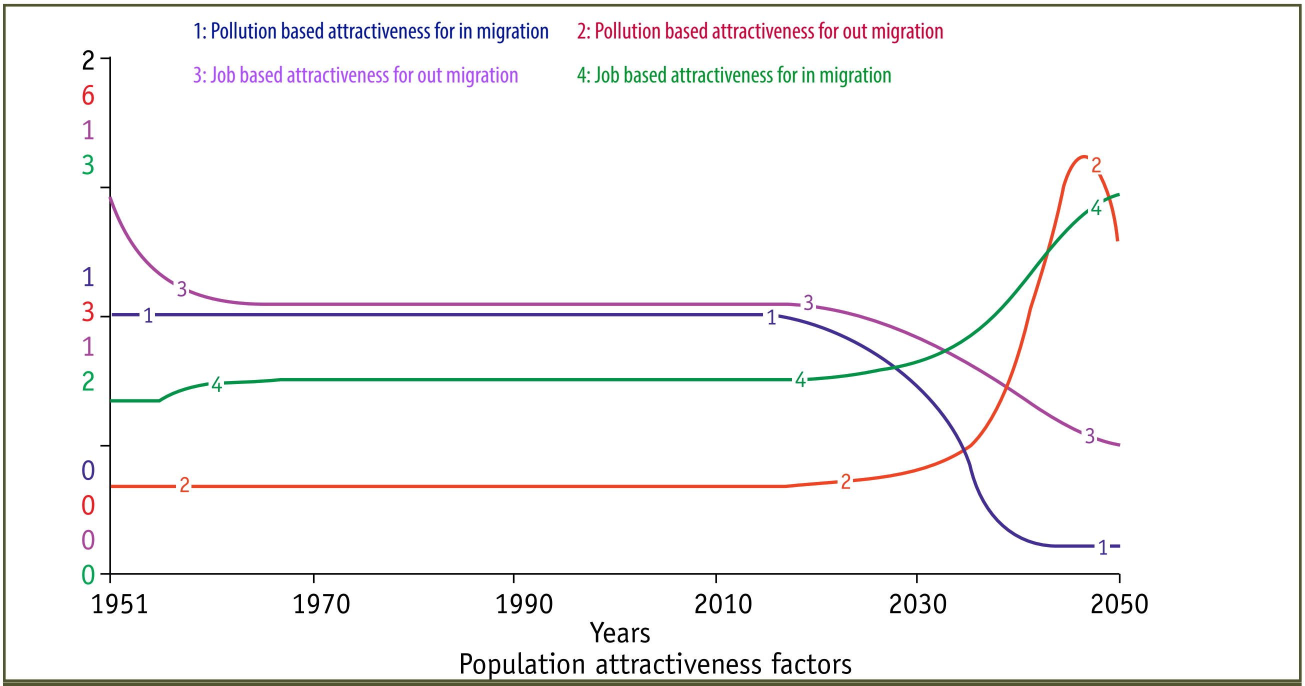

Figure 3: Population attractiveness factors

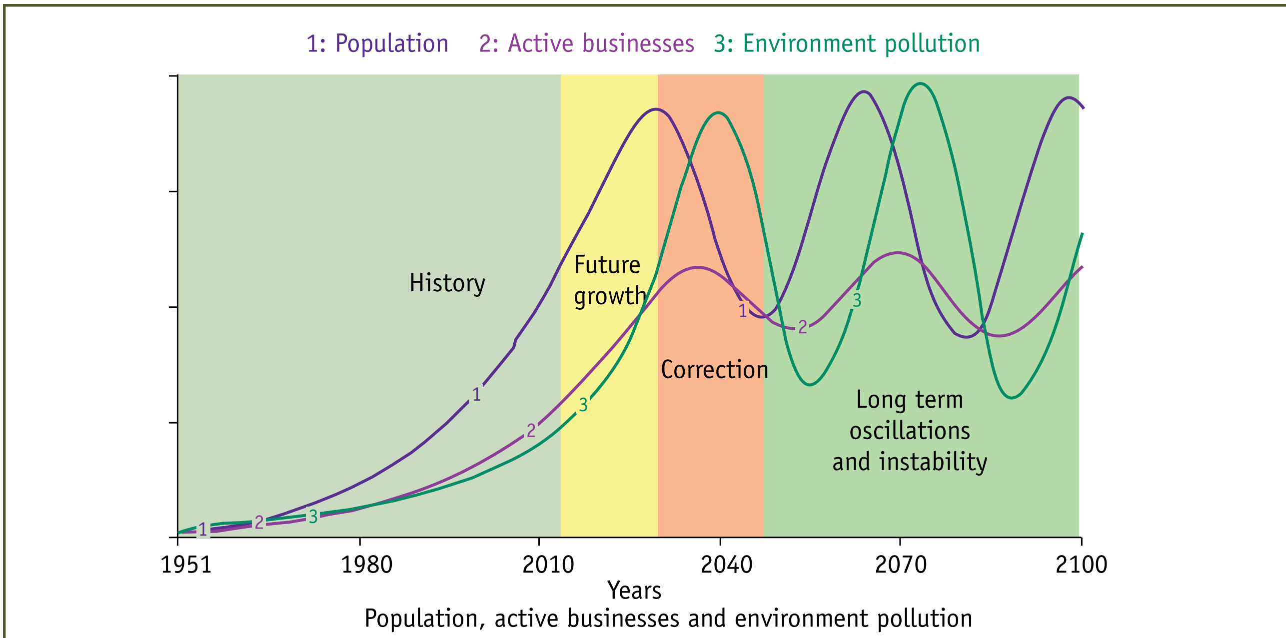

Figure 4: Long-term simulation of population, active businesses

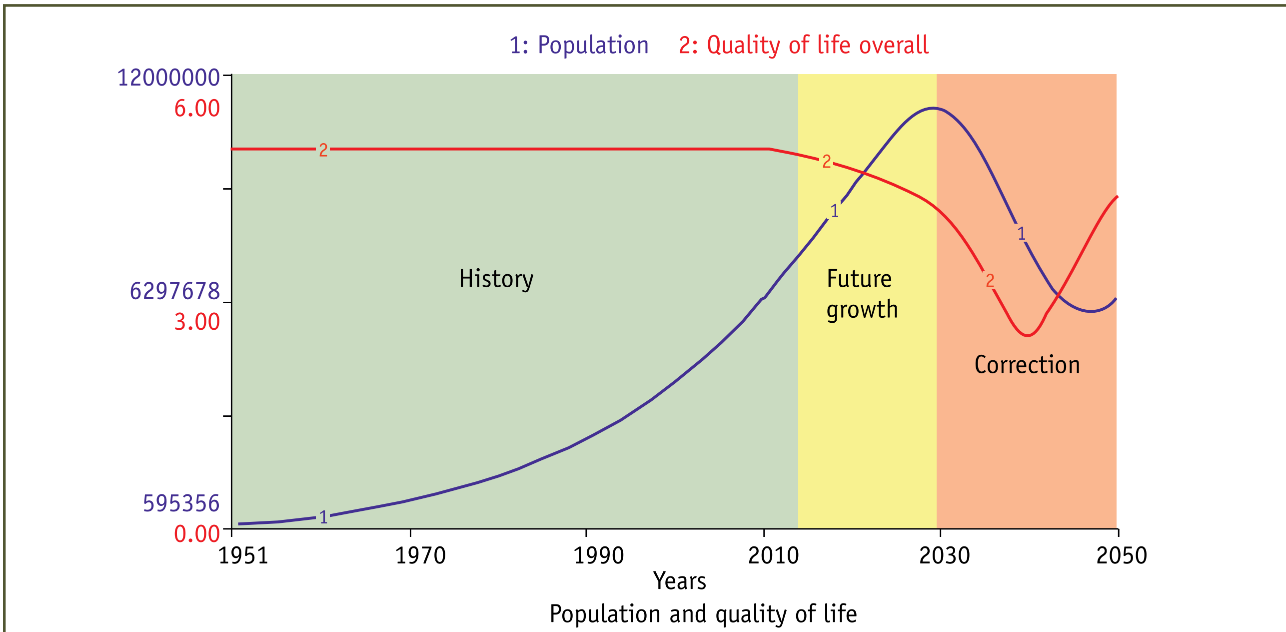

Figure 5: Population and QoL

is felt. This means that the population will be living on a highly compromised QoL before undergoing correction. Only when the stresses on resources are reduced, after population stock reduces, does the QoL begin to rise. In our model due to increasing pollution levels, the QoL starts falling much before the population correction happens.

Nested Limits

If environmental pollution is checked, it is quite possible that the population will be allowed to get further concentrated in the city, but water could become a second limit. Water availability is not a problem in the model due to high rainfall and water expansion plans for Surat city. Thus, the first limit the city faces in the model run is environmental pollution (these limits or constraints could be different for other cities). Another limit could be available open land. The falling open land stock makes the city less attractive for new businesses to come in while businesses continue to close at their normal rate. With increasing construction taking place all along, the space-based attractiveness for population and land-based attractiveness for new businesses would fall in the long run.

Thus, our model demonstrates that there are nested limits coming from environmental pollution, water availability, and land, which limit the growth of the urban centre. It must be noted that the model assumes limitless supply of food, capital, and energy to the city and still the city faces limits to its growth. Urban planners need to be cautious of not considering the external environment as a limitless source, which is taken as an assumption in the model. These multiple limits will restrict growth of urbanization and any of the limits could strike first. Policies that help overcome one limit could delay the growth correction but might make the collapse from another limit in the future more severe.

Discussion and Conclusion

The modelling exercise reveals that the urban-environment system is a highly complex one, having multiple feedback loops with time delays that challenge human cognition to understand the system's behaviour over time. However, considering real-world situations to be much more complex than what the model suggests, there would always remain a band of uncertainty in the multiple feedback processes as highlighted in the paper. For example, the impact of environmental pollution on health or the impact of decreasing water tables on people take effect only after the situation deteriorates to a great extent and when it becomes difficult for rapid adjustments to be made. This makes policy formulation for sustainable development of urban areas a very challenging exercise. The complexity must be appreciated and understood before any interventions claiming to better the situation are implemented. Policy support systems that enable decision makers to test the underlying assumptions before rolling our interventions must be developed.

To conclude, this study demonstrates how QoL could be measured through a composite index that reflects the overall well-being of the population and health of the city. It also shows that measuring and monitoring QoL could give lead indication about the health of the city. Due to its composite nature, maintaining QoL could be seen as the most holistic way of managing sustainable urbanization. This becomes even more relevant since QoL is being termed to be an important factor to be considered in developing India's smart cities.

