URBAN DYNAMICS, MODELS AND APPLICATIONS (IATB LOOP)

CNRS SUMMER SCHOOL

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Definition and Scope = Urban Dynamics analyzes the dynamics of the urban life cycle in order to answer a number of pressing questions:

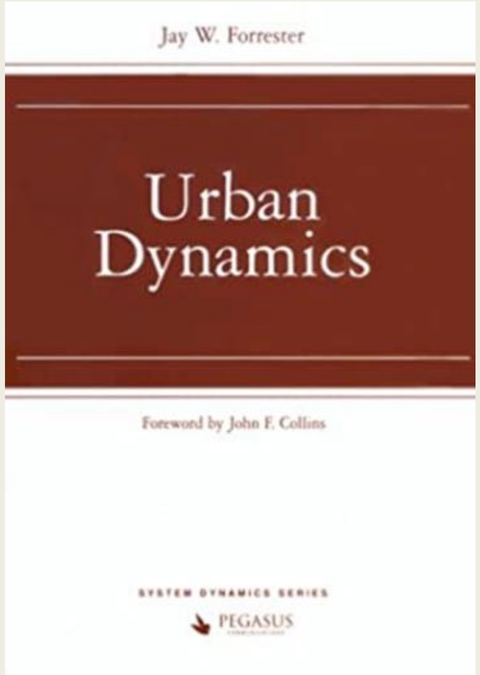
What makes cities develop sustainably or grow chaotically?
What can be done to revitalize deprived or stagnant urban areas?
What kind of urban management programs have to be implemented in order to sustainably harvest urban resources and enable a harmonious development of city areas?

Methodology : Cities and urban areas are complex systems which are non-linear, and involve multiple feedback loops and time delays (Diemer, Nedelciu, 2020), J.W Forrester (1969) introduced a methodology called *Urban Dynamics.* Urban Dynamics proposes a new analysis of the urban dilemma based on System Dynamics. Simulation computing models are used to isolate the dynamic characteristics of the system, to stimulate the behavior of the system and to show how the behavior of the system might be modified.

System Dynamics for Sustainable Urban Planning

System dynamics was developed at MIT during the 1950s by J.W. Forrester. His first book *Industrial Dynamics* (1961) contains the seeds of a method that was to prove successful in the 1970s, notably through the *Limits to Growth* (Meadows et al. 1972). For Forrester (1961), industrial dynamics was a way of studying the behavior of industrial systems to show how policies, decisions, structure and delays are interrelated to influence growth and stability. To speak of systems "*implies a structure of interacting functions. Both the separate functions and the interrelationships as defined by the structure contribute to the system behavior*" (Forrester 1967: 1). To describe a system, we have to describe not only the separate functions, but their method of interaction. Thus, to identify the structure of a specific system, one should understand the fundamental nature of the structure common to all dynamic systems.

In *Principles of systems* (1968) and *Urban Dynamics* (1969), Forrester proposed a detailed description of the system dynamics approach and recognized four hierarchies of structure: (1) closed boundary around the system; (2) feedback loops as basic structural elements within the boundary; (3) Level (state) variables representing accumulations within the feedback loops; (4) Rate (flow) variables representing activity within the feedback loops.



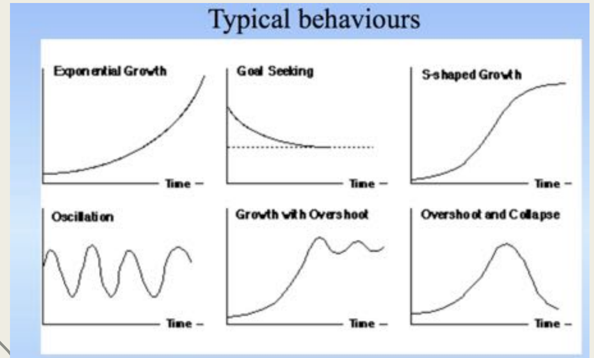
A Closed boundary	
1 Feedback loops	
	a Levels b Rates

(Forrester 1967, p. 2).

Table 1. Leverage points of Donella Meadows. Places to intervene in a system (in increasing order of effectiveness).

12) Constants, parameters, numbers (such as subsidies, taxes, standards)	6) The structure of information flows (who does and does not have access to what kinds of information)
11) The sizes of buffers and other stabilizing stocks, relative to their flows.	5) The rules of the system (such as incentives, punishments, constraints)
10) The structure of material stocks and flows (such as transport networks, population age structures)	4) The power to add, change, evolve, or self-organize system structure
9) The lengths of delays, relative to the rate of system change	3) The goals of the system
8) The strength of negative feedback loops, relative to the impacts they are trying to correct against	2) The mindset or paradigm out of which the system—its goals, structure, rules, delays, parameters—arises
7) The gain around driving positive feedback loops	1) The power to transcend paradigms

Source: Meadows (1999).



Archetypes

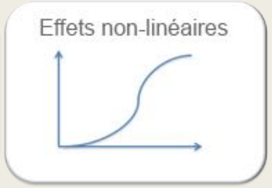
Leverage Points

Limits of the system

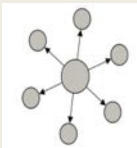
Forest Thinking

Causalities vs correlation

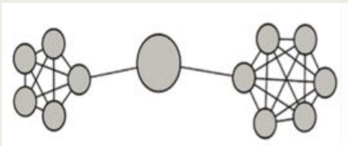
Loops CLD, SFD

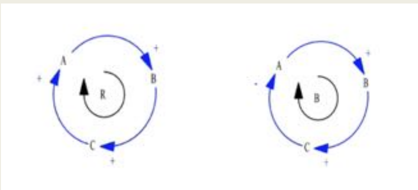


High level of exits

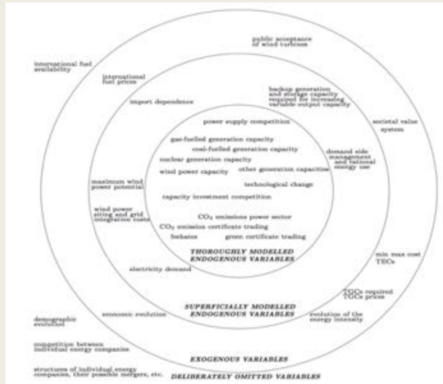


Mediation





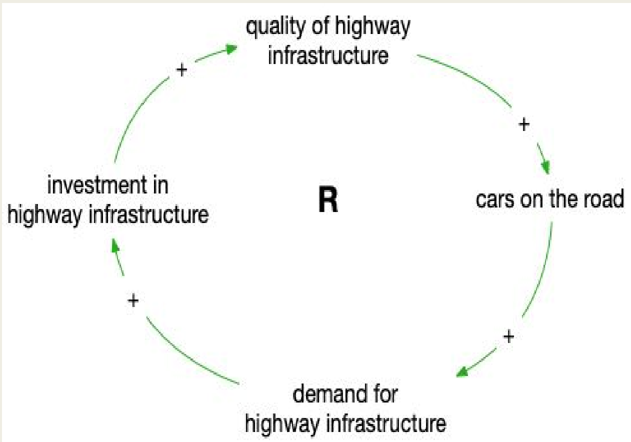
Source : Sterman (2000), Diemer (2004)

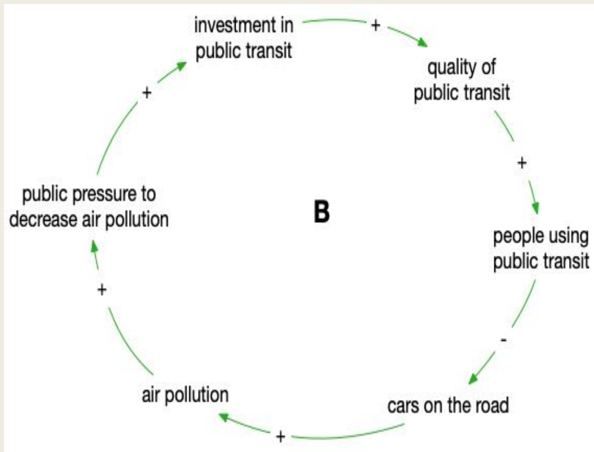


Closing the loop vs
Opening the loop

Feedback loop structure: The dynamic behavior of systems is generated within feedback loops (Roberts 1975). A feedback loop is composed of two kinds of variables, called rate and level variables. A feedback loop is a structure within which a decision point – the rate equation – controls a flow or action stream. The action is integrated to generate a system level of behavior. Information about the level is the basis on which the flow rate is controlled.

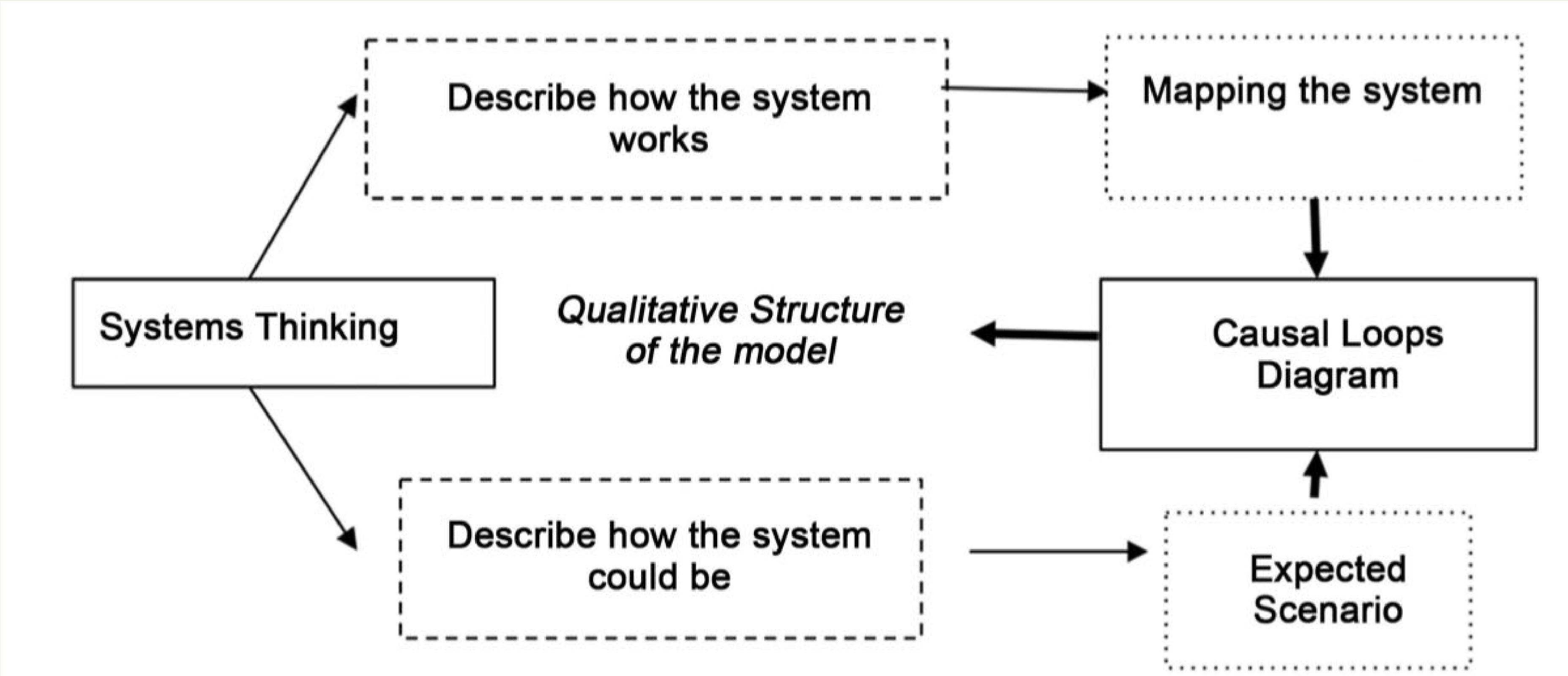
Each causal link in a model has a polarity, the direction of effect that the influencing variable has on the influenced variable. The nature of that influence depends on the type of causal link being considered. In a system dynamics model, the polarity of each feedback loop is a crucial part of understanding the model behavior. The perturbation of a loop may result in the magnification of the original effect; this unstable response is known as a positive feedback loop polarity. Alternatively, a perturbation may be counter-acted, or resisted by the operation of the loop. This equilibrating response is known as a negative feedback loop polarity.

