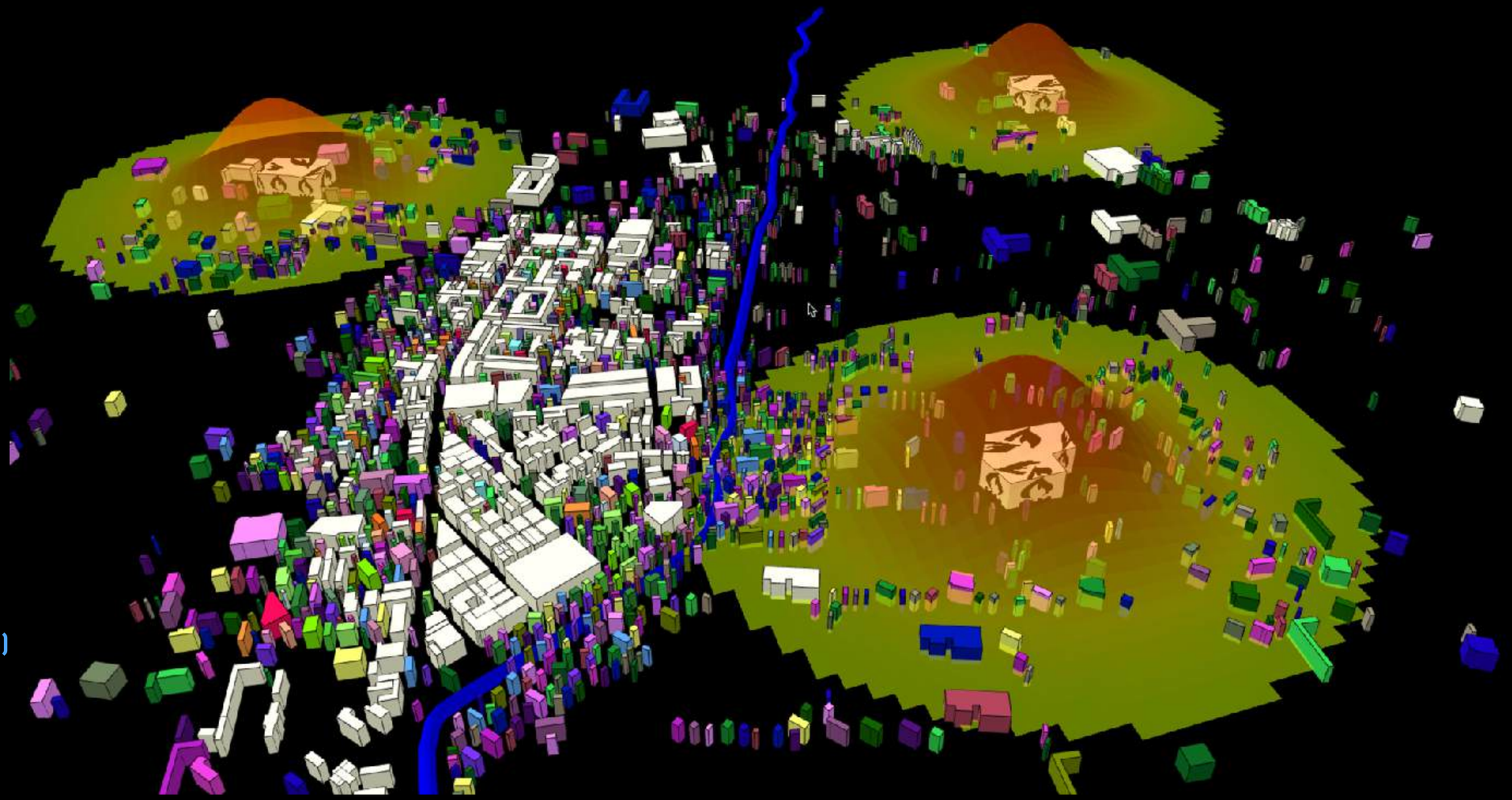
MODELING AND SIMULATION OF COMPLEX SYSTEMS



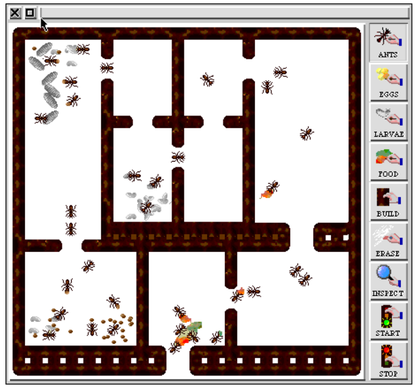
Institut de Recherche pour le Développement
FRANCE

Alexis Drogoul (w. Benoit Gaudou)
UMI 209 UMMISCO
alexis.drogoul@ird.fr

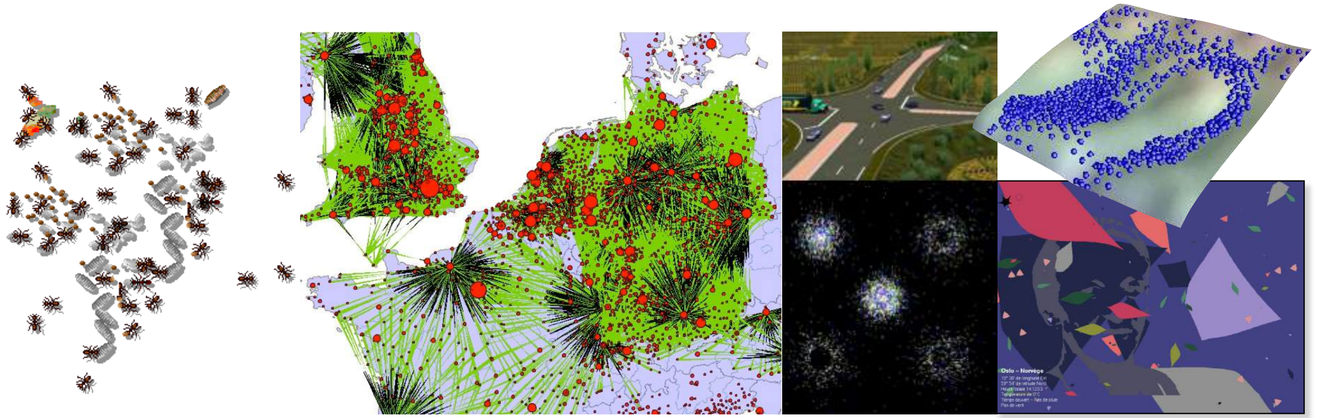
« All models are **wrong**,
but some are **useful** »

Box, G. E. P. (1979), "Robustness in the strategy of scientific model building", in Launer, R. L.; Wilkinson, G. N. (eds.), *Robustness in Statistics*, Academic Press, pp. 201–236

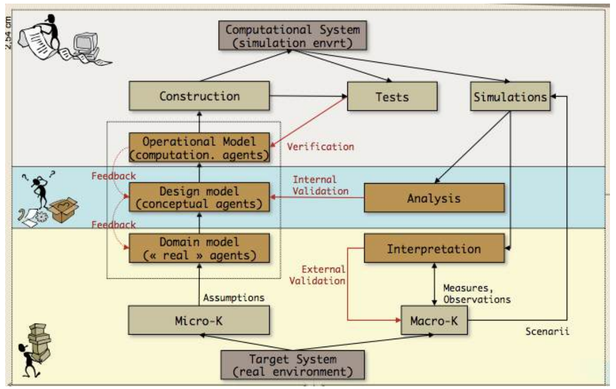
MY PHD AND FIRST CAREER WERE DEVOTED TO ARTIFICIAL LIFE, I.E. THE CONSTRUCTION OF A VIRTUOUS CIRCLE BETWEEN AGENT-BASED SIMULATION, COLLECTIVE ROBOTICS AND AI



Manta (Agent-Based Modeling)



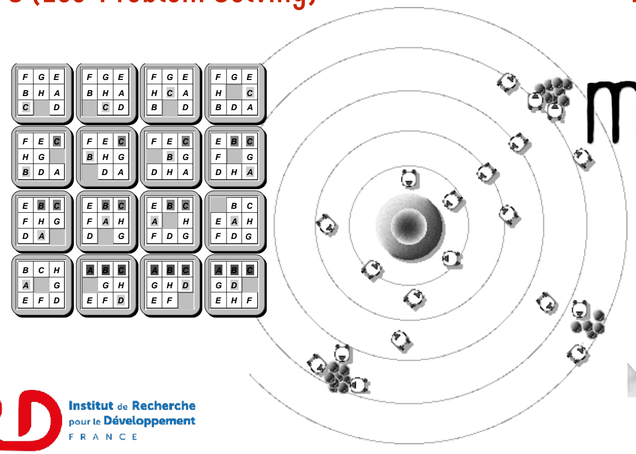
SimPop2, Archisim, Garden of Chances, Rivages...



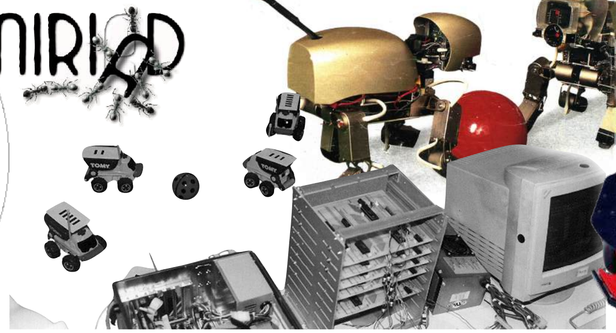
Agent-Based Meta-Modeling

PhD at Paris 6 University, from 1990 to 1993	Assistant Professor at Paris 6, from 1995 to 2000	Full Professor at Paris 6, from 2000 to 2004

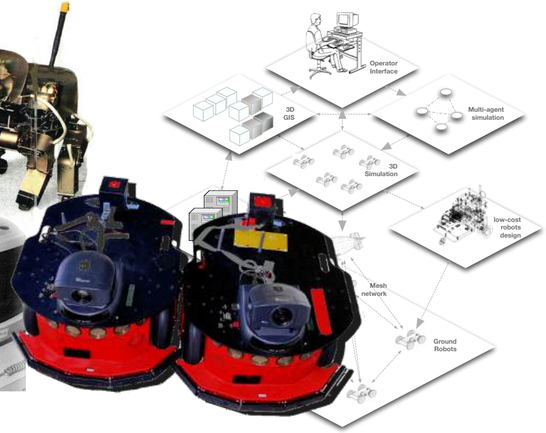
EPS (Eco-Problem Solving)