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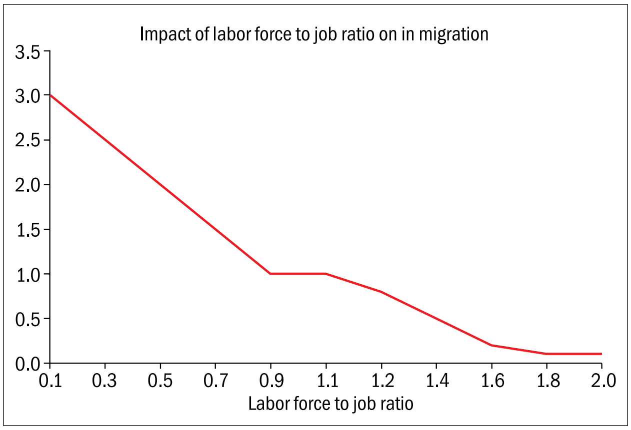
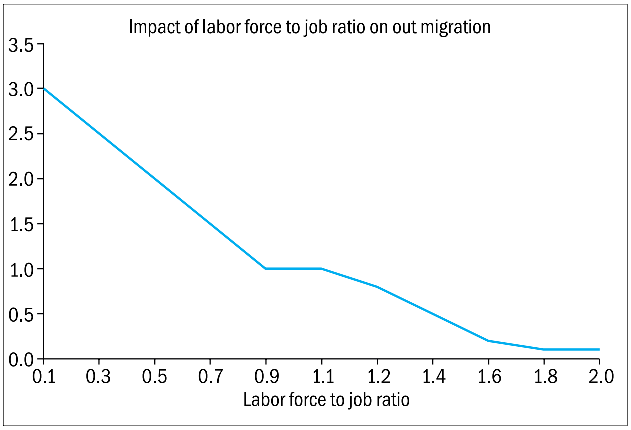
Annexure

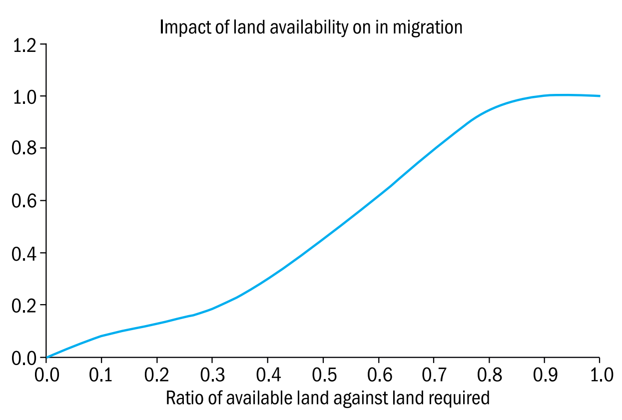
Key Parameter Values and Sources

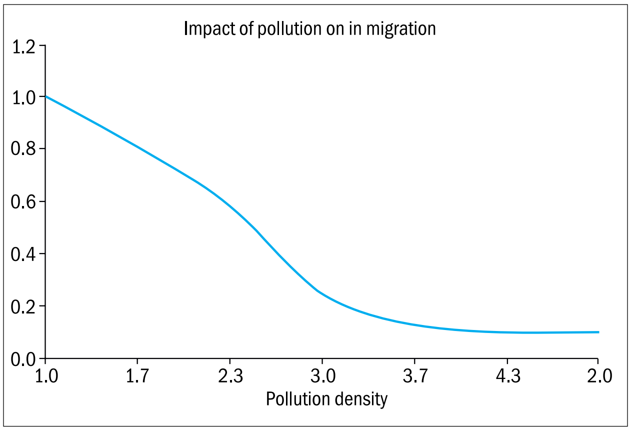
Sl. No	Parameter	Value	Source
1	Population birth rate normal	1.5%	Surat Municipal Corporation (n.d.)
2	Population death rate normal	0.4%	Surat Municipal Corporation (n.d.)
3	Labour force percentage	40%	Surat Municipal Corporation (n.d., p. 2)
4	New business start-up rate normal	5.0%	Estimated through sensitivity runs
5	Active business life cycle (years)	40	Estimated through sensitivity runs
6	Jobs per business (people)	40	Estimated through sensitivity runs
7	Annual rainfall (mm)	1,200	Agriculture Contingency Plan, Surat District (Government of India) (Agriculture Contingency Plan n.d.)
8	Water infiltration rate	8.0%	Dynamic Groundwater Resources of India—2011 (Central Groundwater Board 2011)
9	Per capita water required (litres per day)	165	Service delivery of water and sanitation, challenges faced by metropolitan cities (Surat city) (ICRIER 2013)
10	Per business water required (litres per year)	220,000	Service delivery of water and sanitation, challenges faced by metropolitan cities (Surat city) (ICRIER 2013)
11	Per capita solid waste generation (kilograms per day)	0.30	CPCB status report on municipal solid waste management (Central Pollution Control Board n.d.)
12	Solid waste collection fraction	0.9	Surat Municipal Corporation (n.d., p. 3)
13	Solid waste treatment fraction	0.7	Approximated based on (Surat Municipal Corporation n.d., p. 3)
14	Total open land available (hectares)	319,125	Surat Urban Development Authority (Surat Urban Development Authority n.d.)
15	Per capita open land required (hectares)	0.005	Calculated based on (Sustainability Outlook 2012)
16	Per business open land required (hectares)	0.06–0.001	Approximated based on (Sustainability Outlook 2012)
17	1950 Level of population stock	600,000	Approximated through sensitivity runs and using Surat Municipal Corporation data (n.d, p. 4)
18	1950 Level of active business stock	6000	Approximated through sensitivity runs