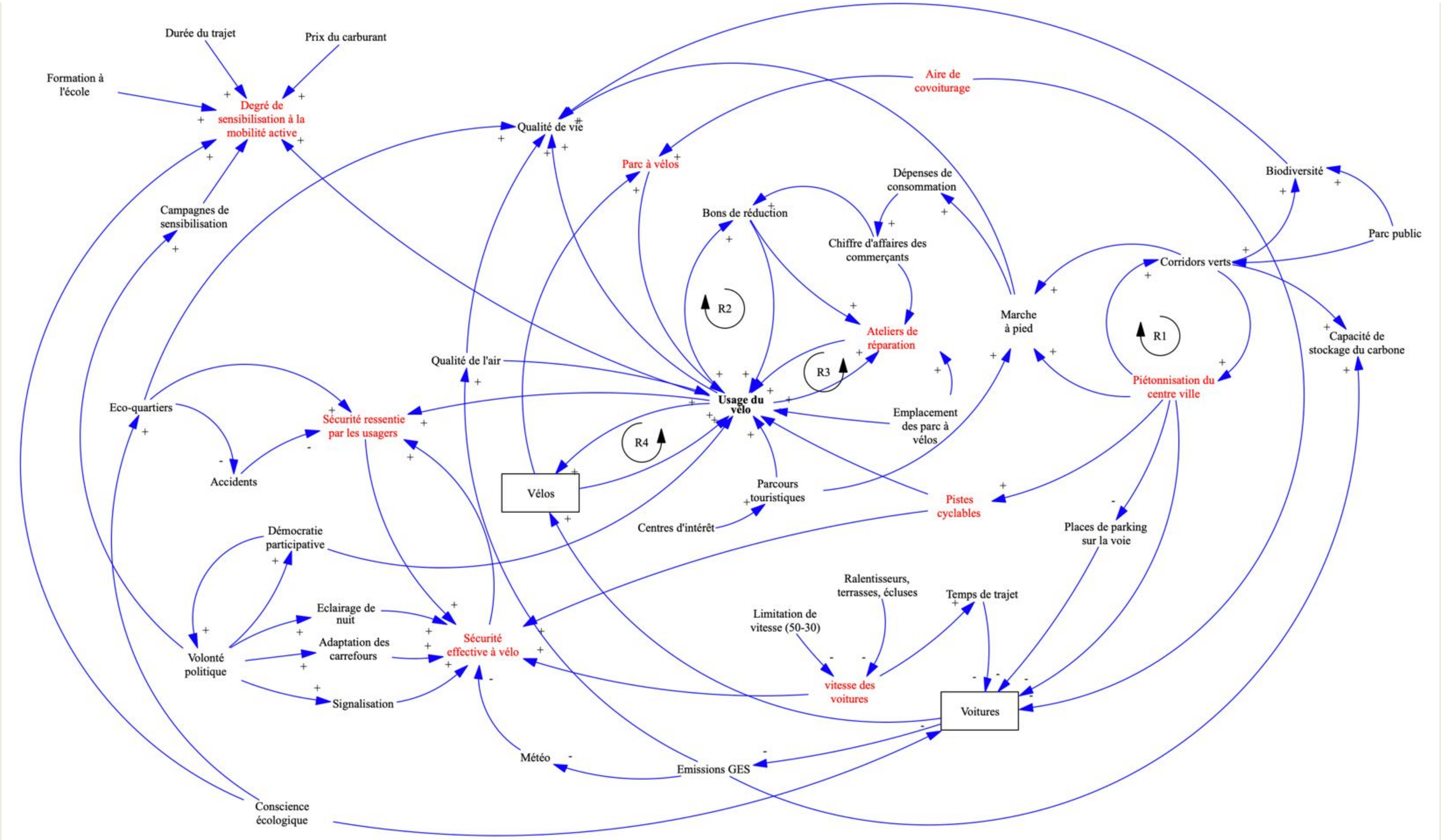




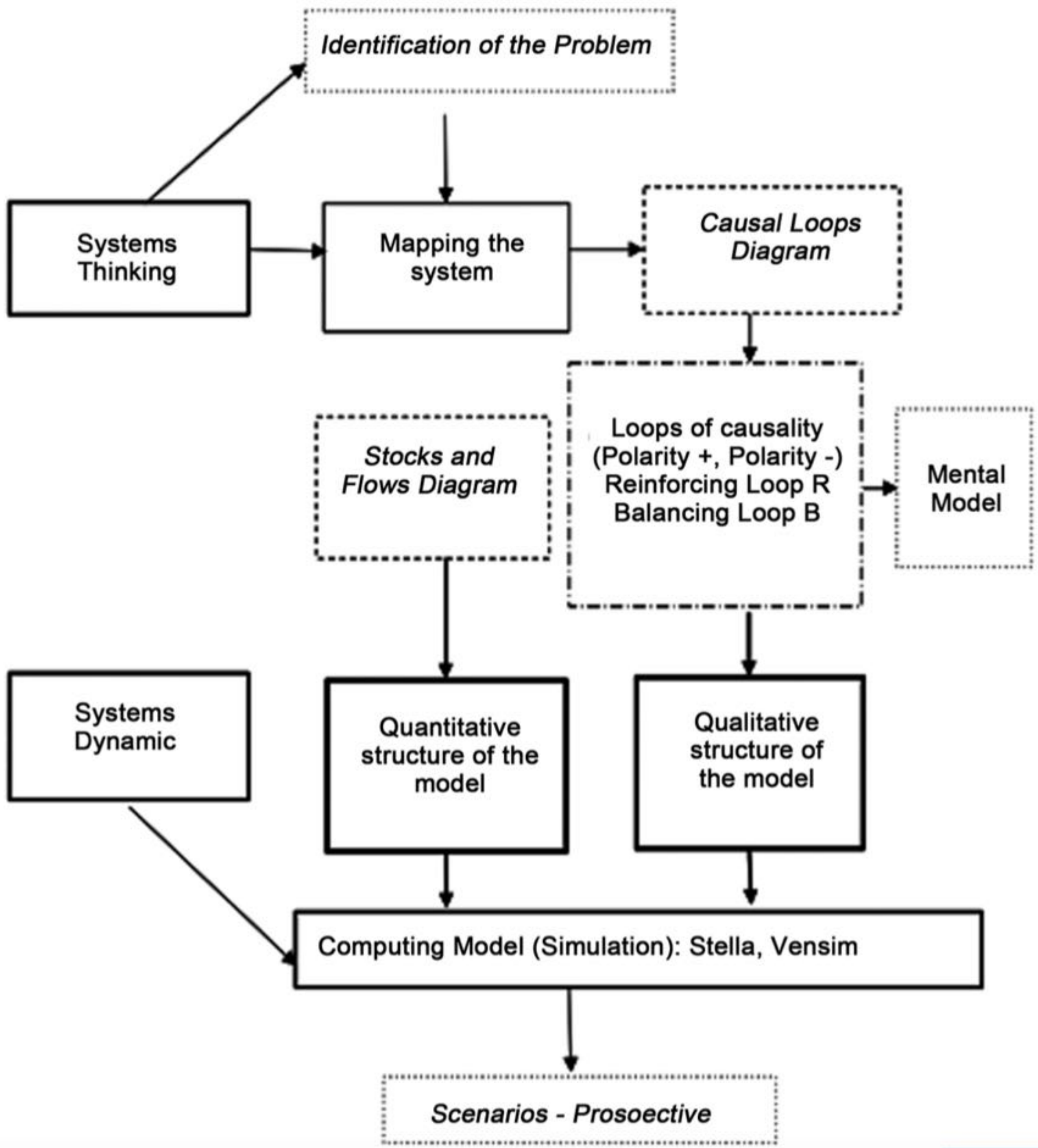
Source : Diemer, Nedelciu, 2020

Methodology

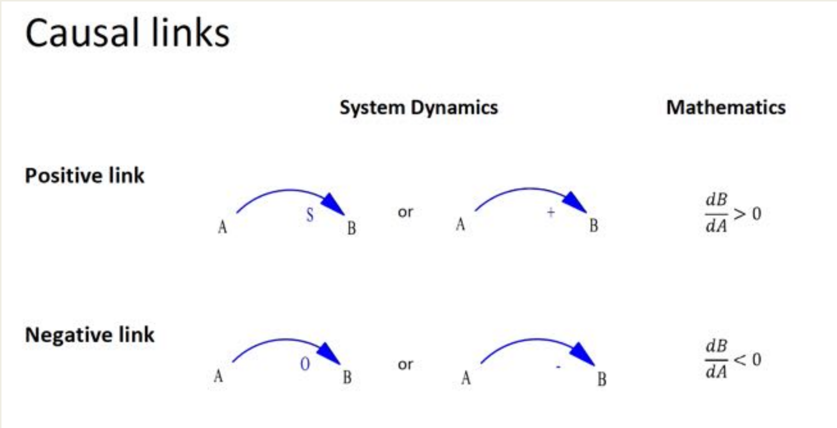


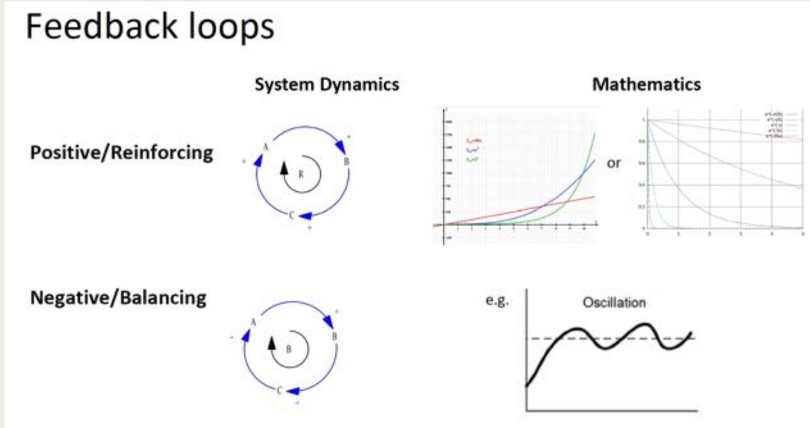


Durée du trajet
Prix du carburant
Formation à l'école
Degré de sensibilisation à la mobilité active
Qualité de vie
Aire de covoiturage
Parc à vélos
Dépenses de consommation
Biodiversité
Bons de réduction
Chiffre d'affaires des commerçants
Parc public
Campagnes de sensibilisation
Corridors verts
R2
Ateliers de réparation
Marche à pied
R1
Capacité de stockage du carbone
Qualité de l'air
R3
Piétonnisation du centre ville
Eco-quartiers
Sécurité ressentie par les usagers
Usage du vélo
Emplacement des parc à vélos
R4
Accidents
Vélos
Parcours touristiques
Pistes cyclables
Centres d'intérêt
Places de parking sur la voie
Démocratie participative
Ralentisseurs, terrasses, écluses
Temps de trajet
Limitation de vitesse (50-30)
Eclairage de nuit
Adaptation des carrefours
Sécurité effective à vélo
Volonté politique
vitesse des voitures
Signalisation
Voitures
Météo
Emissions GES
Conscience écologique


Identification of the Problem
Systems Thinking
Mapping the system
Causal Loops Diagram
Stocks and Flows Diagram
Loops of causality (Polarity +, Polarity -) Reinforcing Loop R Balancing Loop B
Mental Model
Systems Dynamic
Quantitative structure of the model
Qualitative structure of the model
Computing Model (Simulation): Stella, Vensim
Scenarios - Prosoective