RoboCup



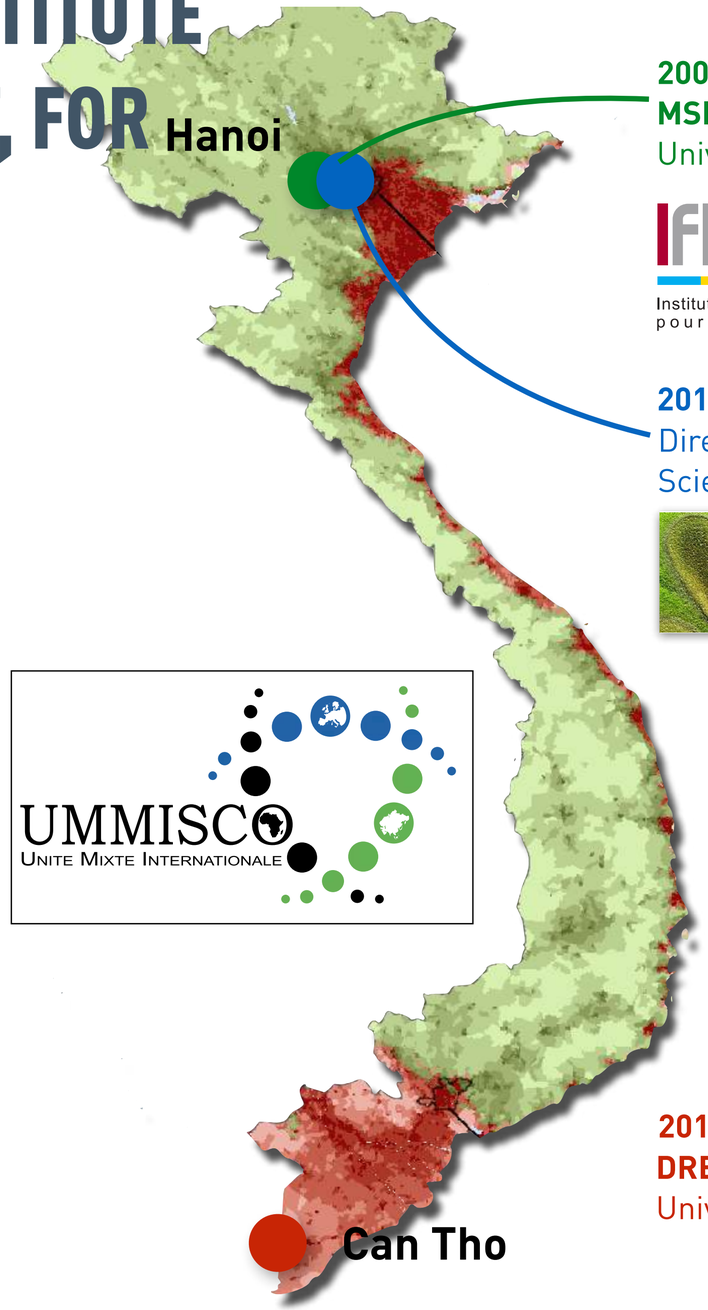
Microbes Social Robots



ComMod (Participatory Simulations)

I MOVED IN 2005 TO IRD, A RESEARCH INSTITUTE DEDICATED TO SUSTAINABLE DEVELOPMENT, FOR WHICH I HAVE BEEN WORKING IN VIETNAM

- As the deputy director of the maths/computer science team UMMISCO
- As the designer of the GAMA modelling and simulation platform
- As the representative of IRD in Vietnam and Philippines between 2017 and 2022
- As the deputy director of the ACROSS laboratory in Thuyloi University.



2007 - 2011
MSI team (IFI, Hanoi National University, IRD associated team)

IFI Institut de la Francophonie pour l'Informatique
AGENCE UNIVERSITAIRE DE LA FRANCOPHONIE

2015 - 2017
Director of **ICTLab** (University of Science and Technology of Hanoi)

ICTLab
USTH VIETNAM FRANCE UNIVERSITY

UMMISCO Unite Mixte Internationale

ĐẠI HỌC CẦN THƠ

2011 - 2014
DREAM research team (Can Tho Univ., IRD associated team)

IRD IS A FRENCH PUBLIC INSTITUTE THAT UNDERTAKES RESEARCH & CAPACITY BUILDING ACTIVITIES IN PARTNERSHIP TO ADDRESS THE CHALLENGES OF SUSTAINABLE DEVELOPMENT

- 75 research units (jointly with other institutions)
- 77 International laboratories (in partner countries)
- 850 researchers, 2050 agents and a community of 7000 French researchers
- Over 1500 publications/year, 60% in co-publication with partners

ECOBIO Ecology, biodiversity and ecosystems

OCEANS Oceans, Climate and Resources

DISCO Internal dynamics and continents surface

SOC Societies and globalisation

SAS Health and Societies

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

Institut de Recherche pour le Développement
FRANCE

IRD UNDERTAKES RESEARCH & CAPACITY BUILDING IN PARTNERSHIP TO ADDRESS THE CHALLENGES OF SUSTAINABLE DEVELOPMENT IN ~50 COUNTRIES OF THE GLOBAL SOUTH

A KEY GLOBAL ACTOR OF **SUSTAINABILITY SCIENCE**

HUMAN ACTIVITIES OVER THE PAST 50 YEARS HAVE ALTERED ECOSYSTEMS AROUND THE WORLD FASTER AND MORE EXTENSIVELY THAN AT ANY OTHER TIME IN HISTORY.

NOT SUSTAINABLE !

60% of wildlife

World population (2.5B to 7.7B)

Global crop production x 3

Urbanised areas x 3

Energy consumption x 6

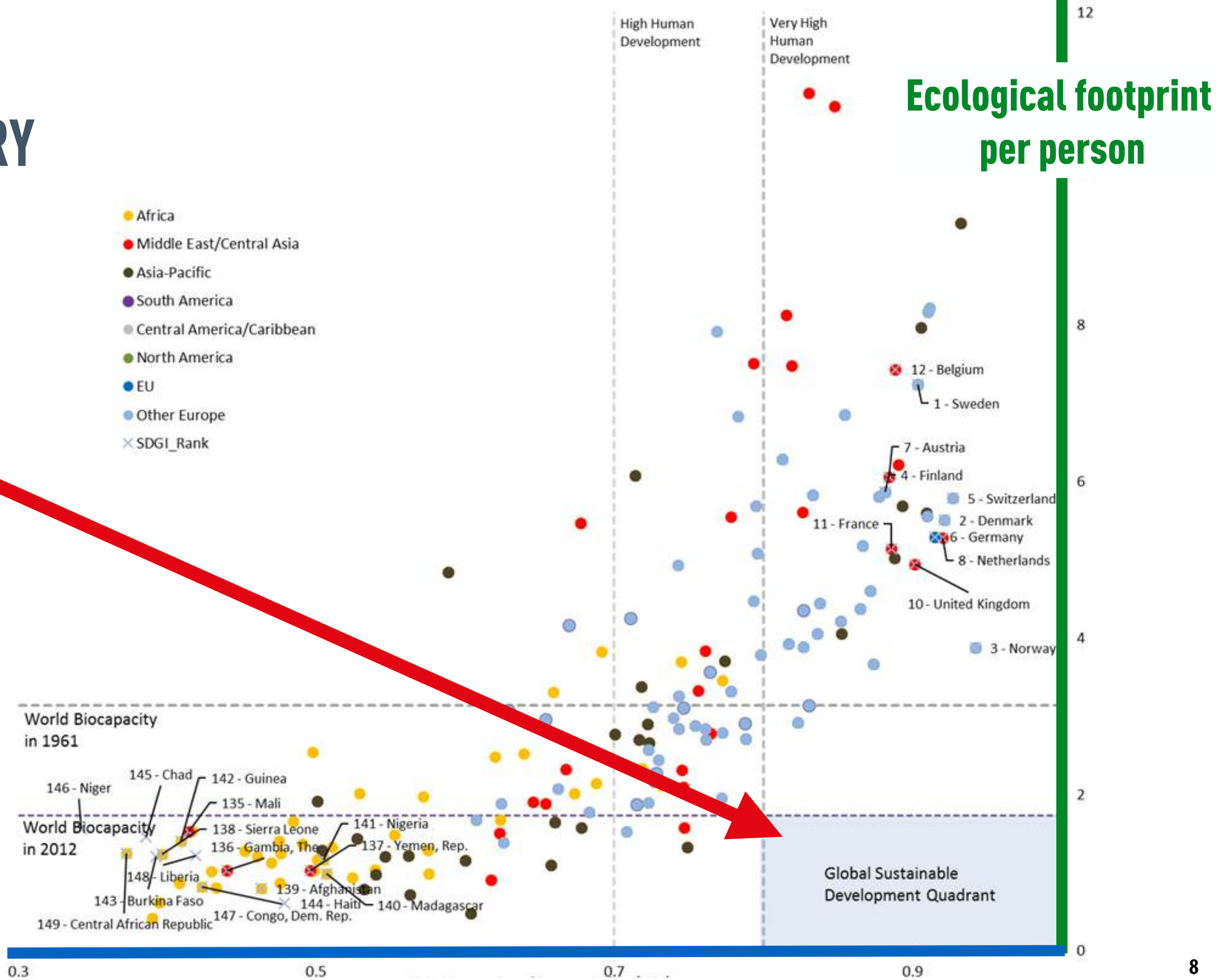
CO2 emissions x 7

International tourists x 48

Freshwater use x 3

https://ourworldindata.org/

NOT A SINGLE COUNTRY HAS ACHIEVED A HIGH LEVEL OF HUMAN DEVELOPMENT IN A SUSTAINABLE WAY



UN Human Development Index (HDI)

Institut de Recherche pour le Développement FRANCE
French National Research Institute for Sustainable Development