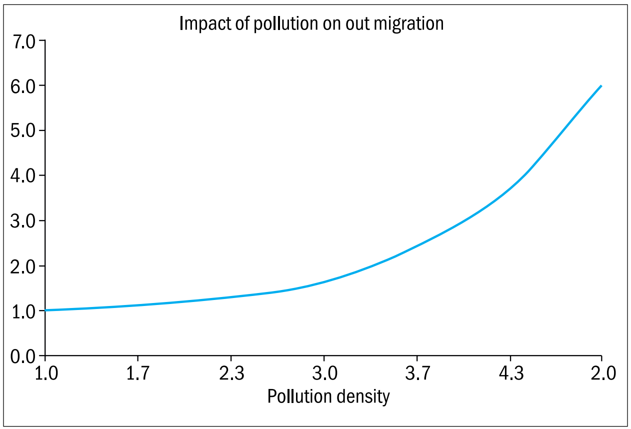
Graphical functions

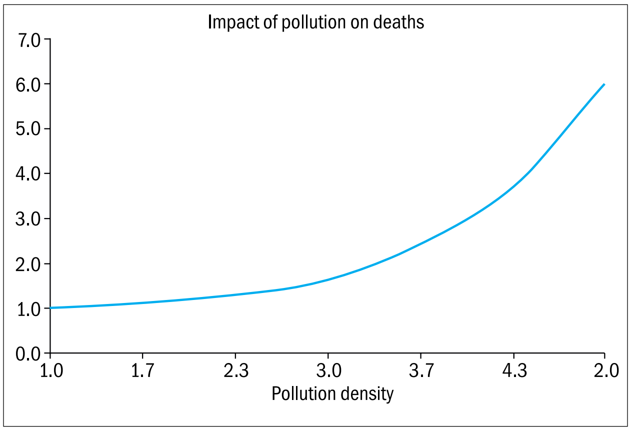


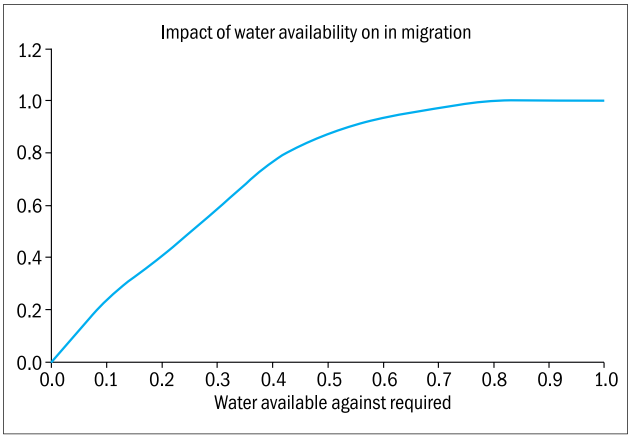


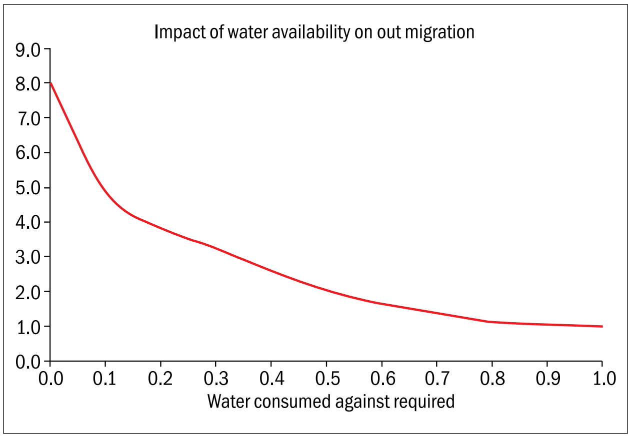


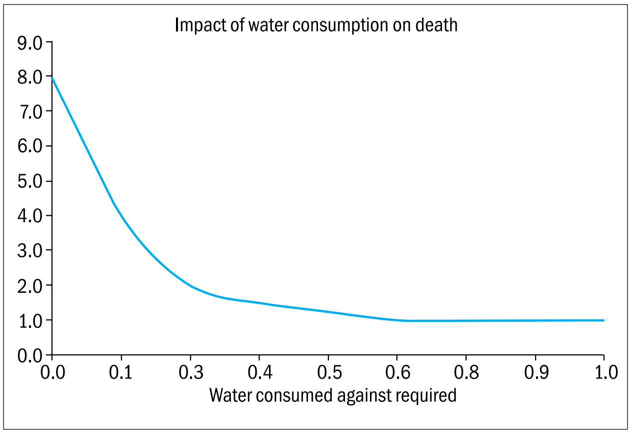











Impact of water consumption on death
9.0
8.0
7.0
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3.0
2.0
1.0
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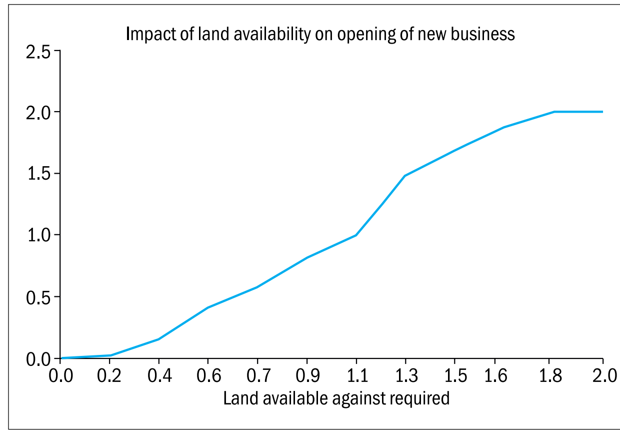
0.0 0.1 0.3 0.4 0.5 0.6 0.8 0.9 1.0
Water consumed against required