Mathematical structure of modelling



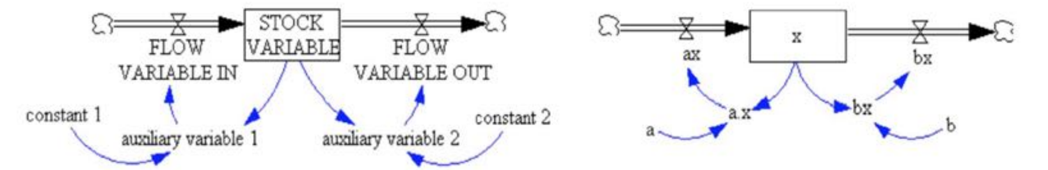


STOCKS : State Variable

They accumulate inflows and outflows of materials and information. They change slowly (Delays) Mathematically: Integral flow calculation

$$\mathrm{Stock}(t) = \int_{t_0}^{t} [\mathrm{Inflow}(s) - \mathrm{Outflow}(s)]ds + \mathrm{Stock}(t_0)$$

$$x = x_0 + \int_{t_0}^{t} (+ax - bx)\, dt$$



Urban Dynamics Structure

Urban Dynamics presented system dynamics as a computer simulation model of how a city grows, stagnates or decays. It is also a tool to be used by urban policy makers to tackle different challenges and to initiate scenario planning (Diemer et al., 2018). It is possible to present the structure of the urban model as following:

(1) *Definition of urban system boundaries*. The model shows how an area develops from empty land. Afterwards, the behavior of a city is directly dependent on its ability to change the internal mix of industry, housing and population. These three subsystems have been chosen because they appear to be the dynamic framework of urban structures. The changes in housing, population and industry are the central processes involved in growth and stagnation of the city. For Forrester, "*these three key drivers are more fundamental than city government, social culture or fiscal policy*" (1969: 17).

(2) *The environment as a Point of Reference*. If the conditions in the urban area are more favorable than those outside, people and industries will move in (the reverse is also true). Thus, the urban area is represented as a living, self-controlling system that regulates its own flows of people to and from the outside environment.

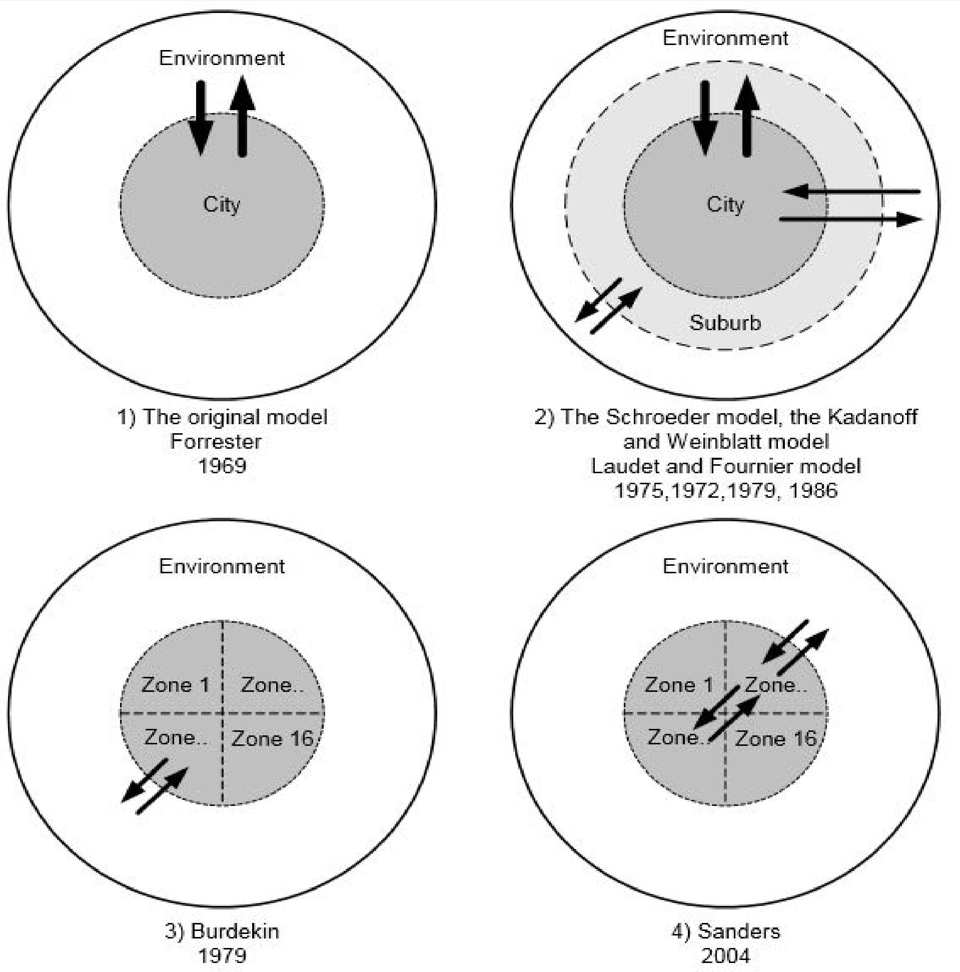
(3) *Relative attractiveness*. The model shows how the area becomes more or less attractive than the surrounding country and other cities and thereby causes the movement of industry and population to and from the area. Thence, differences in attractiveness between the city and environment are significant.

(4) *The internal System*. From the three subsystems, it is possible to differentiate the top subsystem (business activity), the middle subsystem (housing) and the lower subsystem (population). The top subsystem contains three levels and four rates representing business activity. At the beginning, new enterprise units are created. An enterprise unit is taken as a standard land and building area. The new enterprise - as a function of time and aging - shifts to the category of mature business. After the further passage of years mature business ages into the category of declining industries and still later is demolished and disappears. The middle system consisting of three levels and six rates, represents the construction, aging and demolition of housing. Premium housing is associated with the managerial-professional population. After an aging time and depending on the need for premium housing, the premium housing declines into the worker-housing category. In addition worker housing is constructed directly without passing through the premium-housing category. Worker housing ages and declines into the underemployed-housing category. The lower system with three levels and twelve rates represents the population.

Three categories of people are defined: manager-professional, labor and underemployed. The labor is skilled labor fully participating in the urban economy. Underemployed workers include unemployed and unemployable people, people in unskilled jobs, those in marginal economic activity and those not seeking employment but who might work in a period of intensive economic activity. People can enter each category from outside environment and leave to the outside. Each category has an internal birth rate. There is also an upward (and downward) economic mobility from the underemployed to the labor class and from the labor class to the managerial-professional group (and vice versa).

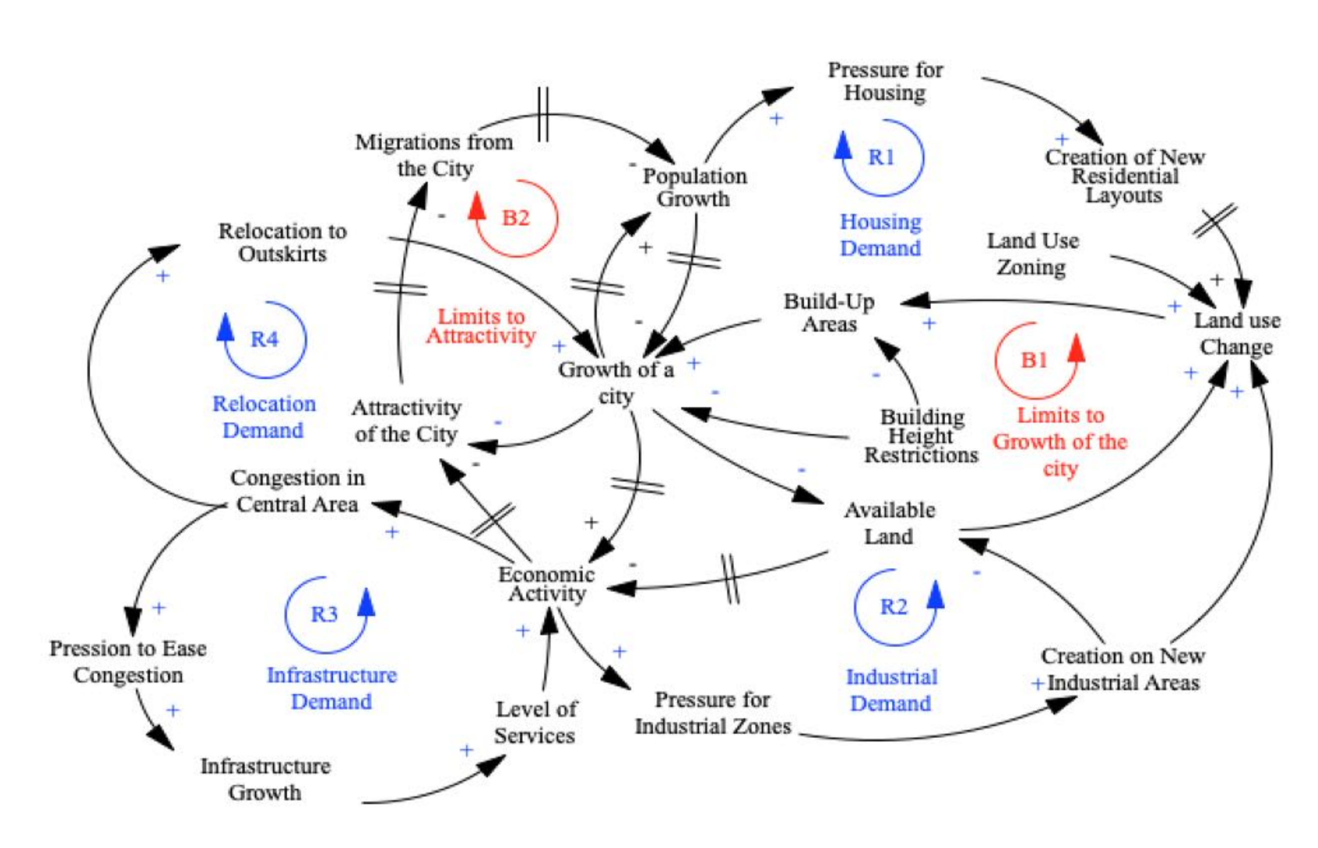
Sub-systems	Business Activity	Housing	Employment
Levels	New Enterprise Mature Business Declining Industries	Premium Housing Worker Housing Underemployment Housing	Manager-Professional Labor Underemployment
Rates	1/ New-Enterprise Construction 2/ New-Enterprise Decline 3/ Mature-Business Decline 4/ Declining-Industry Demolition	1/ Premium Housing Construction 2/ Premium Housing Obsolescence 3/ Worker Housing Construction 4/ Worker Housing Obsolescence 5/ Low Cost Housing Program 6/ Slum Housing Demolition	1/ Underemployed Birth Rate 2/ Labor to Underemployed 3/ Underemployed to Labor 4/ Underemployed Departures 5/ Labor Birth Rate 6/ Labor Arrivals 7/ Labor Departures 8/ Labor to Manager 9/ Managerial Professional Birth Rate 10/ Manager Arrival 11/ Manager Departures 12/ Manager to Labor
Parameters in the simulation model	New-enterprise assessed value Mature-business assessed value Declining-industry assessed value	Land Area, Land per house, Land per productive unit Premium-housing population density, worker-housing population density, under-employed-housing population density Premium-housing assessed value, worker-housing assessed value, underemployed-housing assessed value	Managerial-Professional family size Labor family size Underemployed family size Tax per management person Tax per labor person Tax per underemployed person Tax assessment normal

Finally, the model contains the major components of the city: three classes of population (the underemployed, labor and management), three types of housing (one for each of the population classes) and three types of industry (new, mature and declining). The changes over time of each of these drivers are controlled by one or more of the 22 rate variables which are functions of behavior characteristics, exogenously set policies. The driver are, what produce the cities' perception. Urban Dynamics shows how urban problems such as housing shortages or unemployment are generated by internal forces and cannot be solved by placing accountability on external symptoms.