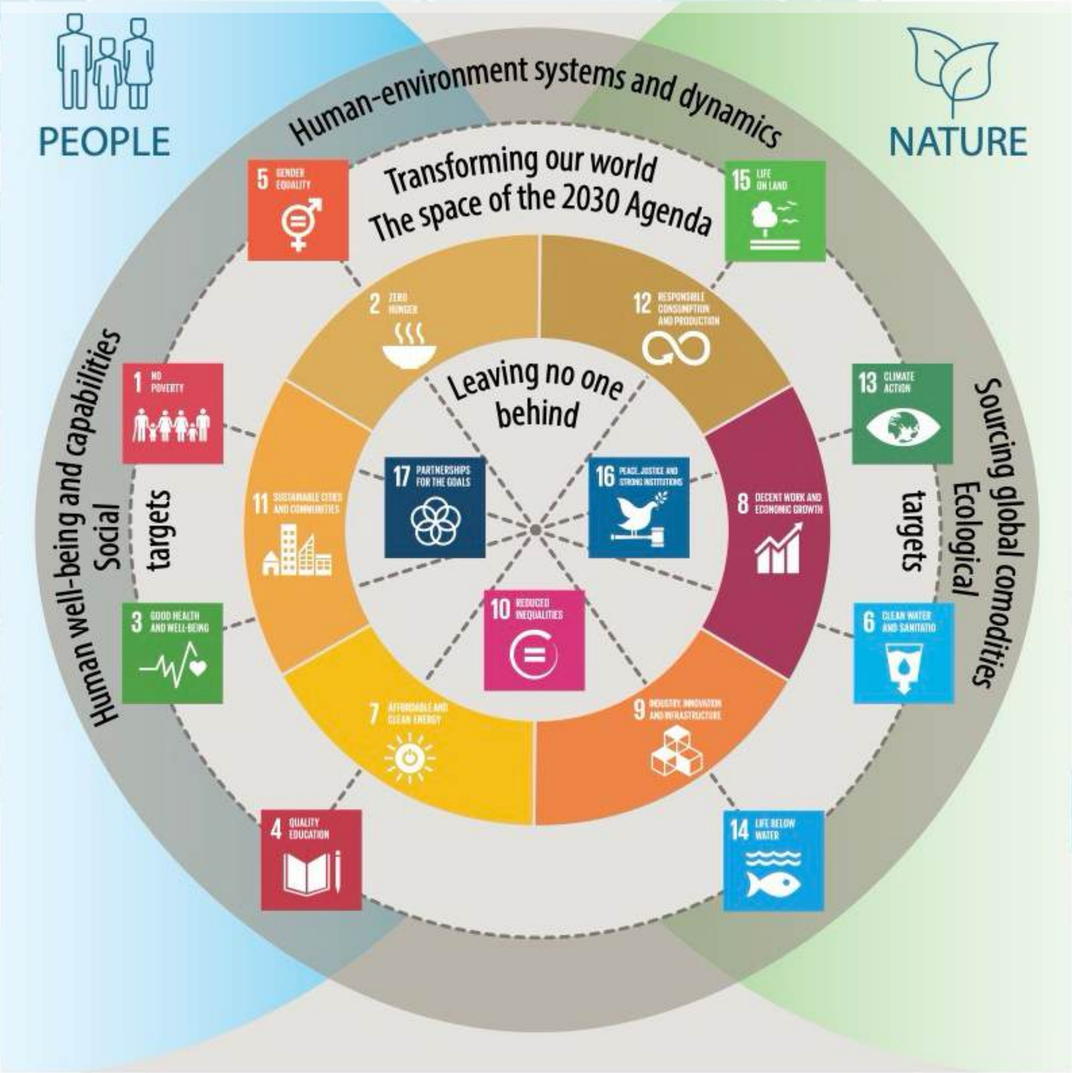
IN 2015, THE 17 SUSTAINABLE DEVELOPMENT GOALS WERE ADOPTED, LINKING SOCIAL AND ENVIRONMENTAL PRIORITIES

ERADICATE POVERTY

FOSTER PROSPERITY

PROTECT THE PLANET

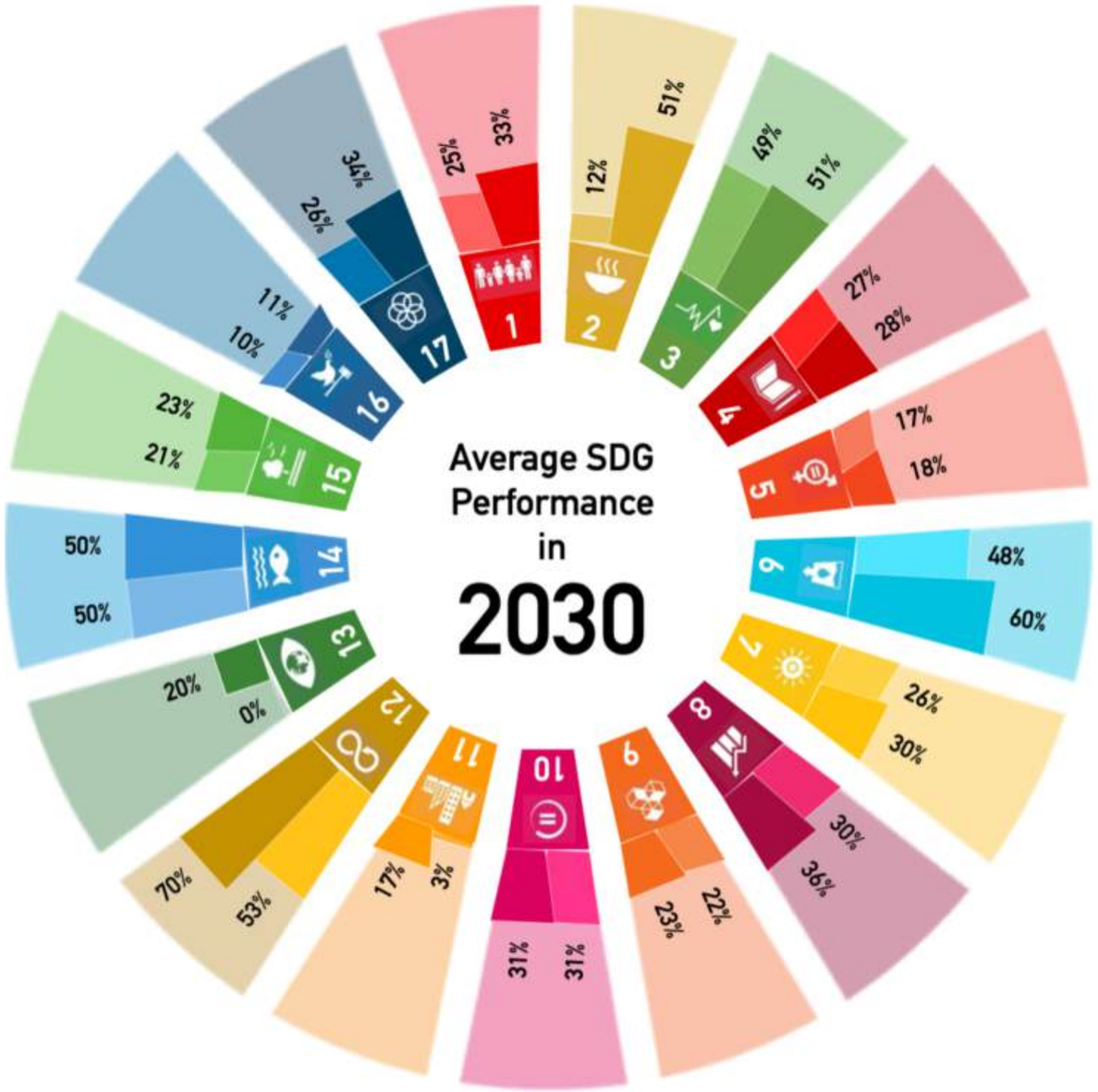
https://sdg-tracker.org



HOWEVER, AS SOON AS 2017, WARNINGS HAVE BEEN EMITTED

Atlas of Sustainable Development Goals
2018 From World Development Indicators

WORLD BANK GROUP



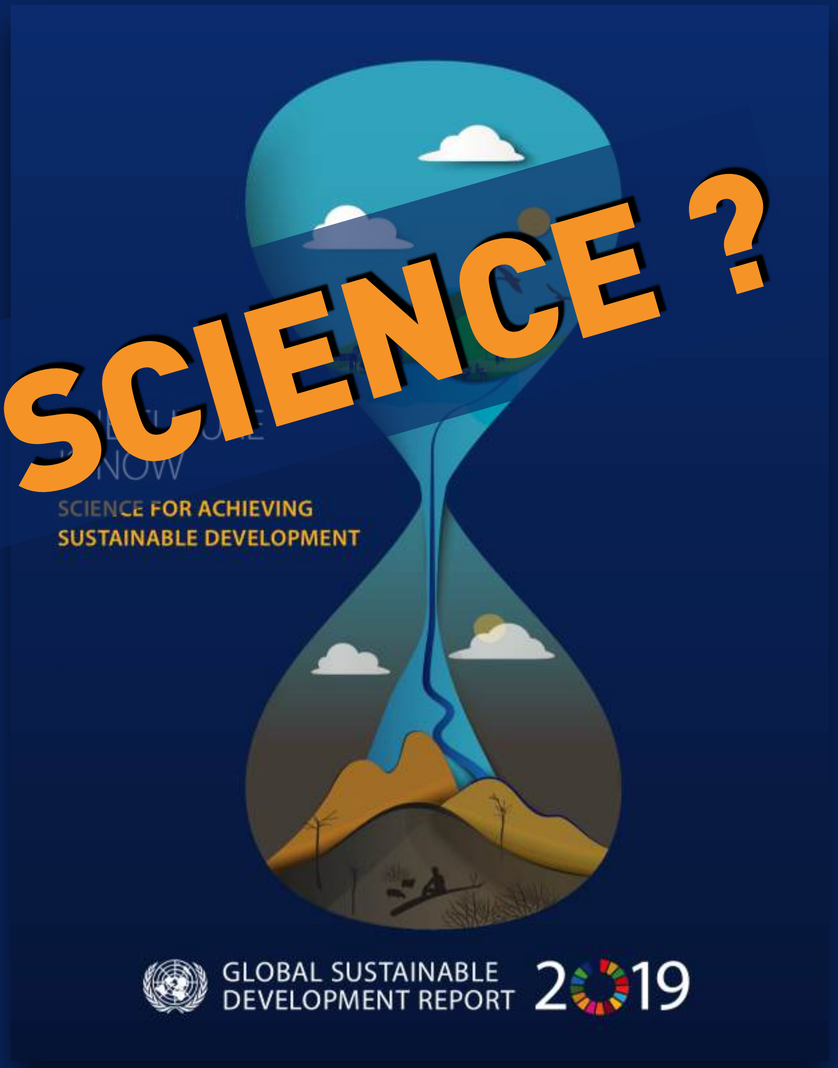
THEN IN 2019, A FIRST INDEPENDENT REPORT WAS PUBLISHED BY SCIENTISTS

Despite considerable efforts these past four years, we are <u>not on track to achieve the Sustainable Development Goals by 2030.</u>