Impact of land availability on opening of new business
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2.0
1.5
1.0
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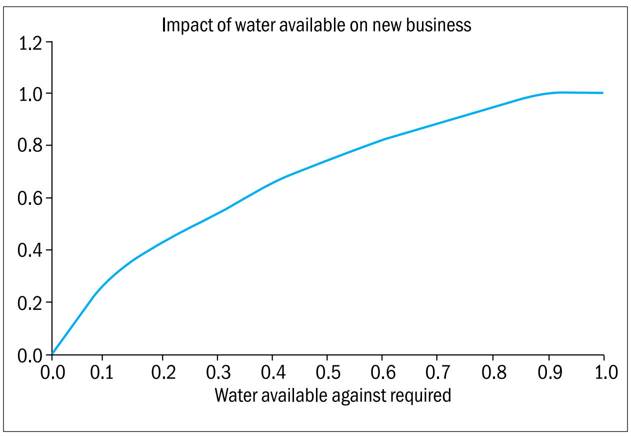
0.0 0.2 0.4 0.6 0.7 0.9 1.1 1.3 1.5 1.6 1.8 2.0
Land available against required


Impact of water available on new business
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1.0
0.8
0.6
0.4
0.2
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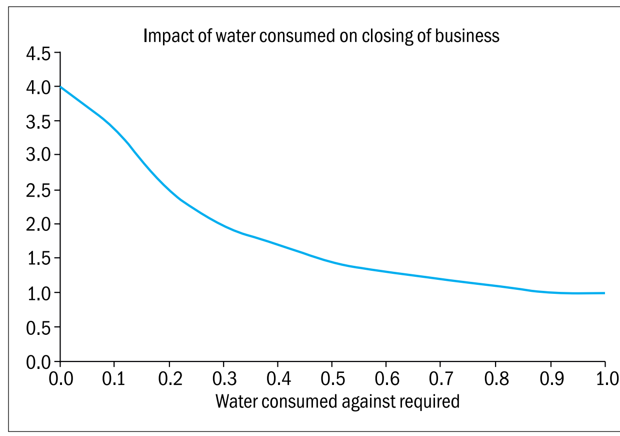
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Water available against required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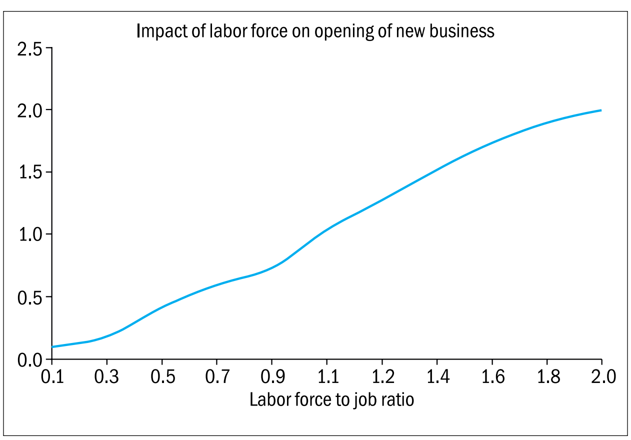
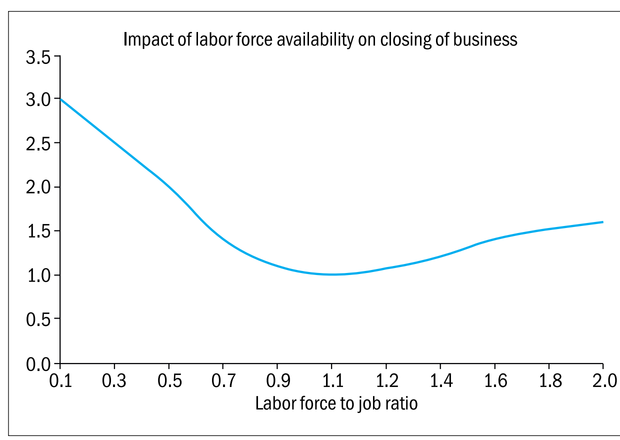
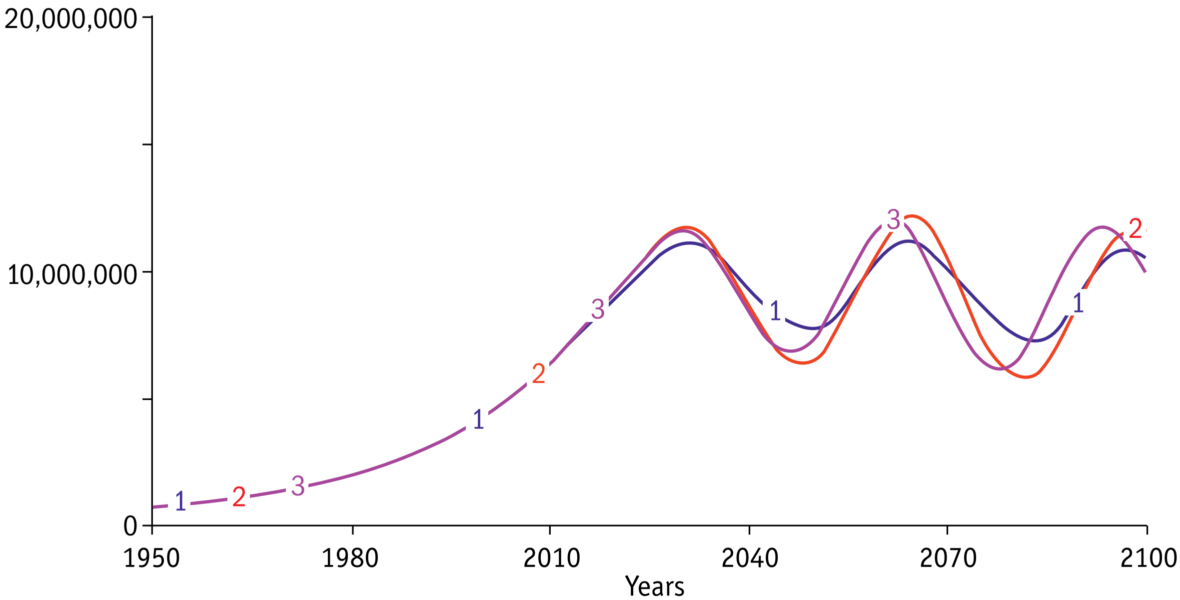
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Water consumed against required