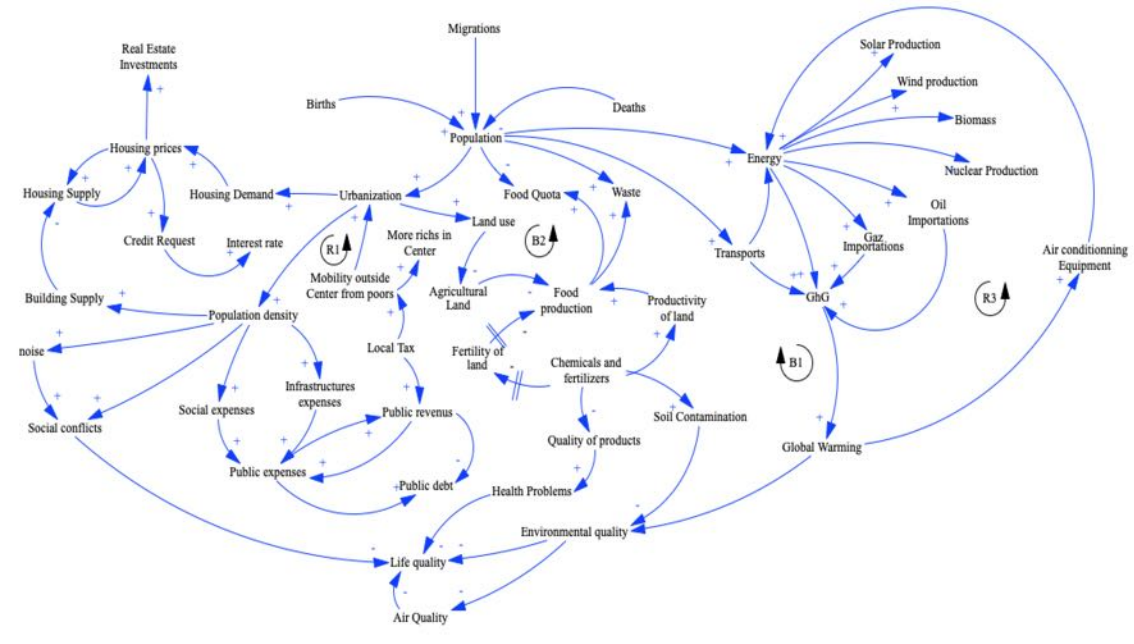
The book generated many controversies. First, there was a *boundary problem*: there are several observations that invalidate the assumption that the environment does not substantially influence the urban area. Second, there was the *problem of the limitless environment*: people are available from the outside for migration into the area whenever this one appears more attractive than the point from which people may come from and vice-versa. Lastly, *the use of the data* issue: the theory was formulated without recording empirical data. Forrester's original idea of Urban Dynamics has been improved over time by Kadanoff & Weinblatt (1972), Schroeder (1975), Laudet & Fournier (1979), Fournier (1986) and Sanders and Sanders (2004). The basic assumption is that there is a normal fraction of residents that migrate into the city (zone) or out. These normal fraction rates are modulated by the attractiveness of the city compared to its environment or other zones (Sanders, Sanders, 2004).

To resume this part, the main purpose of Urban Dynamics modelling is solving a problem by creating causal looping with four basic elements: the variables, the links between them, the signs on the links and the sign of the loop. Figure illustrates the investigating method by Forrester. Here, the key variables are: population growth, economic activity, pressure for new housing, pressure for industrial areas, land-use zoning, available land, built-up area, level of services and building height restrictions. The six feedbacks generated in the system were divided in Reinforcing (R) and Balancing (B) loops: housing demand (R1) ; industrial demand (R2) ; infrastructure demand (R3) ; relocation demand (R4) ; limits to growth for the city (B1) and limits to attractivity (B2).



Sustainability challenges for Urban Dynamics

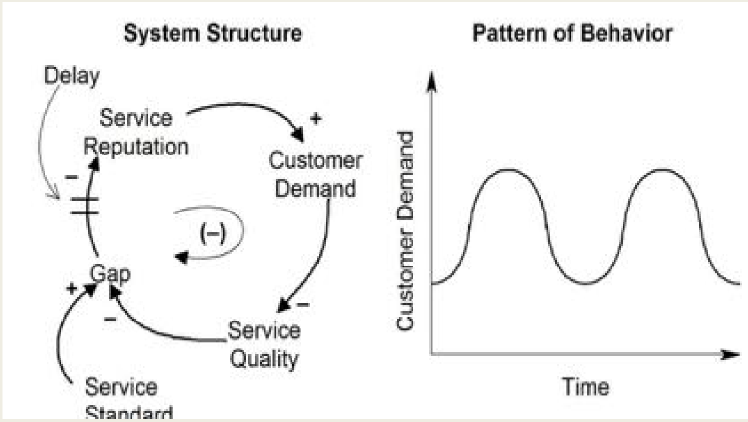
Since Forrester's work, a large number of research studies (Gale et al. 2001) have sought to analyze the driving forces of city dynamics. While employment, residential preferences and population still feed the underlying trends in urban development, new challenges emerged in the 2000s. Urban Dynamics is now an excellent method for integrating increasingly complex problems and simulating long-term scenarios for public decision-makers. In the following, we will address four of these challenges: (i) the question of exogenous shocks of a global character, such as climate change; (ii) the implementation of an ecological transition aimed at reducing the footprint of human activity; (iii) the consideration of the social and political dimensions of Urban Dynamics (as in the case of governance and the decentralization process); and finally (iv) the integration of post-growth scenarios into the landscape and design of future large metropolitan areas.



(i) Models based on Urban Dynamics methodology have a strong emphasis on the internal dynamics of the system. The driving forces of the system are endogenous (Sanders and Sanders 2004) and what could be called an environment -or exogenous variables- is generally considered to be given and local (Forrester 1969). However, climate change introduces a new issue, that of the resilience of cities (Meerow et al. 2016). What will be the policies for adaptation and mitigation of climate change at the city level? This is very important because cities are both places where greenhouse gases are produced and places where the consequences of these emissions are increasingly visible.

(ii) The ecological transition of cities is largely based on their ability to incorporate issues (Seeliger and Turok 2013), such as the preservation of biodiversity into their long-term strategy; consumption and production of renewable energies; the use of water; the different forms of mobility and their CO2 intensity; an air quality. Urban Dynamics must give policy makers the tools to understand the global scope of their actions. Climate - Energy - Air local plans are a good illustration of political actions accompanying the ecological transition of cities, especially for rapidly urbanizing cities in developing countries (Bharat and Ali 2018). In figure , the reinforcing loop (R3) shows that global warming may induce population to buy and use more air-conditioning equipment, which causes the growth of energy demand, creates more carbon emissions and so intensifies global warming. The balancing loop (B2) emphasizes that an increase in population intensifies the urbanization process and generates competition with land use for agriculture. If agricultural land disappears in favour of urban expansion, this can only lead to massive use of agro-chemicals such as fertilizer and pesticide products to maintain yields and food quotas, which could eventually cause health problems and lead to higher mortality rates in the future.

(iii) The social and political dimensions are also one of the research topics in Urban dynamics, particularly because the method combines the structure of the system with the determination of behavioral patterns (Forrester 1971).



Thus, understanding social dynamics is part of Urban Dynamics' research program (Psyllidis 2016). However, issues related to governance, centralization and decentralization processes or stakeholder integration are now at the forefront. While Urban Dynamics provides a good method for scenarizing the future, it also takes account of stakeholders through what is usually called Participatory Modelling. Participatory modeling is a purposeful learning process for action that engages the implicit and explicit knowledge of stakeholders to create formalized and shared representations) of reality. In this process, the participants co-formulate the problem and use modeling practices to aid in the description, solution, and decision-making actions of the group (Videira and Ali 2010; Voinov 2018).

(iv) It is generally accepted to emphasize that system dynamics, as a method, describes what is, not what should be (Sterman 2000). Thus, the data collection and scenarios considered are based on an objective and reasoned understanding of a complex system. For example, System Dynamics can be used to identify the consequences of an expansion of the city on the consumption of natural resources. System Dynamics would thus be linked to a more global approach, Systems Thinking (Meadows 2008). However, research on the Post-Growth movement, which is both academic but also rooted in utopian and ideological debates, tends to underline that the dynamics of systems can also be mobilized to design what should be (Jackson 2009). Thus, it would be possible to transpose certain forms of strong sustainability (e.g. organic food, short circuits, agro-ecology, sustainable mobility, renewable energy, non-profit organizations, local currencies, etc.) into an integrated system.

The causal loop diagrams (CLDs) are powerful tools for identifying driving forces and controversies associated with societal issues (Abson & ali 2017), as well as for identifying leverage points of intervention in the system.

Urban dynamics : Applications

Scale

iSDG Model (national)