Antonio Gutteres - UN Secretary-General

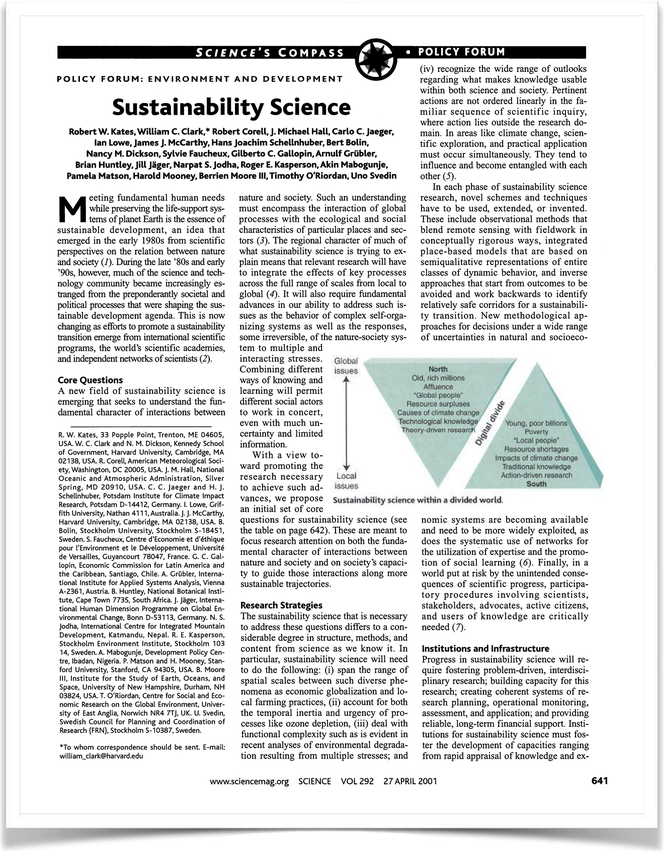
(...) we need to overcome the gap between what we know and what is being done. We believe that scientific evidence must contribute to formulating effective policies for the necessary transformations. (p. 140)

BUT WHAT KIND OF SCIENCE ?



http://is.gd/gsdr2019

THE IDEA OF A "SUSTAINABILITY SCIENCE" WAS BROADLY INTRODUCED AS AN EMERGING RESEARCH FIELD WITH A SEMINAL ARTICLE IN 2001.



SCIENCE'S COMPASS • POLICY FORUM

POLICY FORUM: ENVIRONMENT AND DEVELOPMENT

Sustainability Science

Robert W. Kates, William C. Clark,* Robert Corell, J. Michael Hall, Carlo C. Jaeger, Ian Lowe, James J. McCarthy, Hans Joachim Schellnhuber, Bert Bolin, Nancy M. Dickson, Sylvie Faucheux, Gilberto C. Gallopin, Arnulf Grübler, Brian Huntley, Jill Jäger, Narpat S. Jodha, Roger E. Kasperson, Akin Mabogunje, Pamela Matson, Harold Mooney, Berrien Moore III, Timothy O'Riordan, Uno Svedin

Meeting fundamental human needs while preserving the life-support systems of planet Earth is the essence of sustainable development, an idea that emerged in the early 1980s from scientific perspectives on the relation between nature and society (*1*). During the late '80s and early '90s, however, much of the science and technology community became increasingly estranged from the preponderantly societal and political processes that were shaping the sustainable development agenda. This is now changing as efforts to promote a sustainability transition emerge from international scientific programs, the world's scientific academies, and independent networks of scientists (*2*).

Core Questions

A new field of sustainability science is emerging that seeks to understand the fundamental character of interactions between nature and society. Such an understanding must encompass the interaction of global processes with the ecological and social characteristics of particular places and sectors (*3*). The regional character of much of what sustainability science is trying to explain means that relevant research will have to integrate the effects of key processes across the full range of scales from local to global (*4*). It will also require fundamental advances in our ability to address such issues as the behavior of complex self-organizing systems as well as the responses, some irreversible, of the nature-society system to multiple and interacting stresses. Combining different ways of knowing and learning will permit different social actors to work in concert, even with much uncertainty and limited information.

With a view toward promoting the research necessary to achieve such advances, we propose an initial set of core questions for sustainability science (see the table on page 642). These are meant to focus research attention on both the fundamental character of interactions between nature and society and on society's capacity to guide those interactions along more sustainable trajectories.

Research Strategies

The sustainability science that is necessary to address these questions differs to a considerable degree in structure, methods, and content from science as we know it. In particular, sustainability science will need to do the following: (i) span the range of spatial scales between such diverse phenomena as economic globalization and local farming practices, (ii) account for both the temporal inertia and urgency of processes like ozone depletion, (iii) deal with functional complexity such as is evident in recent analyses of environmental degradation resulting from multiple stresses; and (iv) recognize the wide range of outlooks regarding what makes knowledge usable within both science and society. Pertinent actions are not ordered linearly in the familiar sequence of scientific inquiry, where action lies outside the research domain. In areas like climate change, scientific exploration, and practical application must occur simultaneously. They tend to influence and become entangled with each other (*5*).

In each phase of sustainability science research, novel schemes and techniques have to be used, extended, or invented. These include observational methods that blend remote sensing with fieldwork in conceptually rigorous ways, integrated place-based models that are based on semiqualitative representations of entire classes of dynamic behavior, and inverse approaches that start from outcomes to be avoided and work backwards to identify relatively safe corridors for a sustainability transition. New methodological approaches for decisions under a wide range of uncertainties in natural and socioeconomic systems are becoming available and need to be more widely exploited, as does the systematic use of networks for the utilization of expertise and the promotion of social learning (*6*). Finally, in a world put at risk by the unintended consequences of scientific progress, participatory procedures involving scientists, stakeholders, advocates, active citizens, and users of knowledge are critically needed (*7*).

Institutions and Infrastructure

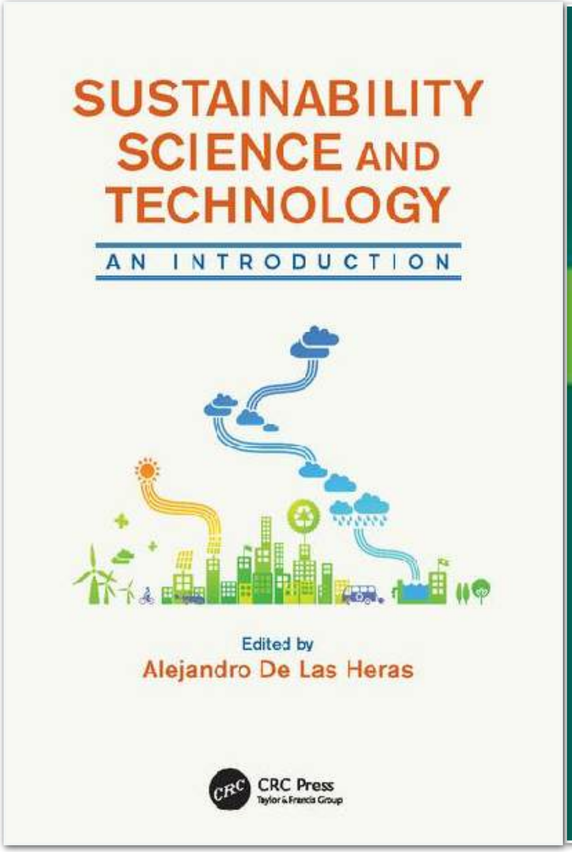
Progress in sustainability science will require fostering problem-driven, interdisciplinary research; building capacity for this research; creating coherent systems of research planning, operational monitoring, assessment, and application; and providing reliable, long-term financial support. Institutions for sustainability science must foster the development of capacities ranging from rapid appraisal of knowledge and ex-

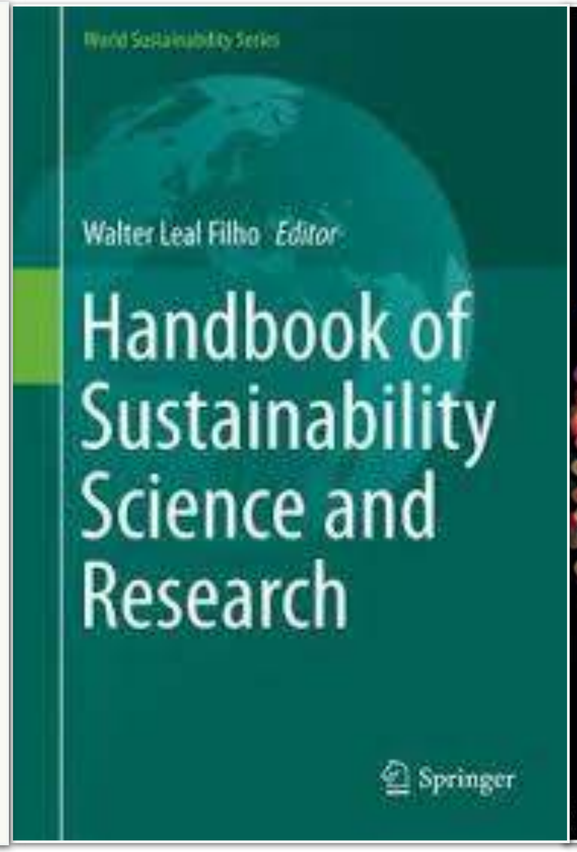
Global issues
North
Old, rich millions
Affluence
"Global people"
Resource surpluses
Causes of climate change
Technological knowledge
Theory-driven research
Digital divide
Young, poor billions
Poverty
"Local people"
Resource shortages
Impacts of climate change
Traditional knowledge
Action-driven research
South
Local issues

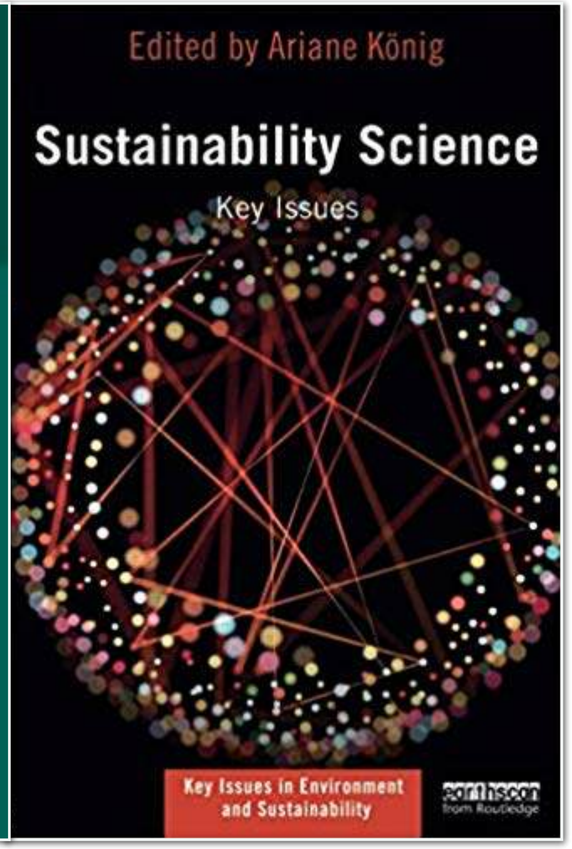
Sustainability science within a divided world.