Impact of labor force on opening of new business
2.5
2.0
1.5
1.0
0.5
0.0
0.1 0.3 0.5 0.7 0.9 1.1 1.2 1.4 1.6 1.8 2.0
Labor force to job ratio


Impact of labor force availability on closing of business
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0.1 0.3 0.5 0.7 0.9 1.1 1.2 1.4 1.6 1.8 2.0
Labor force to job ratio

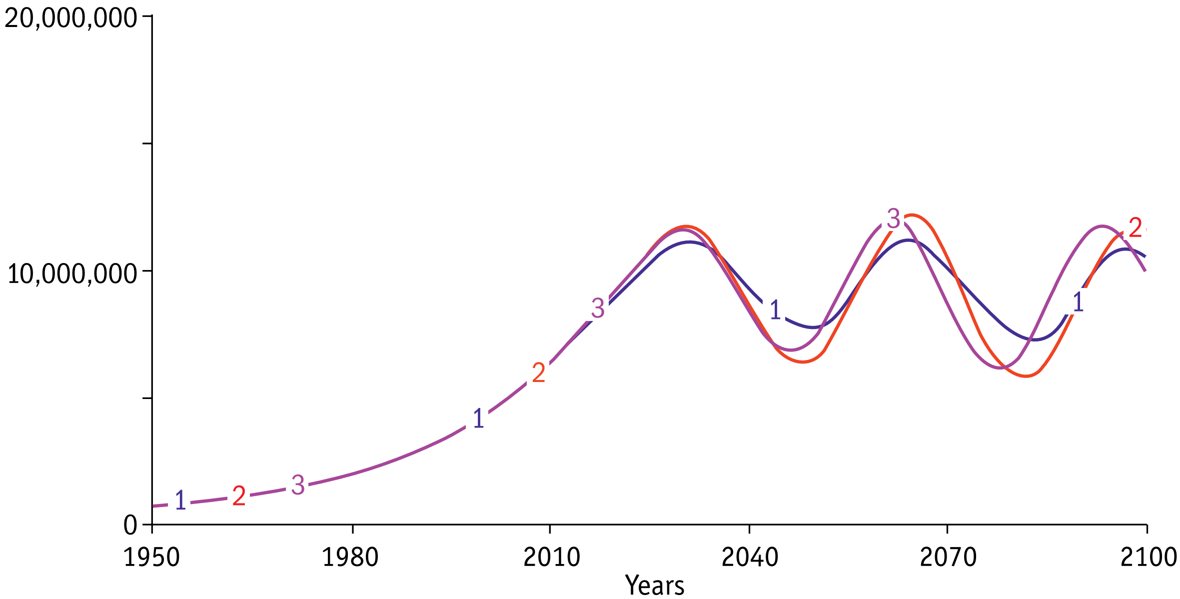
Sensitivity Runs