Recalibrating to the city level or local scale

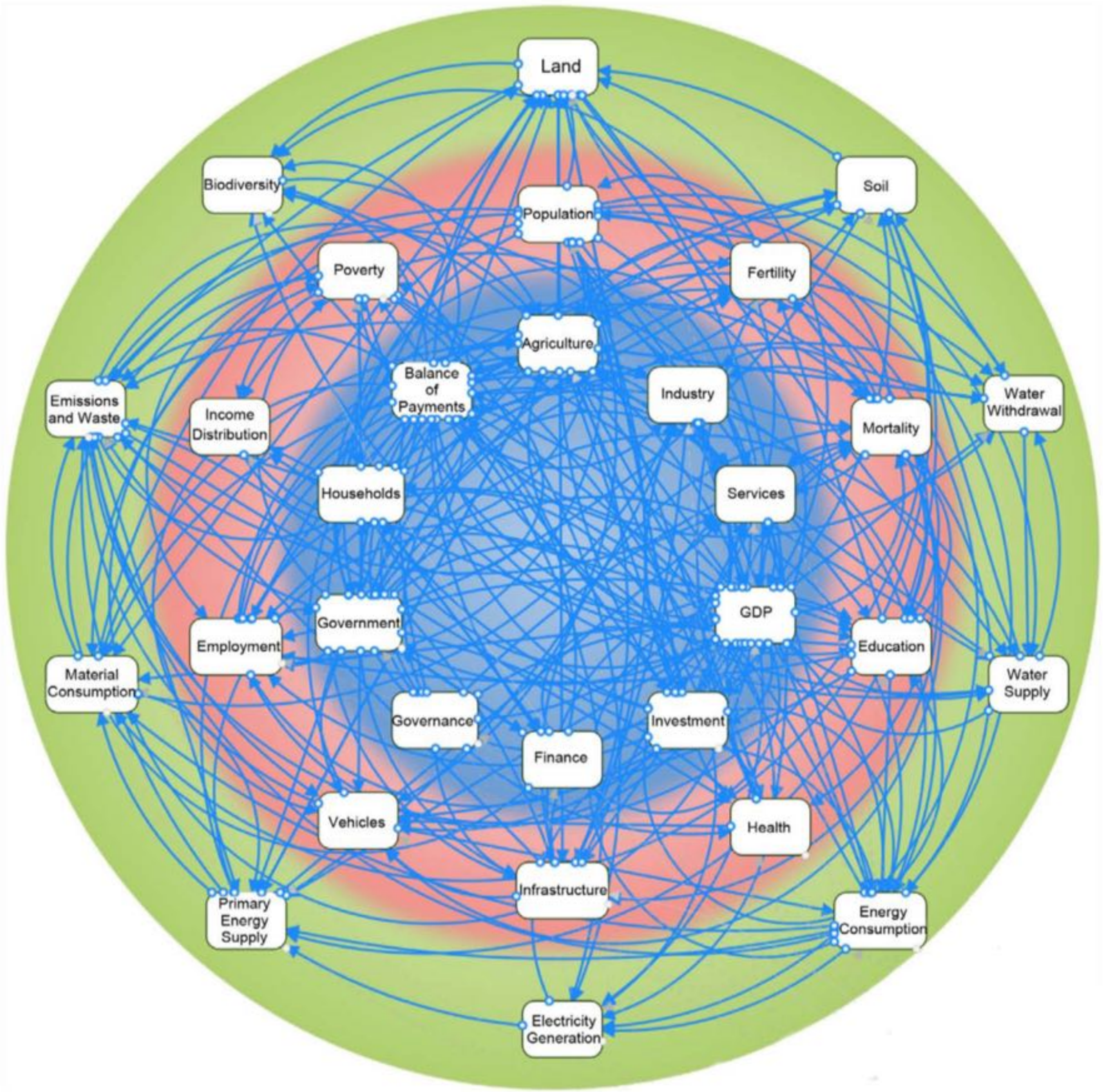


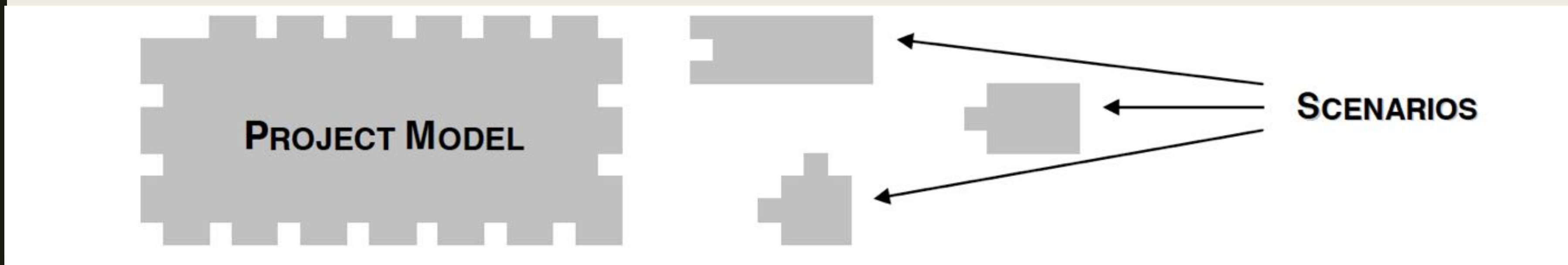
Figure 4. Framework of the T21 model. Source: Millennium Institute.

Scénario – strong sustainability

Boundaries of the system

Structure of the Model → SCENARIOS

Models for climate, energy, food : + 2° C, Carbon tax, 20% solar energy, 25% organic products, CLEWS MODEL, PROMETHEUS MODEL, GEM-E3 MODEL



The project model defines the project's expected behavior, while scenario models describe alternative routes that the project may follow, due to unexpected events.

Leverage points for strong sustainable scenario

Wood Solar Energy Hydro Steam Network Km/passenger Shared Car Electric car

Velo Using Gratuité du transport public Limit speed for car electric bus

Employment population unemployment population Working time Teleworking

Artficialized Land Size of housing Number of vacants units Renovation % of Social Housing

Number of doctors for 1000 habitants Number of beds per hospital Number of Hotels rooms

Number of tourists Number of second homes housing construction

Use of local currency (doume) Payment of part of the salary (20%) in doume

Cultural infrastructure Sports i nfrastructure Road infrastructure

Food Leverage Points

Land use Artificialized Land Urbanization

Soil quality pesticides alternatives solutions

Yields Agricultural lands Crops/Fruits/Casttle

Farmers Age Size of the farm revenus

Agroecology Labels

Meat consumption Meat production quality of meat price of meat

% of local products % of organic products

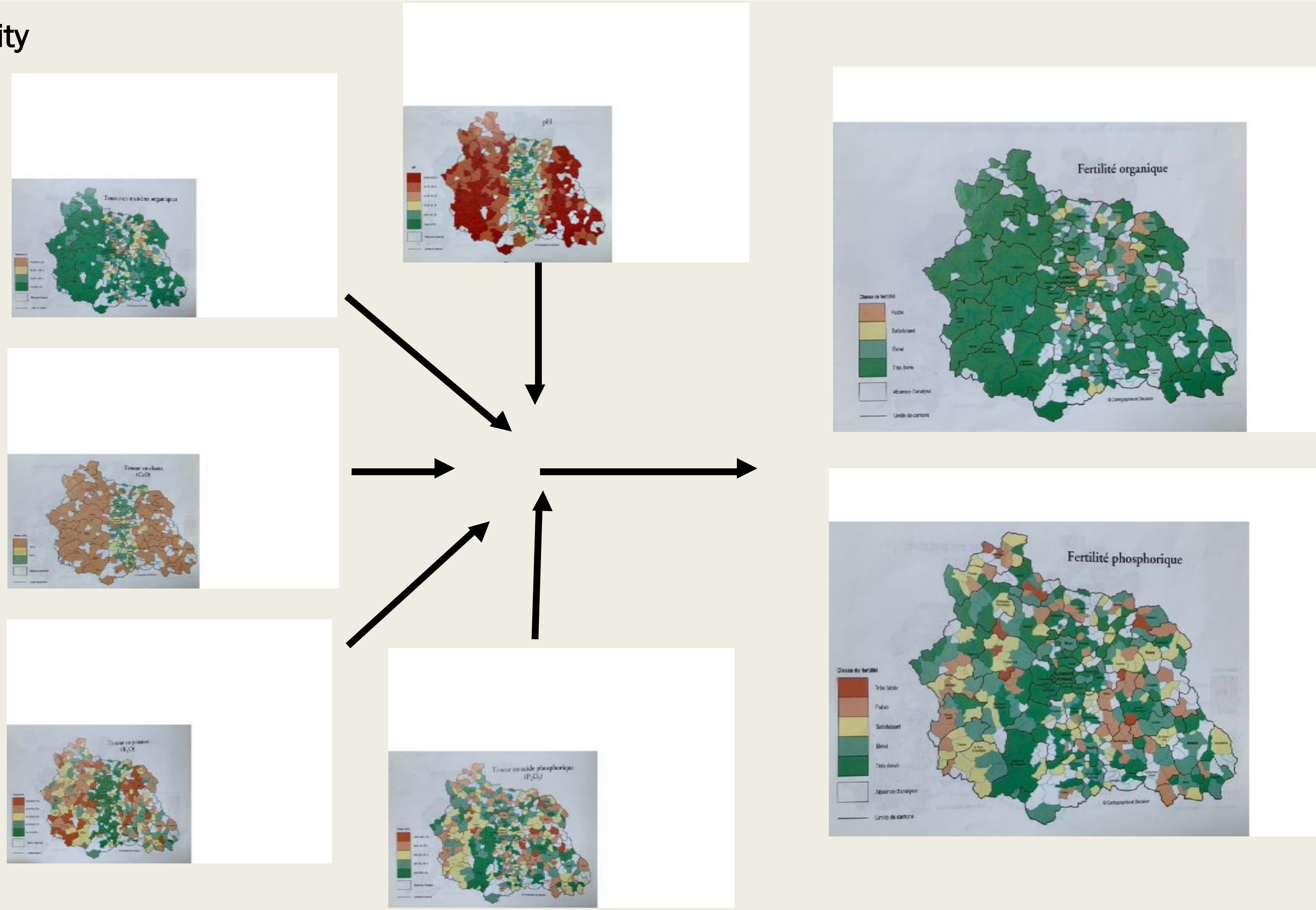
Part of food consumption in the revenue Distribution Short Circuits CSA

Vegetarian Regime Vegan Régime

Kilocalories per adult % of Ultra-transformed Products

Food waste / person Methanization Fertilizer Fertilizer Sludge

Soil Quality



Limits of the urban system ? System can become bigger

Sectors involved

- Population
- Mobility
- Water
- Climate
- Economic Activity
- Building
- Energy
- Food
- Agriculture