R. W. Kates, 33 Popple Point, Trenton, ME 04605, USA. W. C. Clark and N. M. Dickson, Kennedy School of Government, Harvard University, Cambridge, MA 02138, USA. R. Corell, American Meteorological Society, Washington, DC 20005, USA. J. M. Hall, National Oceanic and Atmospheric Administration, Silver Spring, MD 20910, USA. C. C. Jaeger and H. J. Schellnhuber, Potsdam Institute for Climate Impact Research, Potsdam D-14412, Germany. I. Lowe, Griffith University, Nathan 4111, Australia. J. J. McCarthy, Harvard University, Cambridge, MA 02138, USA. B. Bolin, Stockholm University, Stockholm S-18451, Sweden. S. Faucheux, Centre d'Economie et d'Ethique pour l'Environment et le Développement, Université de Versailles, Guyancourt 78047, France. G. C. Gallopin, Economic Commission for Latin America and the Caribbean, Santiago, Chile. A. Grübler, International Institute for Applied Systems Analysis, Vienna A-2361, Austria. B. Huntley, National Botanical Institute, Cape Town 7735, South Africa. J. Jäger, International Human Dimension Programme on Global Environmental Change, Bonn D-53113, Germany. N. S. Jodha, International Centre for Integrated Mountain Development, Katmandu, Nepal. R. E. Kasperson, Stockholm Environment Institute, Stockholm 103 14, Sweden. A. Mabogunje, Development Policy Centre, Ibadan, Nigeria. P. Matson and H. Mooney, Stanford University, Stanford, CA 94305, USA. B. Moore III, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA. T. O'Riordan, Centre for Social and Economic Research on the Global Environment, University of East Anglia, Norwich NR4 7TJ, UK. U. Svedin, Swedish Council for Planning and Coordination of Research (FRN), Stockholm S-10387, Sweden.

*To whom correspondence should be sent. E-mail: william_clark@harvard.edu





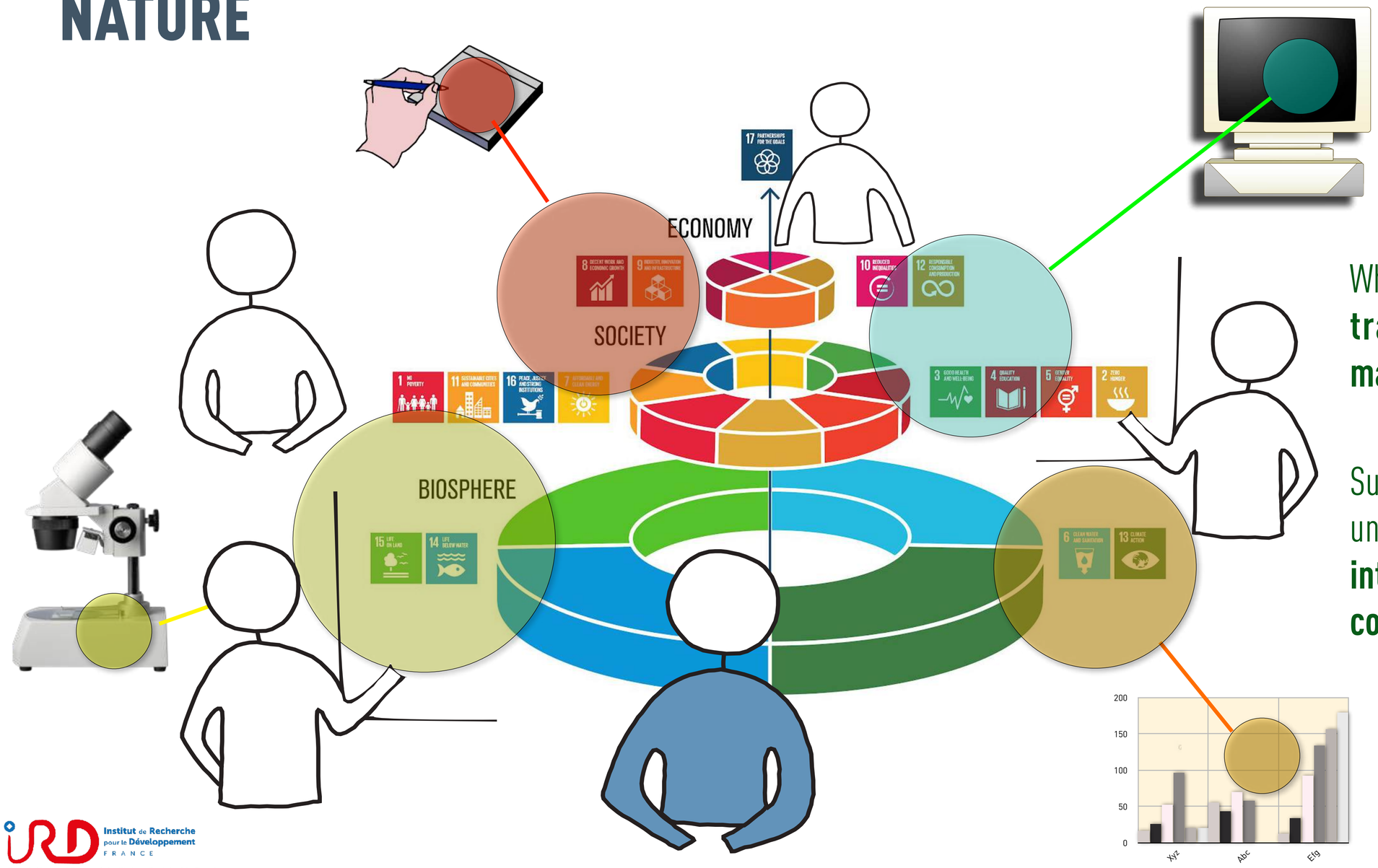


Kates, R.; Clark, W.; Corell, R.; Hall, J.; Jaeger, C.; et al. (2001). "Sustainability science". *Science*. **292** (5517): 641–642.

SUSTAINABILITY SCIENCE (HARVARD UNIV. DEFINITION)

… is a **problem-driven, interdisciplinary** research domain that seeks to facilitate the **design, implementation, and evaluation of effective interventions** that foster **shared prosperity** and **reduced poverty** while **protecting the environment**. It (…) draws from multiple disciplines of the **natural, social, medical and engineering sciences**

BUT SUSTAINABLE DEVELOPMENT ISSUES ARE INTERDISCIPLINARY BY NATURE



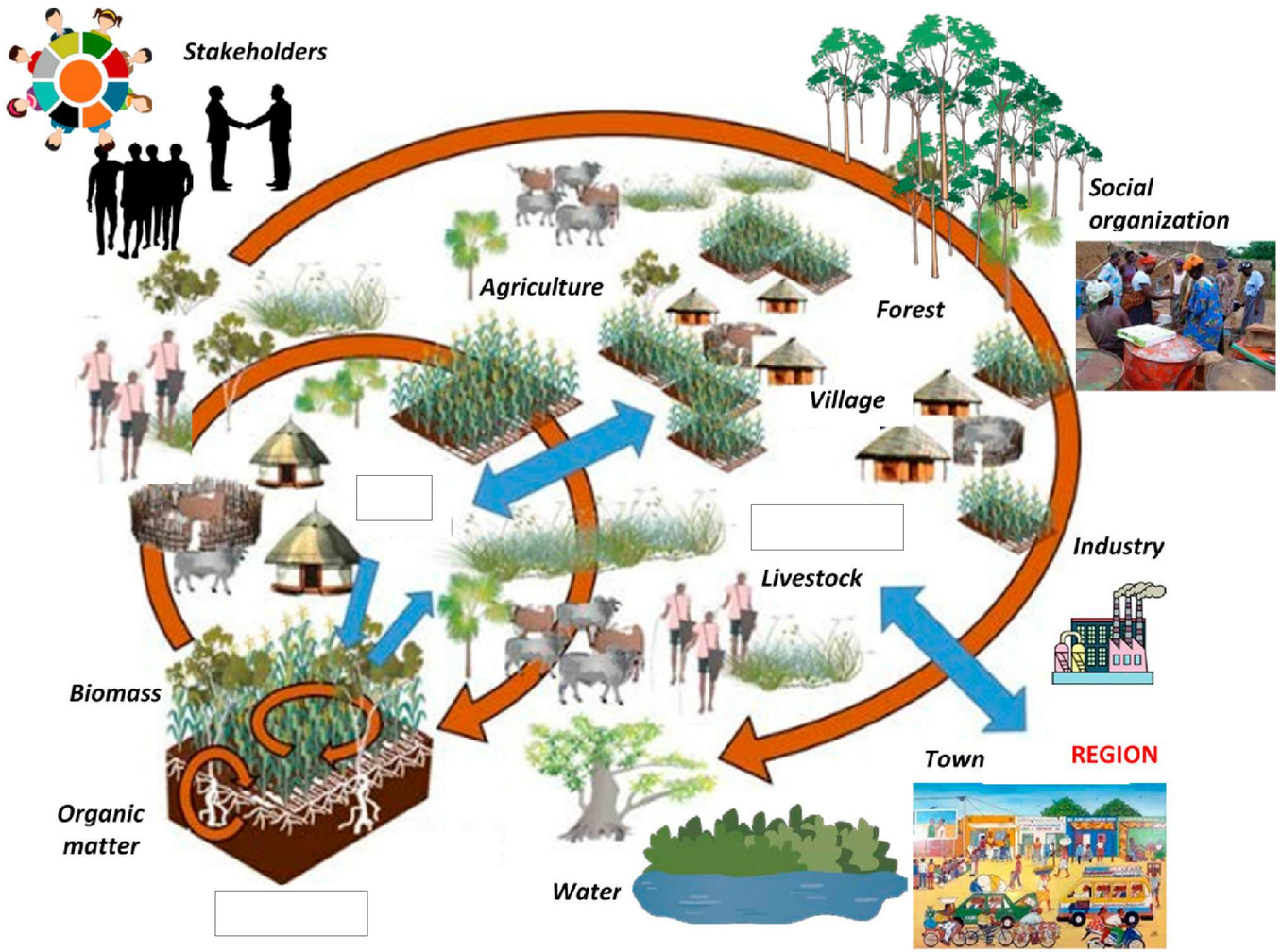
What needs to be studied are **social transformations** in relation to **material limits in the biosphere**.