1. Population sensitivity towards Impact of Environment Pollution on Out migration



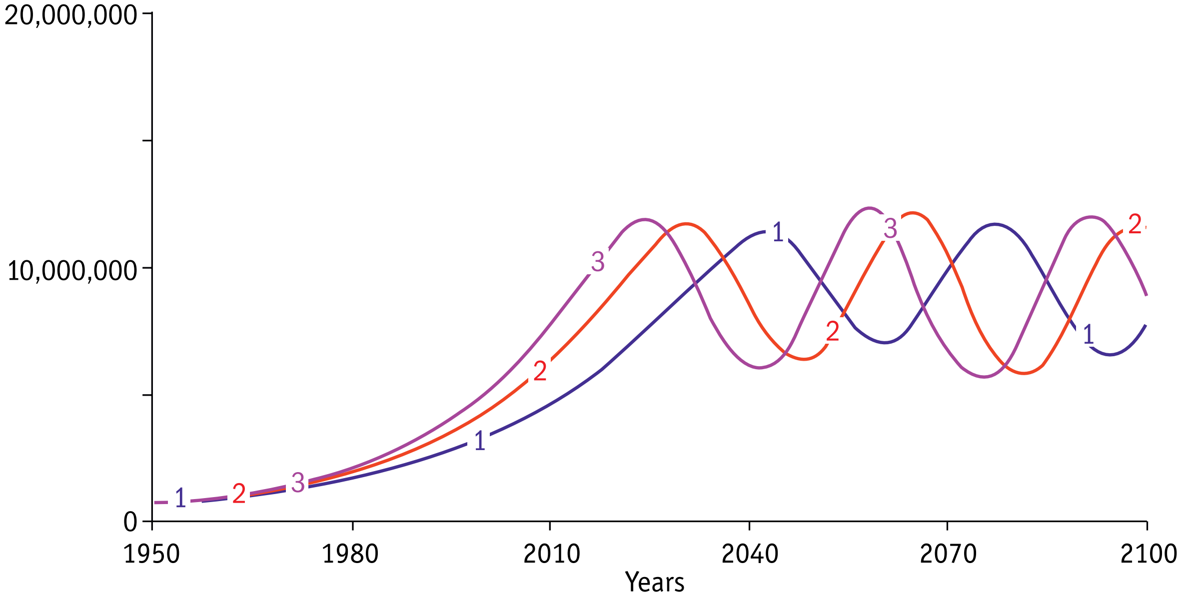
Sensitivity run-environment pollution impaction out migration

2. Population Sensitivity towards Impact of Job Availability on In Migration



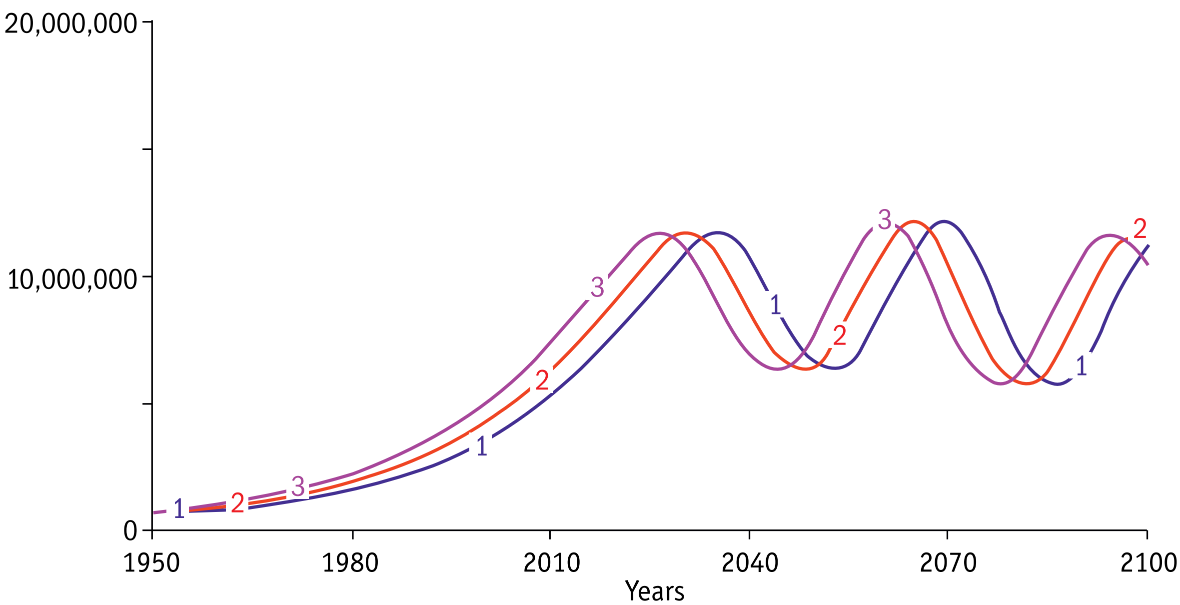
Sensitivity run-environment pollution impaction out migration