Sectors to be involved

- Employment
- Revenue flow
- Governance
- Land
- Soil

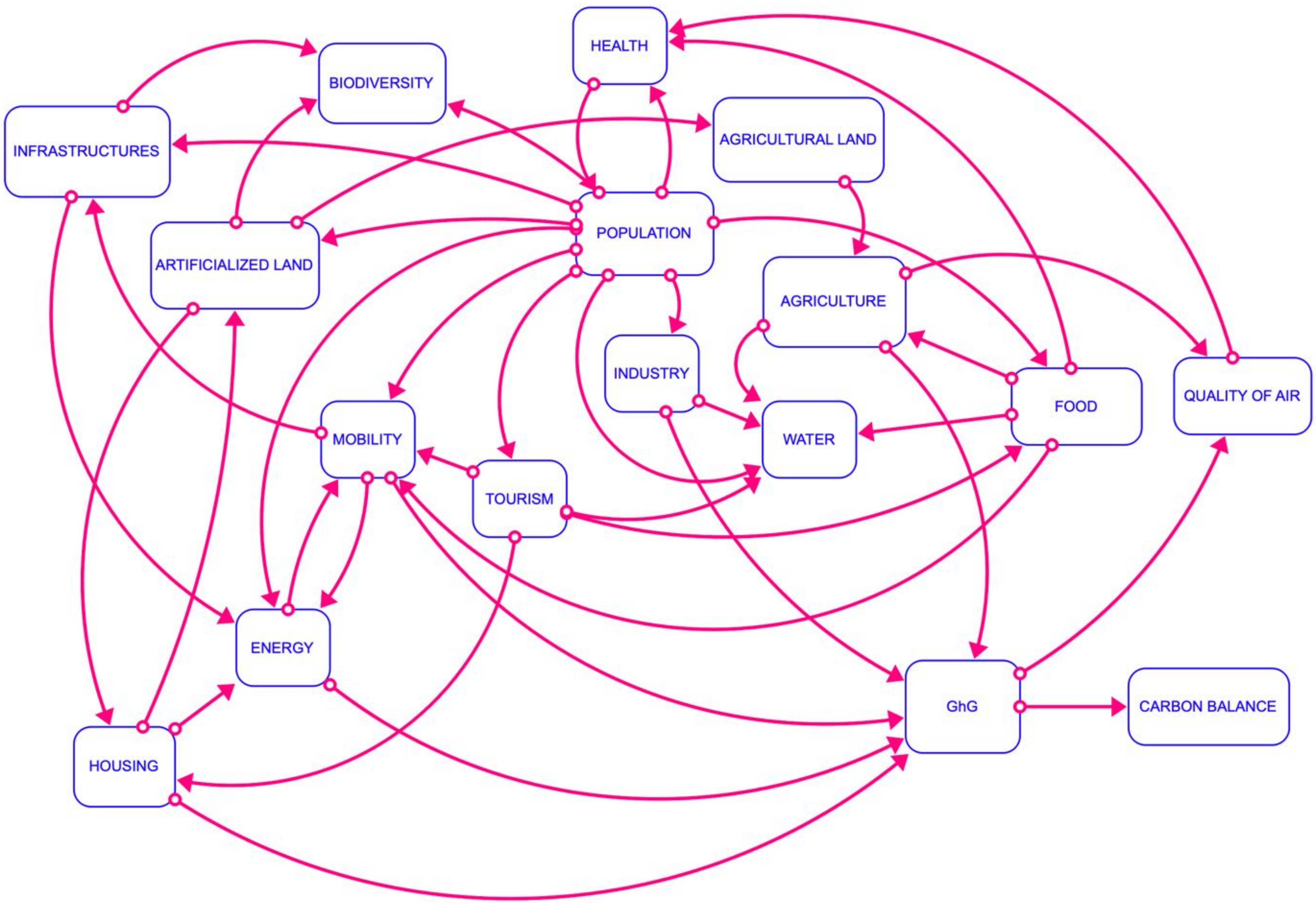
Method

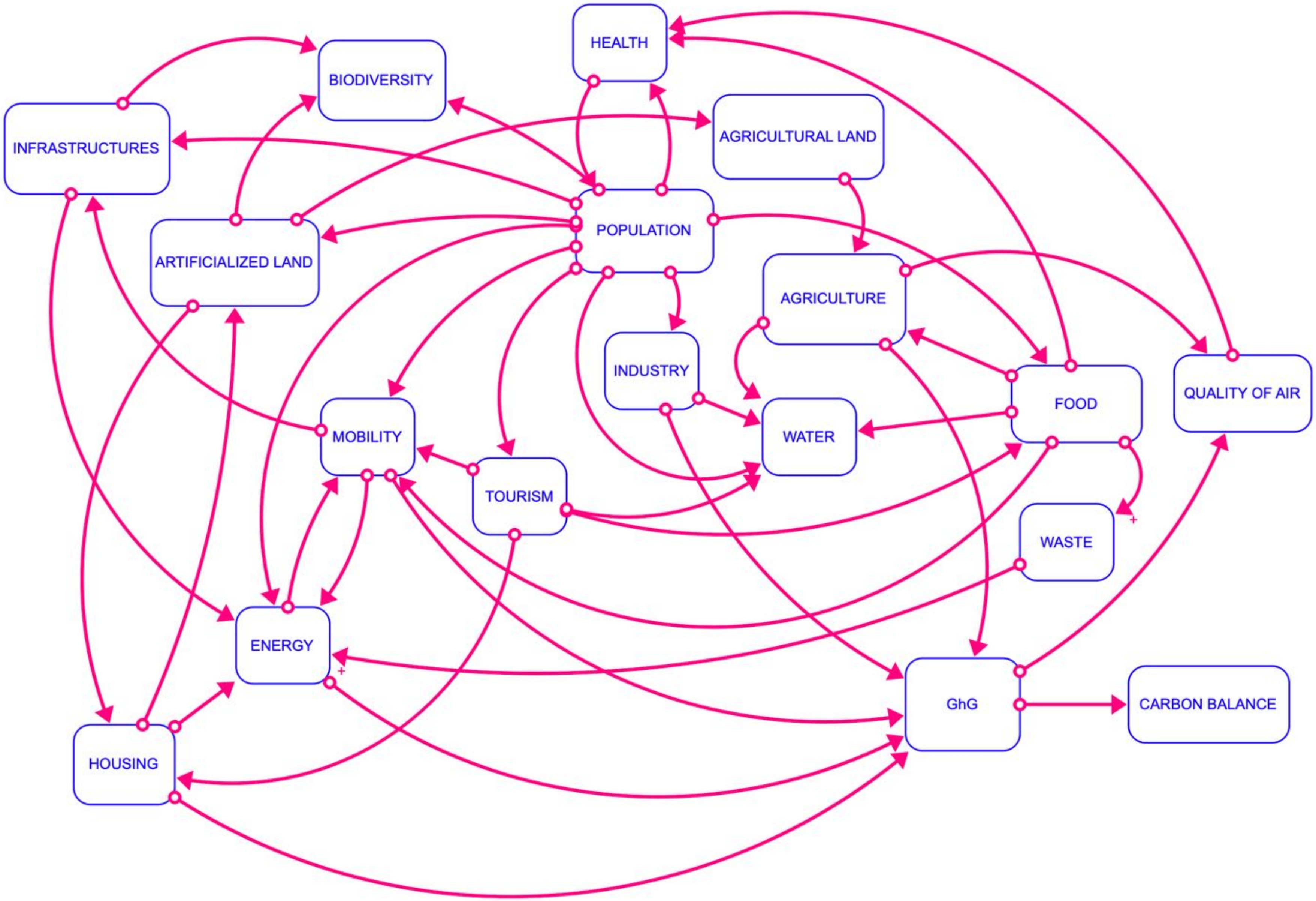
System Dynamics is good for

- Understanding interactions between sectors
- Temporal analysis
- What if analysis (scenario) → Strong scenarios (food security, soft mobility...)

Useful tools

- Causal Loop Diagrams (CLDs)
- Stock-Flow Diagrams (SFDs)
- Mathematical models (Vensim)


HEALTH
BIODIVERSITY
AGRICULTURAL LAND
INFRASTRUCTURES
POPULATION
ARTIFICIALIZED LAND
AGRICULTURE
INDUSTRY
FOOD
QUALITY OF AIR
WATER
MOBILITY
TOURISM
ENERGY
GhG
CARBON BALANCE
HOUSING


HEALTH
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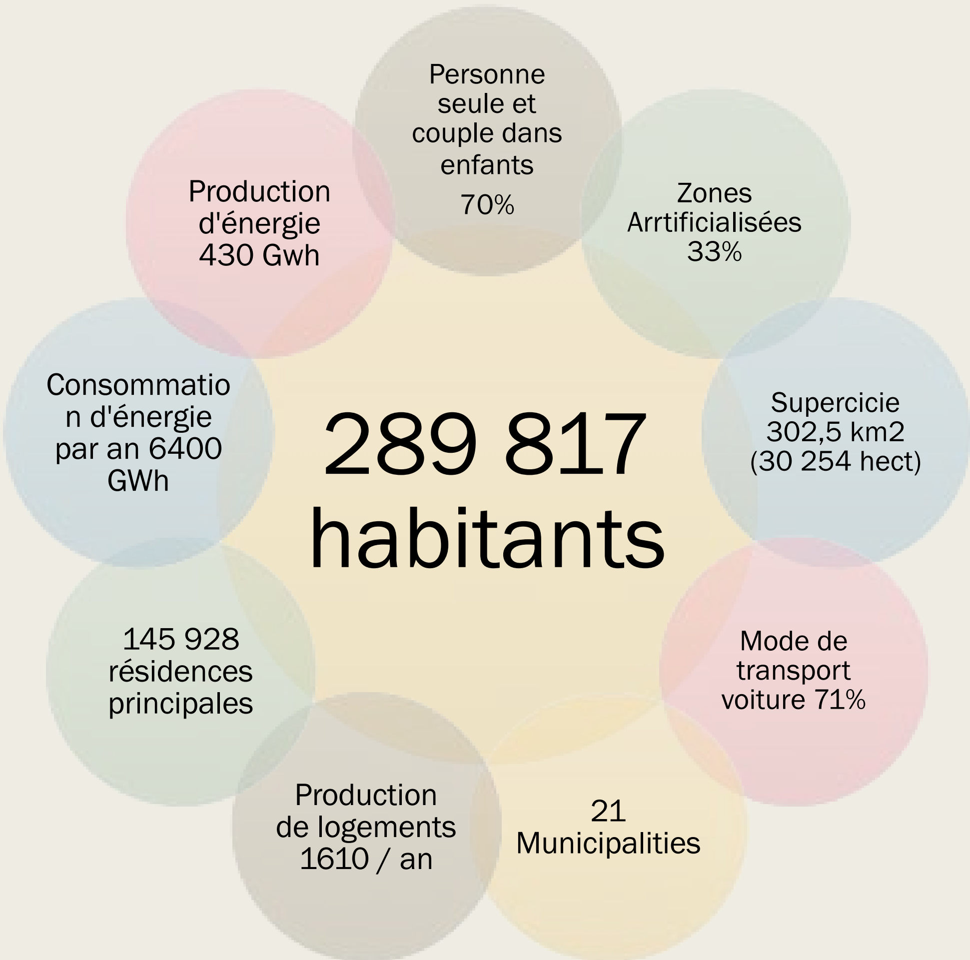
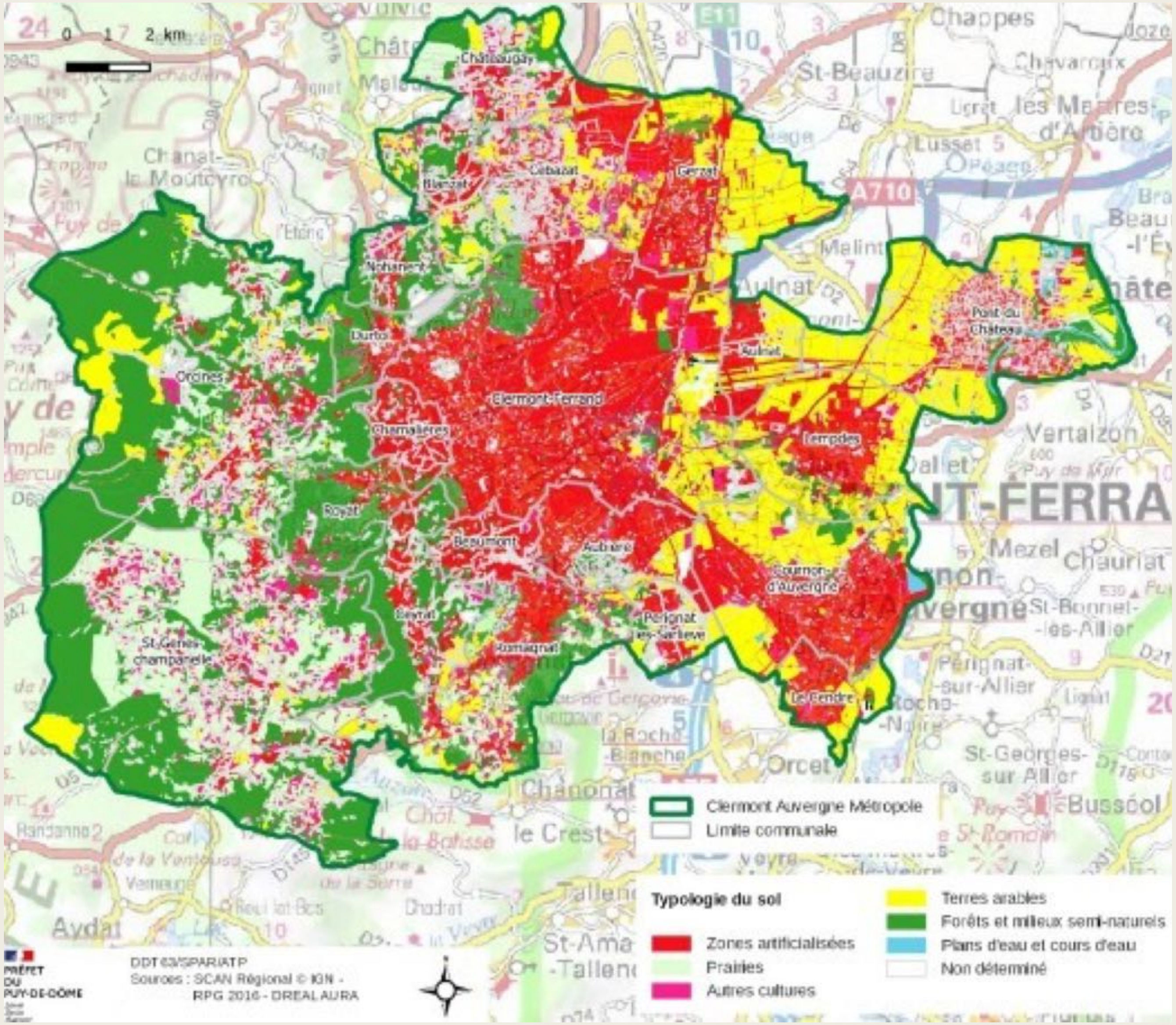
WATER
TOURISM
WASTE
ENERGY
GhG
CARBON BALANCE
HOUSING

Clermont Métropole (set of 21 cities)