Sustainability is a complex field – best understood and explained through **interdisciplinary research in close collaboration with society.**

EXAMPLE: PROMOTING CARBON SEQUESTRATION IN SOILS

DISCIPLINES

- SOCIOLOGY
- POLITICAL SCIENCE
- ANTHROPOLOGY
- DEMOGRAPHY
- AGRONOMY
- ECOLOGY
- PEDOLOGY
- BIOLOGY
- ECONOMICS
- GEOGRAPHY
- HYDROLOGY



STAKEHOLDERS

- FARMERS
- UNIONS
- FOOD INDUSTRY
- HOUSEHOLDS
- AUTHORITIES
- AGRONOMISTS
- SCIENTISTS

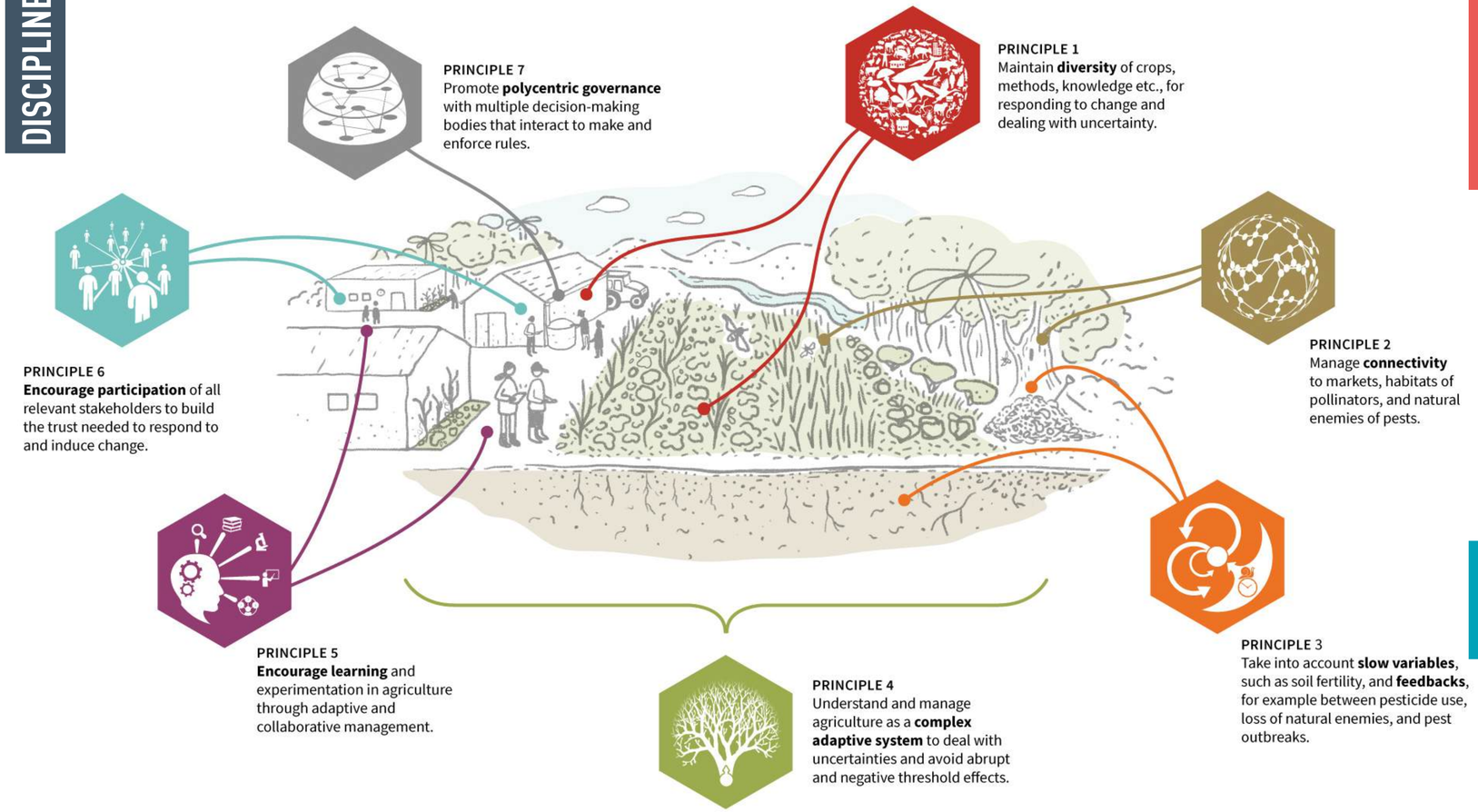
SCALES

- FIELD
- FARM
- VILLAGE
- LANDSCAPE
- REGION

EXAMPLE: ACCOMPANYING TRANSITION TO AGROECOLOGICAL PRACTICES

DISCIPLINES

SOCIOLOGY
POLITICAL SCIENCE
AGRONOMY
ECONOMICS
ETHOLOGY
BIOLOGY
PEDOLOGY
COMPLEXITY



STAKEHOLDERS

FARMERS
BUYERS
HOUSEHOLDS
AUTHORITIES
FOOD INDUSTRY
CONSUMERS
RESELLERS
SCIENTISTS

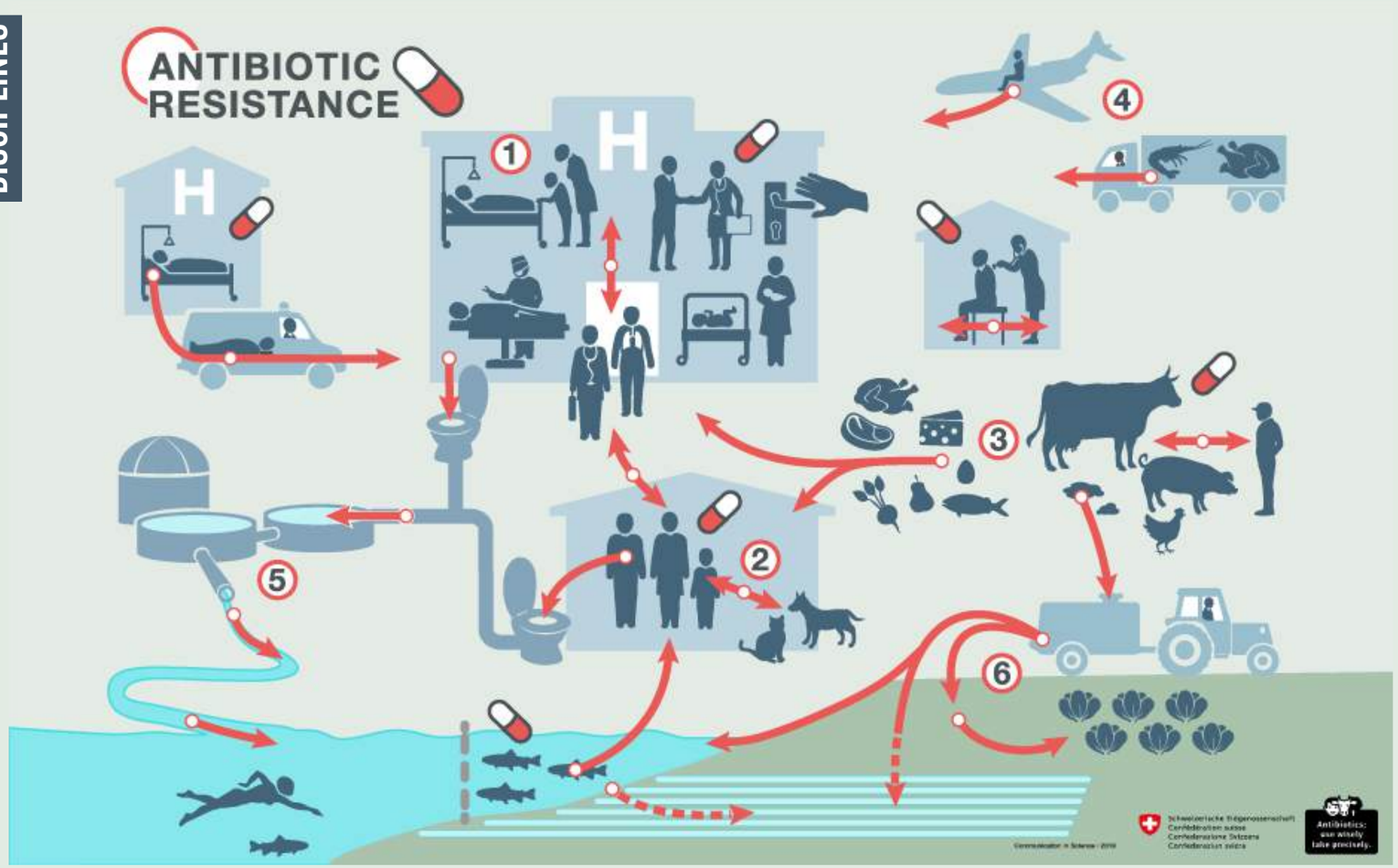
SCALES

PLANTS
PLOTS
FARMS
VILLAGES
WATERSHEDS
REGION

EXAMPLE: FIGHTING ANTIBIOTIC RESISTANCE

DISCIPLINES

- SOCIOLOGY
- HUMAN HEALTH
- ANTHROPOLOGY
- EPIDEMIOLOGY
- BIOCHEMISTRY
- TOXICOLOGY
- FISHERY
- BIOLOGY
- HYDROLOGY
- AGRONOMY