3. Population Sensitivity towards business closing



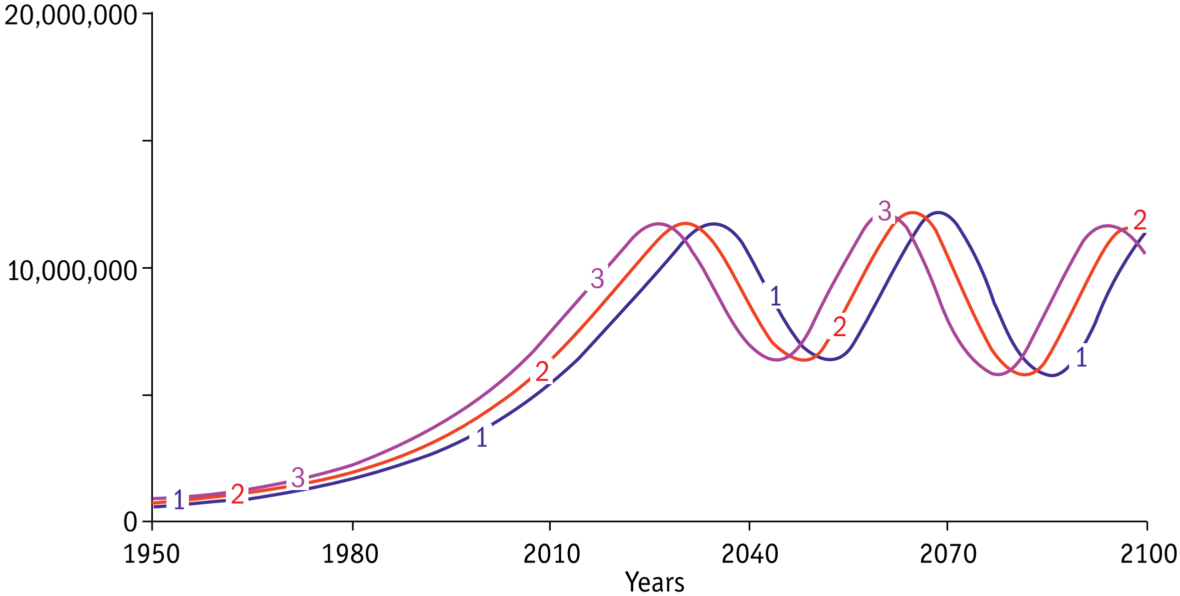
Sensitivity run-business life cycle

4. Population Sensitivity towards Initial Value of Active Businesses



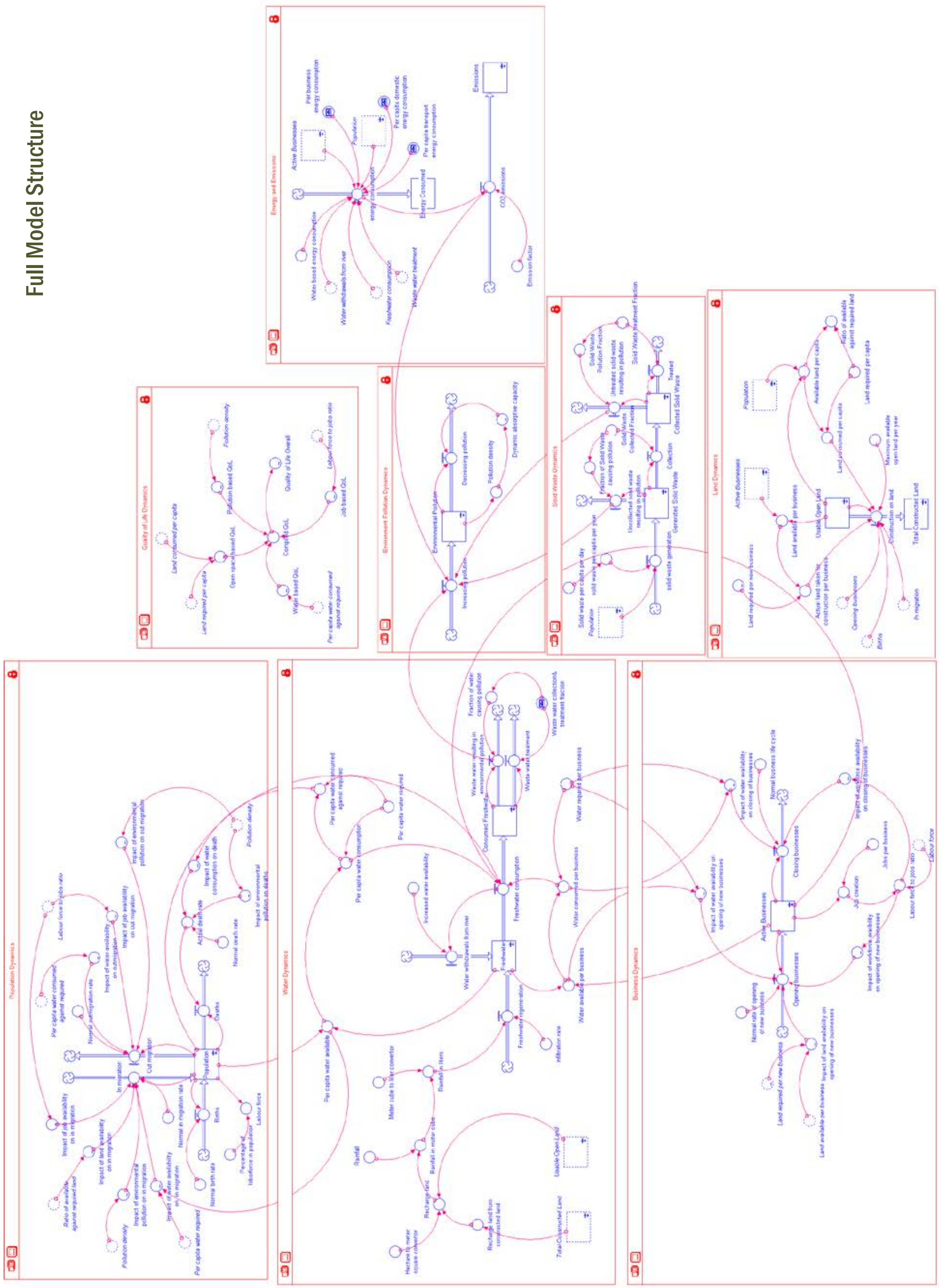
Sensitivity run-initial value of active business

5. Population Sensitivity towards Initial Value of Population Stock



Sensitivity run-initial value of population stock

Full Model Structure



This is part of a series of policy briefs by TERI based on its research work in specific areas. These briefs are made available to Members of Parliament, policymakers, regulators, sectoral experts, civil society, and the media. The briefs are also accessible at http://www.teriin.org/policybrief/. The purpose is to focus on key issues and list our policy recommendations to encourage wider discussion and debate. We would very much value your comments and suggestions.

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