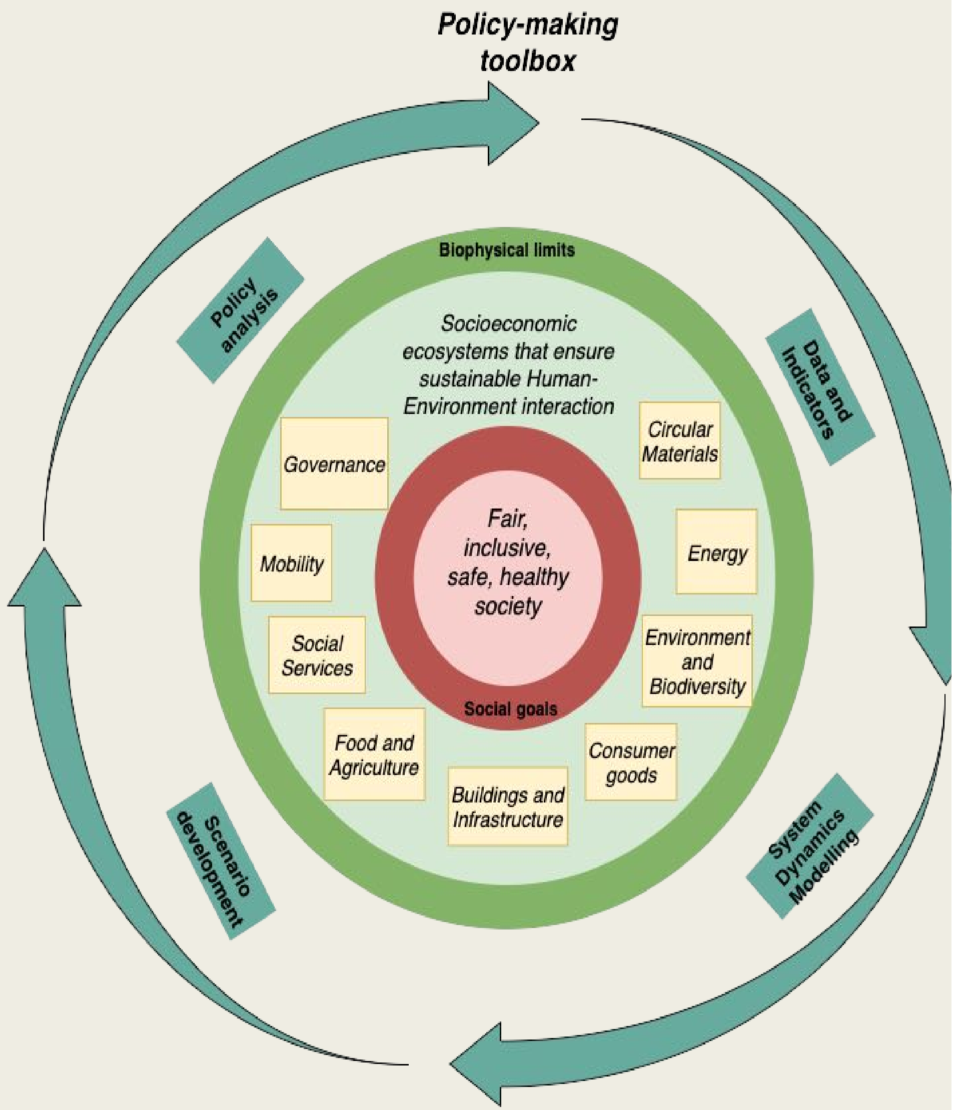
Mapping Location



Project Schedule Time

- Problem definition
- Draw Causal Loop Diagrams
- Create Stock and Flow Diagrams
- Data: Collection, Interpolation & Proxies
- Build model in Vensim and Stella (& add data)
- Design scenarios (& model scenarios)
- Presentation

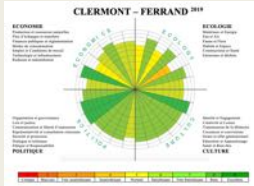
- Collect & add missing data, sectoral scenarios, connect models, system scenarios



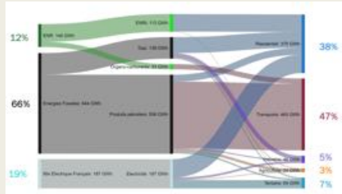
IATB – LOOP

Method of scenarios

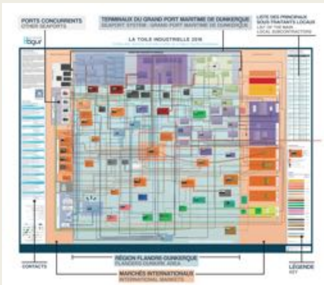
Circles of Social Life



SANKEY Diagrams



Toile Maker



Scenario

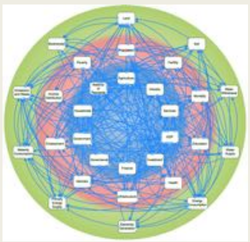
REpresentations

Local Scale Analysis

System Dynamics (CLD, SFD)