STAKEHOLDERS

- PATIENTS
- DOCTORS
- FARMERS
- HOUSEHOLDS
- PUBLIC HEALTH
- PHARMACISTS
- DRUG INDUSTRY
- FOOD INDUSTRY
- SCIENTISTS

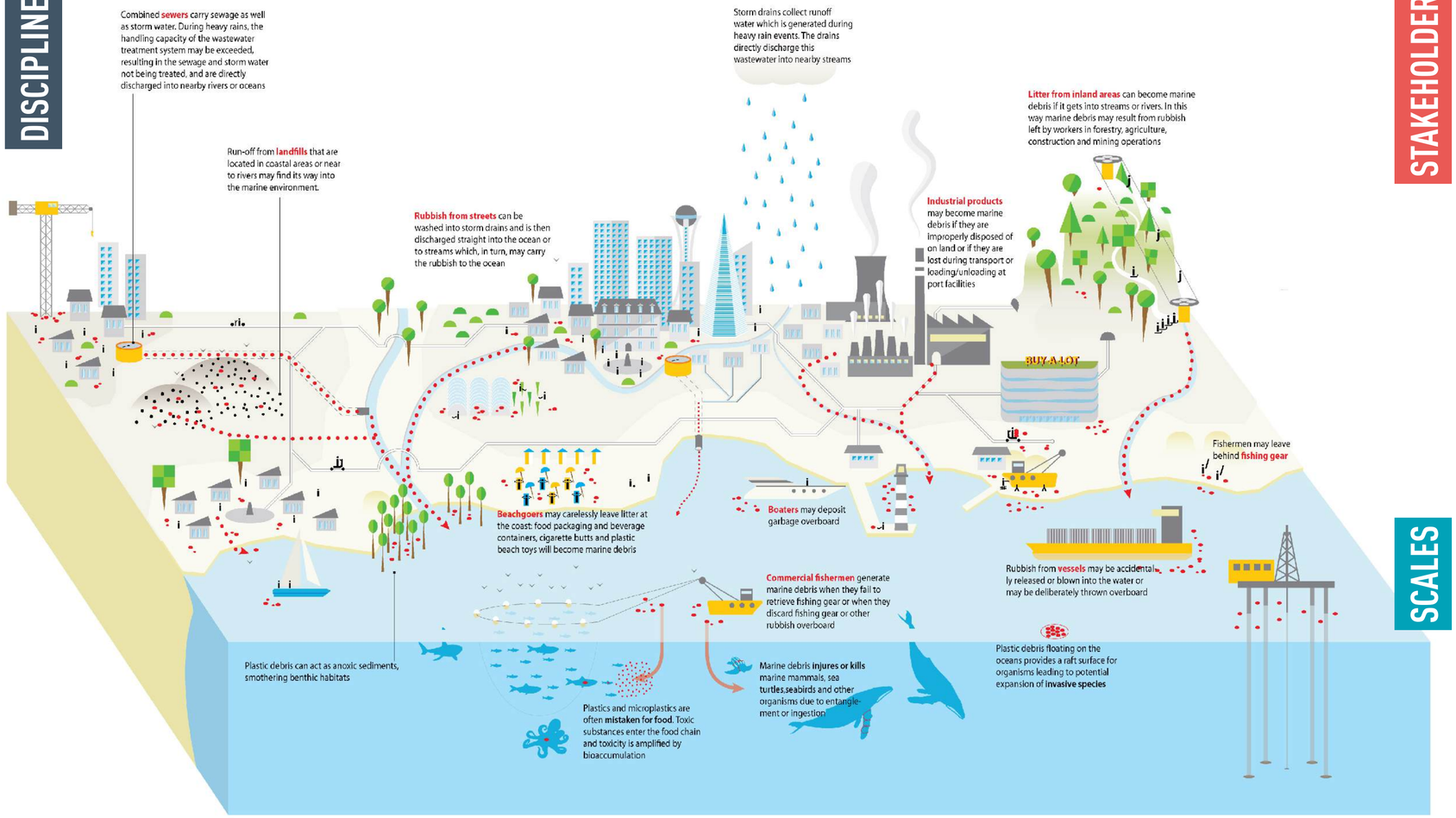
SCALES

- CELLS
- BODIES
- HOUSES
- FARMS
- ECOSYSTEMS
- REGION

EXAMPLE: PREVENTING PLASTIC LEAKAGE AND AQUATIC POLLUTION

DISCIPLINES

- CHEMISTRY
- MATERIAL SCIENCE
- SOCIOLOGY
- AGRONOMY
- ECONOMICS
- HYDROLOGY
- BIOLOGY
- POLITICAL SCIENCE
- ETC...



STAKEHOLDERS

- CONSUMERS
- CITIZENS
- HOUSEHOLDS
- PACKAGING INDUSTRY
- COMMERCE
- ENGINEERS
- FARMERS/FISHERS
- AUTHORITIES
- SCIENTISTS

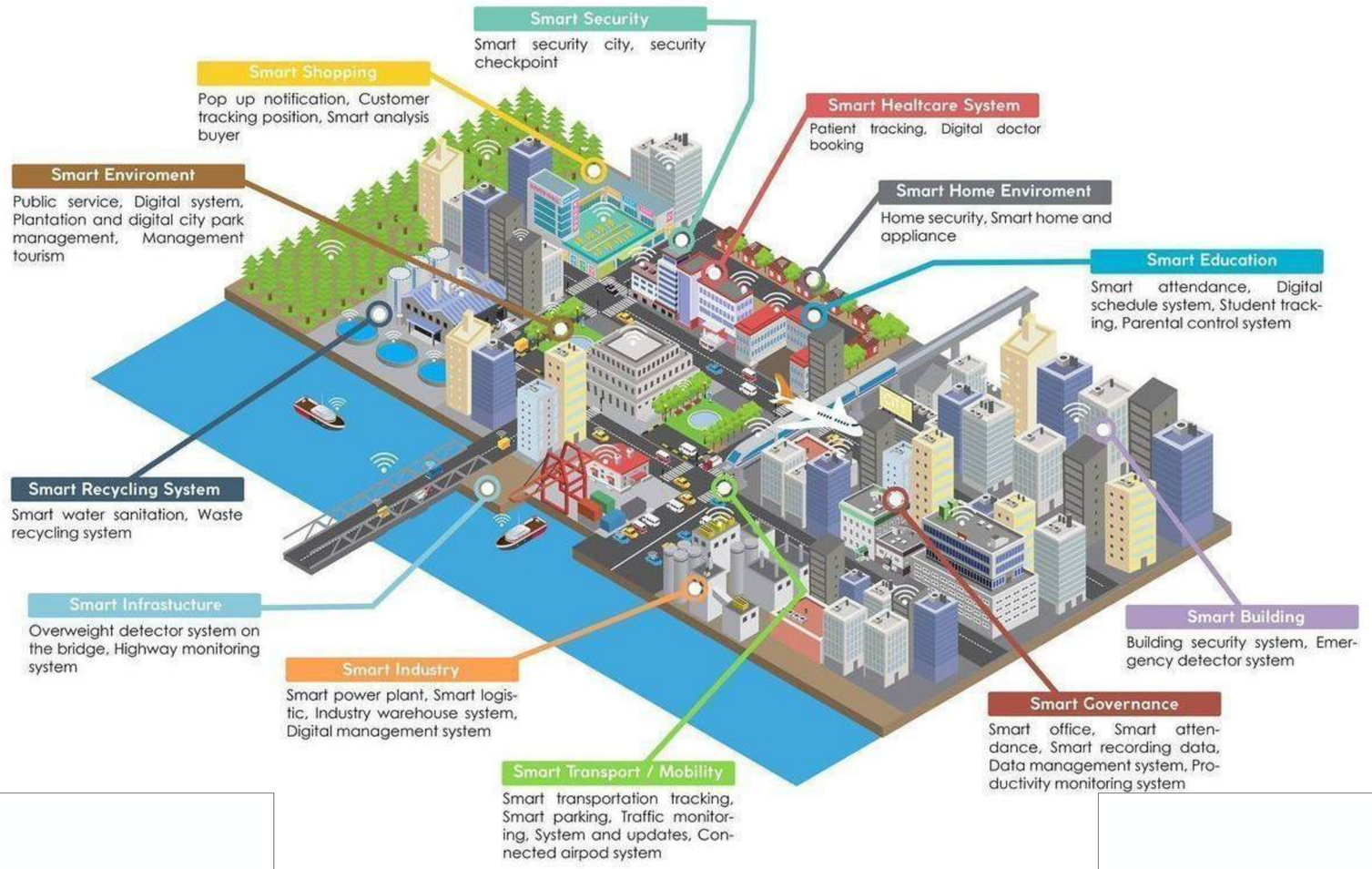
SCALES

- MOLECULES
- PLANTS
- ANIMALS/PEOPLE
- ECOSYSTEMS
- RECYCLING NETWORKS
- COMMERCIAL NETWORKS
- CITIES
- OCEANS

EXAMPLE: DESIGNING SMART CITIES

DISCIPLINES

SOCIOLOGY
URBAN PLANNING
IT / AI
ELECTRONICS
ROBOTICS
HYDROLOGY
AGRONOMY
MATERIAL SCIENCE
ETC...