iSDG

Stella Architect

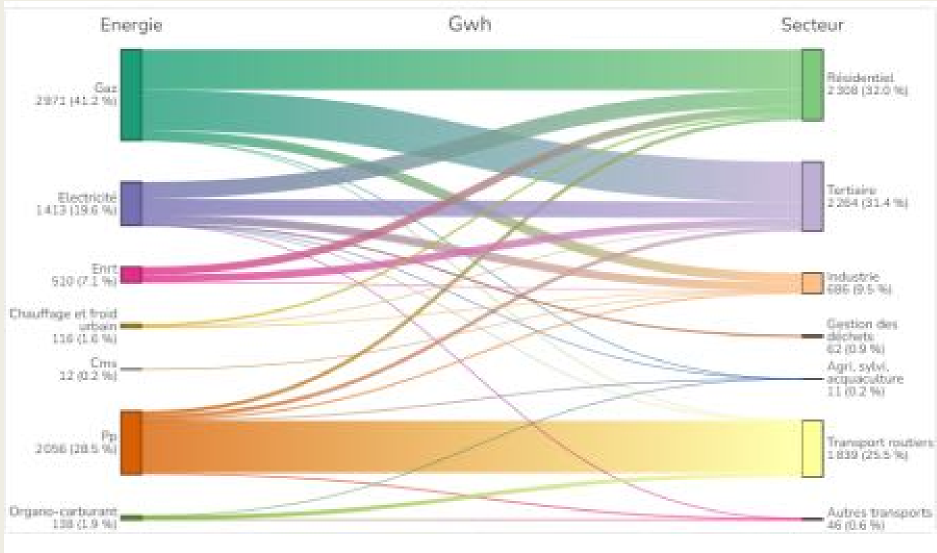


Tools

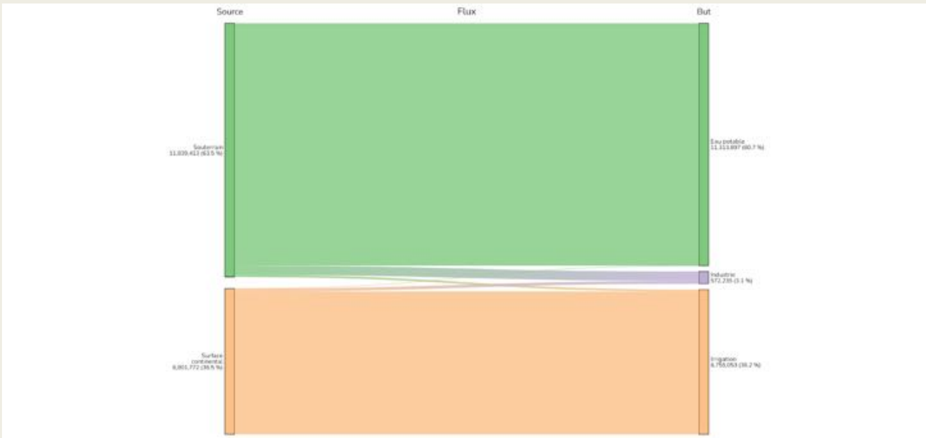
Methodology

Agriculture sector

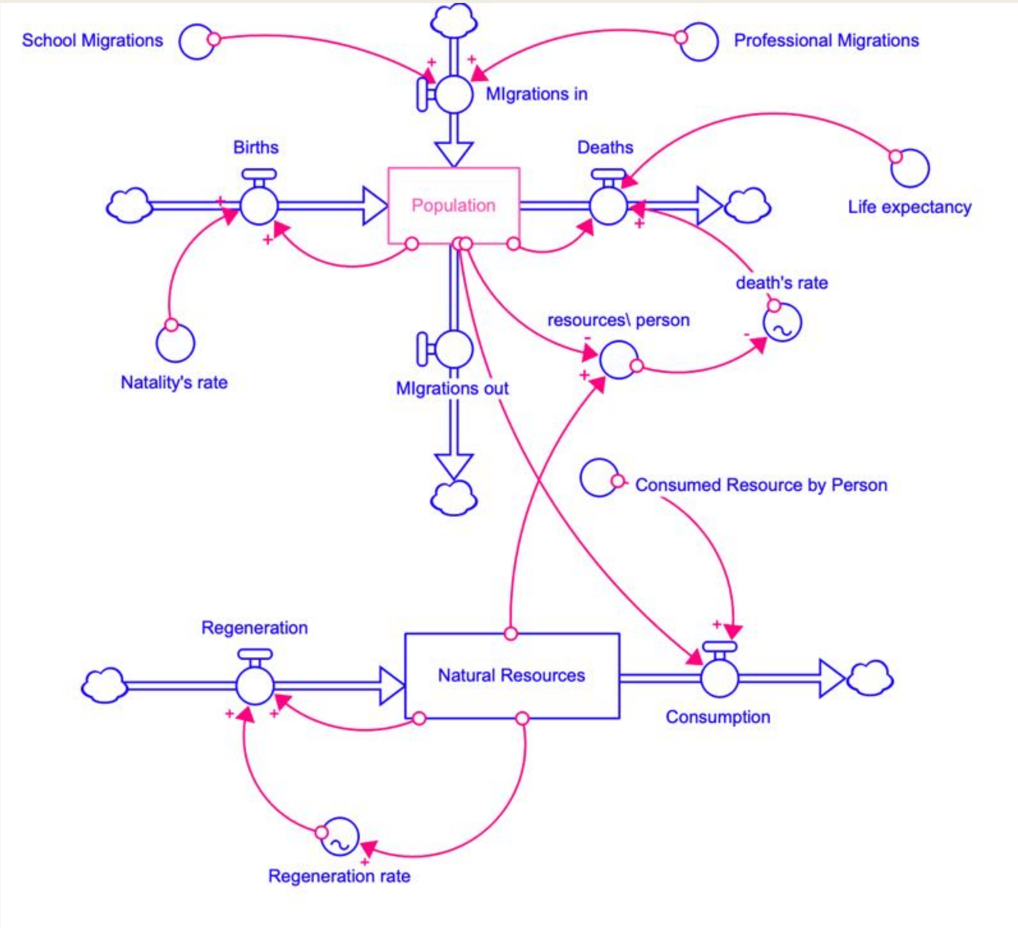
Energy sector

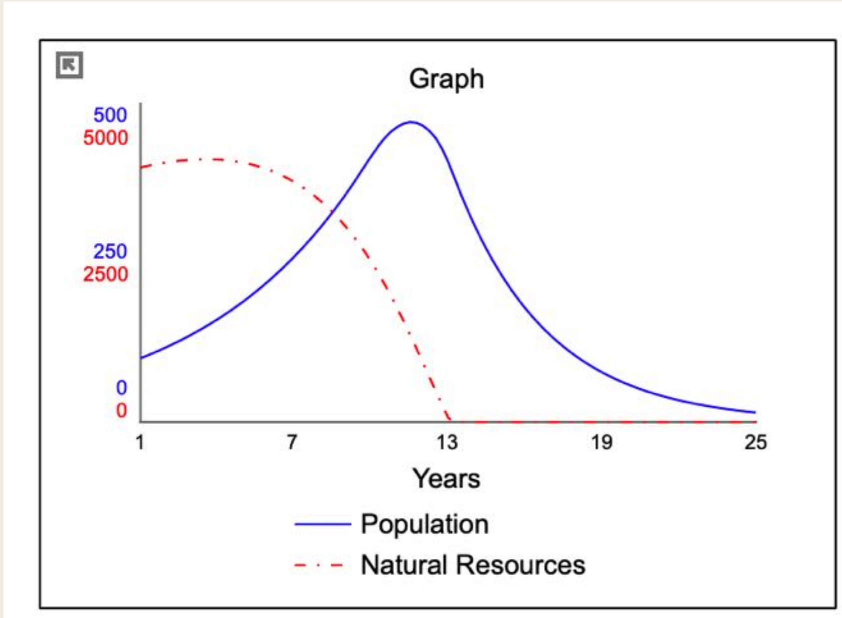


Water Sector

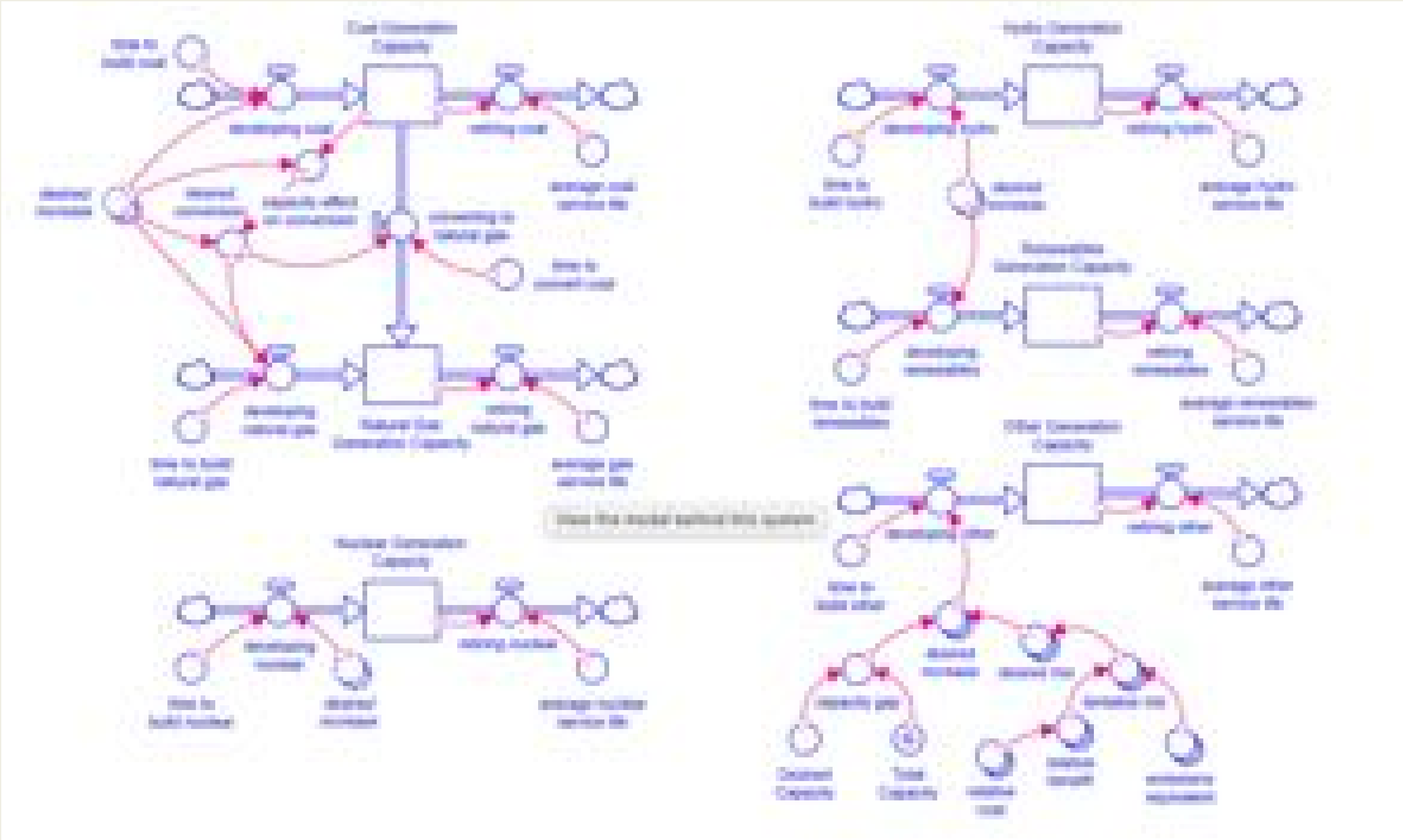


Population sector



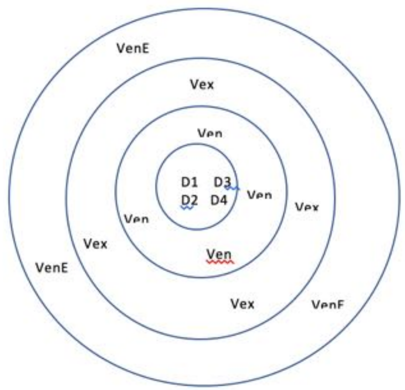


Energy Sector



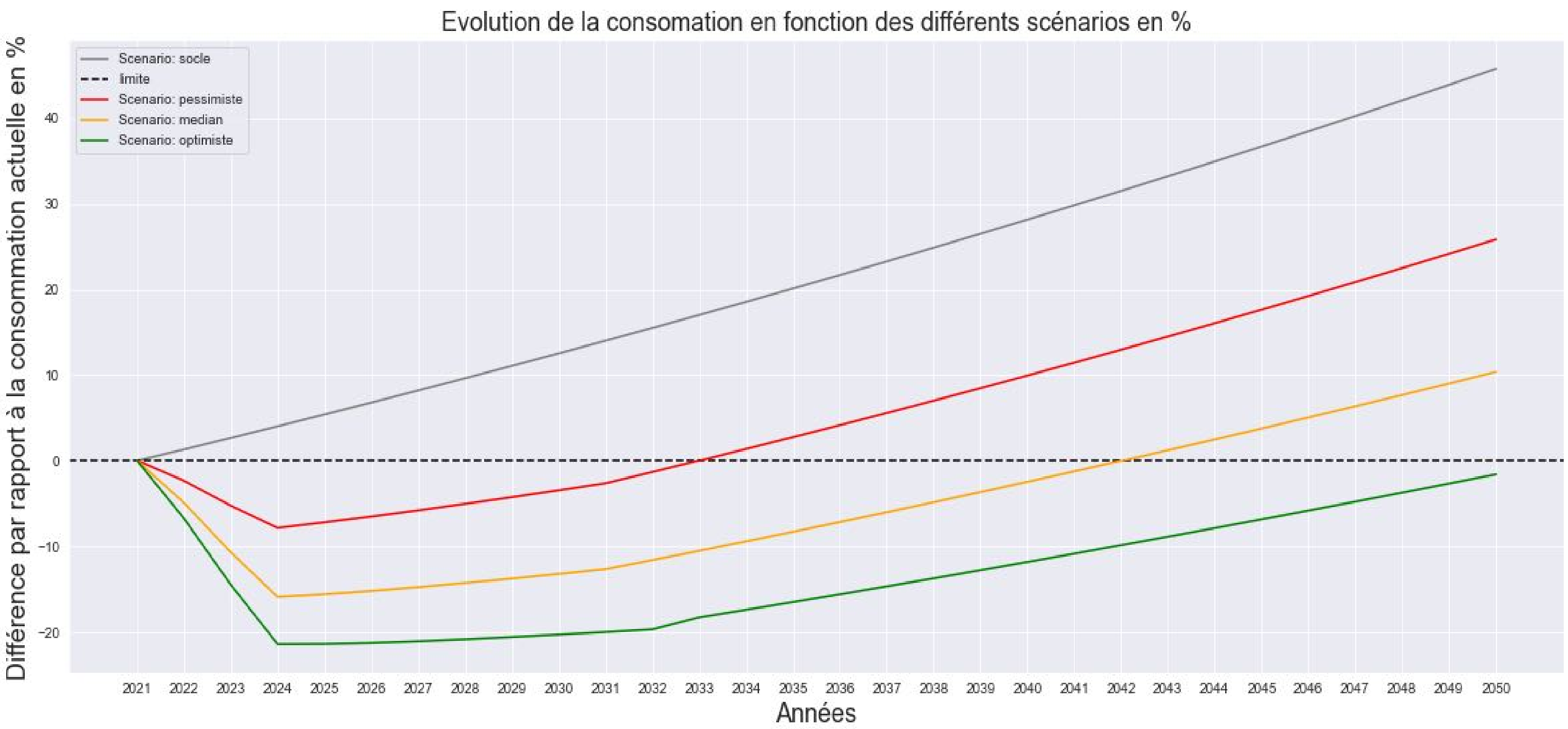
DATA DESIGN MODELLING

Sous-systèmes	Variables Endogène : Ven Exogène : Vex Endogène Exclue : VenE	Quantitatif : Qi Qualitatif : Qf	Driver : D Variable : V Taux : T Paramètre : P	Flux : F Stocks : S	Unité	Boucle Polarité + : R Polarité - : B	Points leviers	Médiateur : M Degré de sortie élevé : DSE Degré de sortie faible : DSF
Agricole								
Alimentaire								
Biodiversité								
Climat								
Culturel								
Déchets								
Eau								
Economique								
Energie								
Logements								
Mobilité								
Population								
Qualité de l'air								
Santé								
Usage du sol								

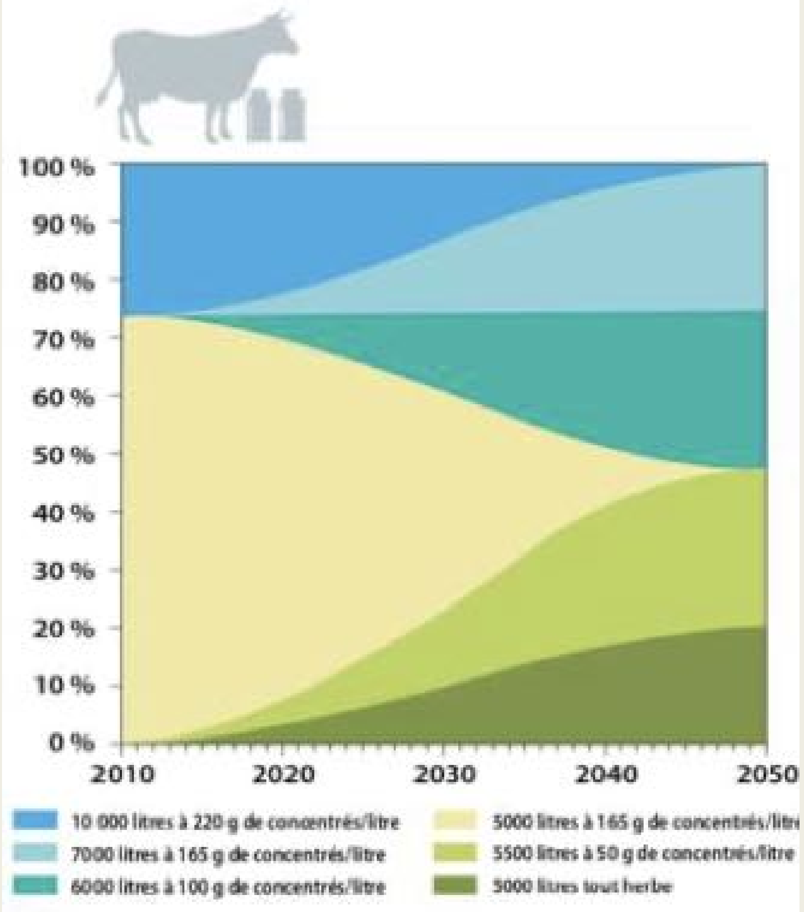


BOUNDARIES OF THE SYSTEM

scenarios of water consumption



Evolution of Meat/Milk production



Évolution des systèmes bovin lait.