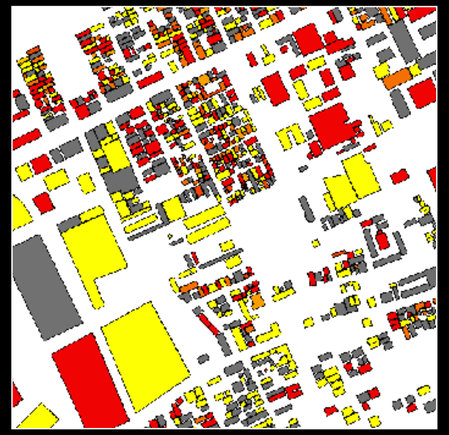
STAKEHOLDERS

SERVICE USERS
CITIZENS
HOUSEHOLDS
INDUSTRIES
COMMERCE
ENGINEERS
URBAN PLANNERS
AUTHORITIES
SCIENTISTS

SCALES

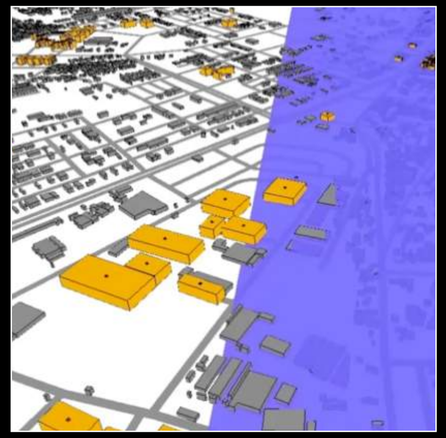
APARTMENTS
BUILDINGS
BLOCKS
DISTRICTS
NETWORKS
PROVINCES

ONE WAY TO TACKLE THESE ISSUES TO BUILD MODELS THAT CAN SIMPLIFY THEIR COMPLEXITY

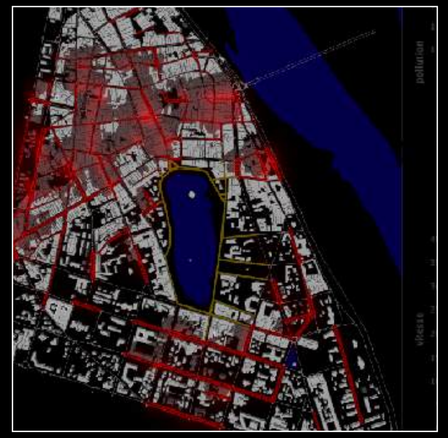


URBAN SEGREGATION

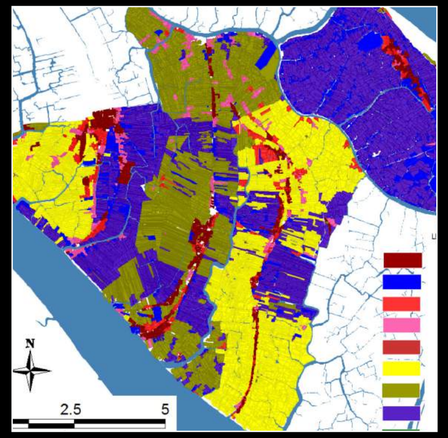
ENERGY TRANSITION



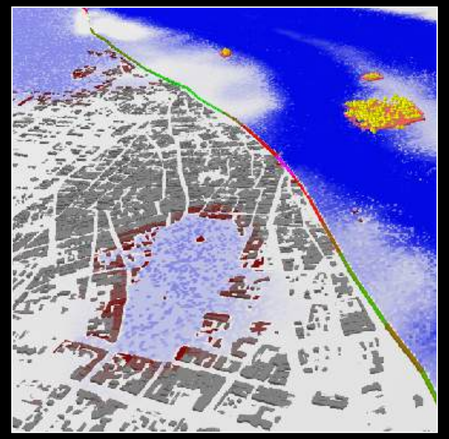
TSUNAMI EVACUATION



URBAN TRAFFIC AND POLLUTION

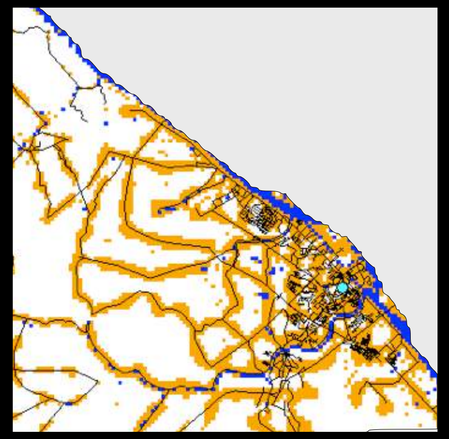


LAND-USE AND SALINISATION



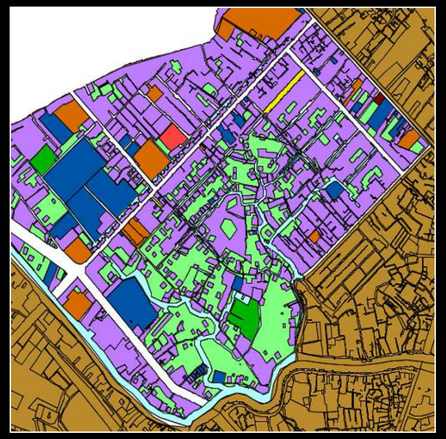
FLOODING

EPIDEMIOLOGY



URBAN GROWTH

FLOODING EVACUATION

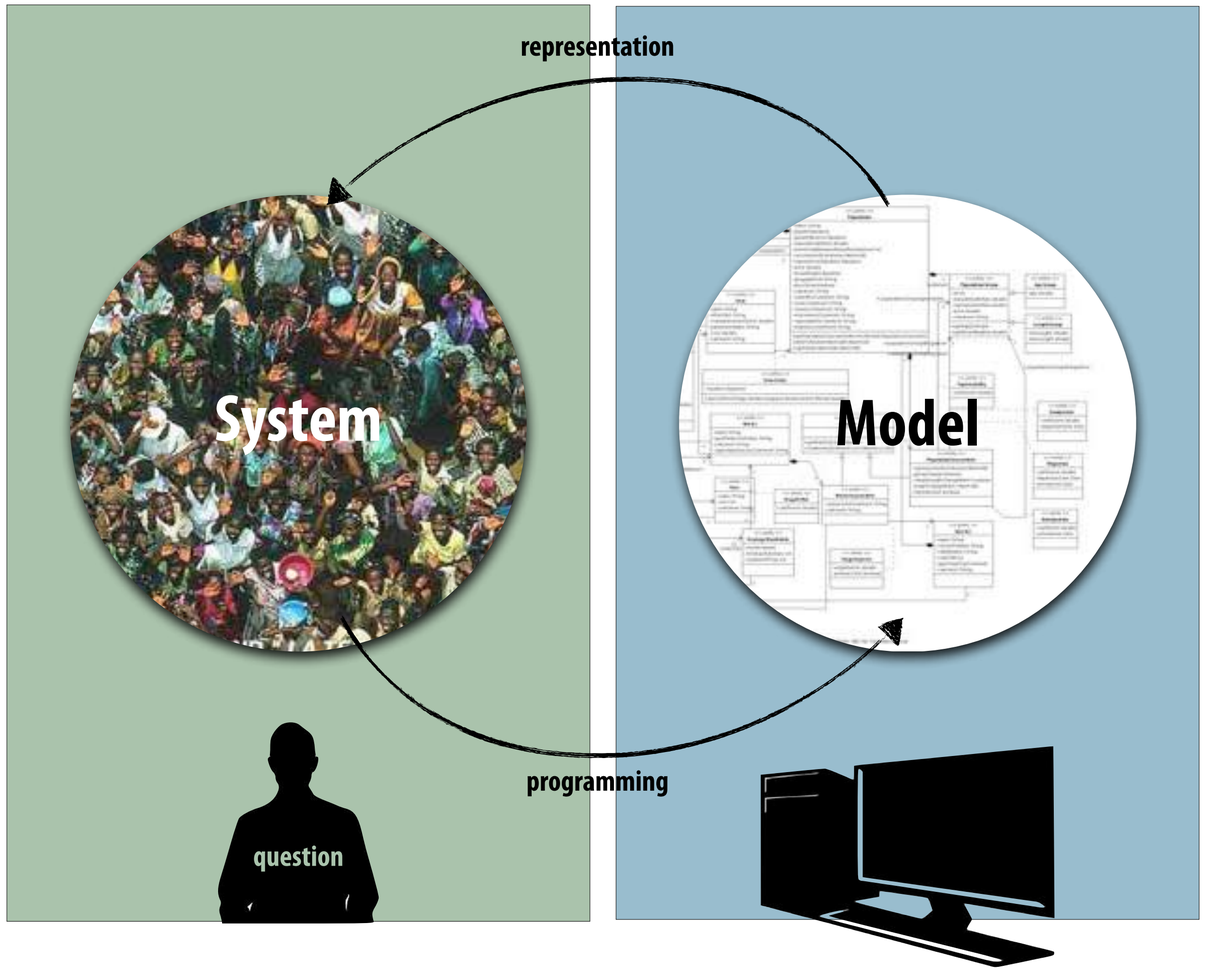


URBAN RESILIENCE

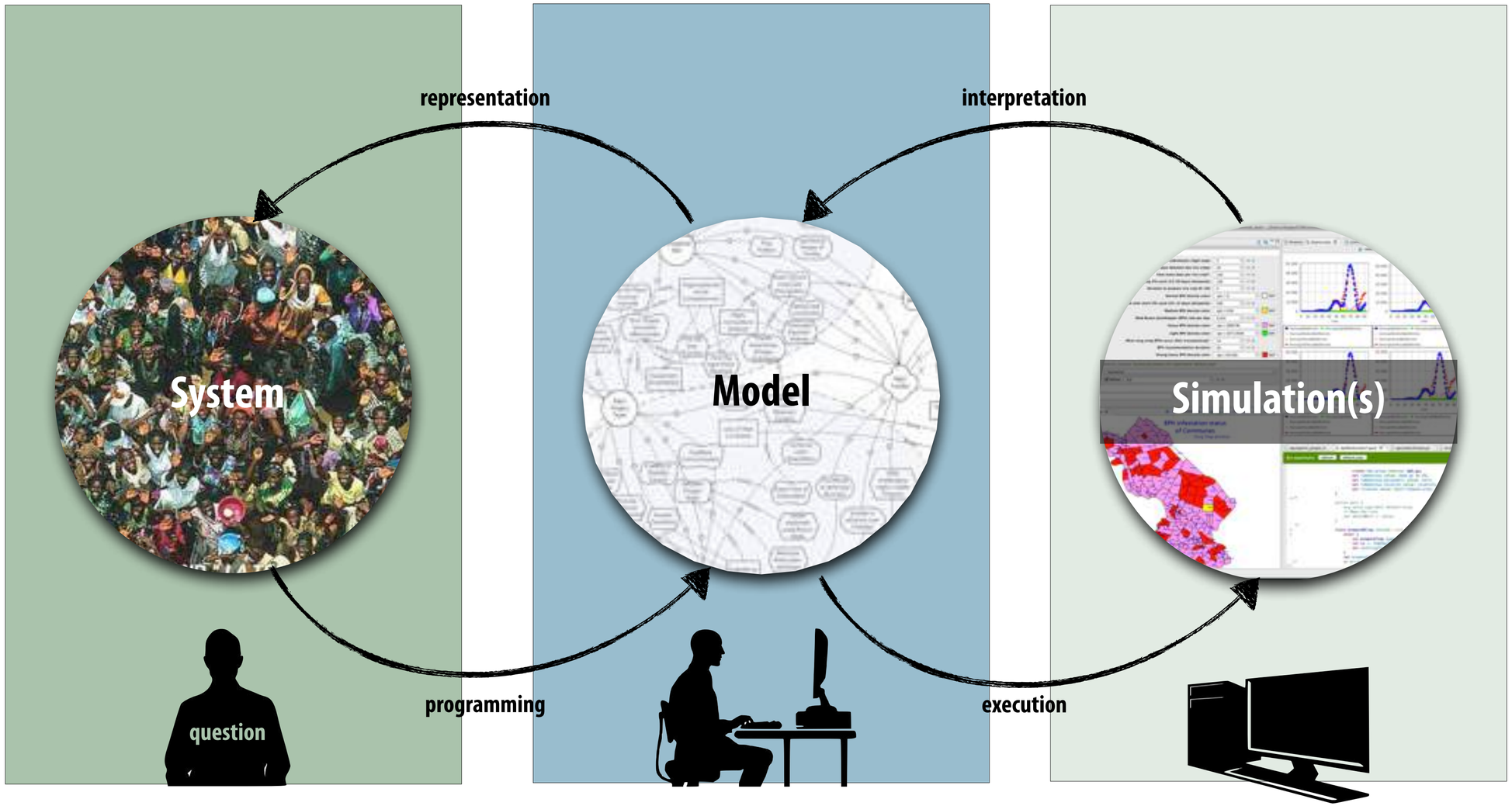
FOR DECISION-SUPPORT, VISUALIZATION, EXPLANATION, FORECASTING, EXPLORATION OF SCENARIOS

A MODEL IS A SIMPLIFIED REPRESENTATION OF A SYSTEM THAT HELPS ANSWERING QUESTIONS ABOUT THIS SYSTEM

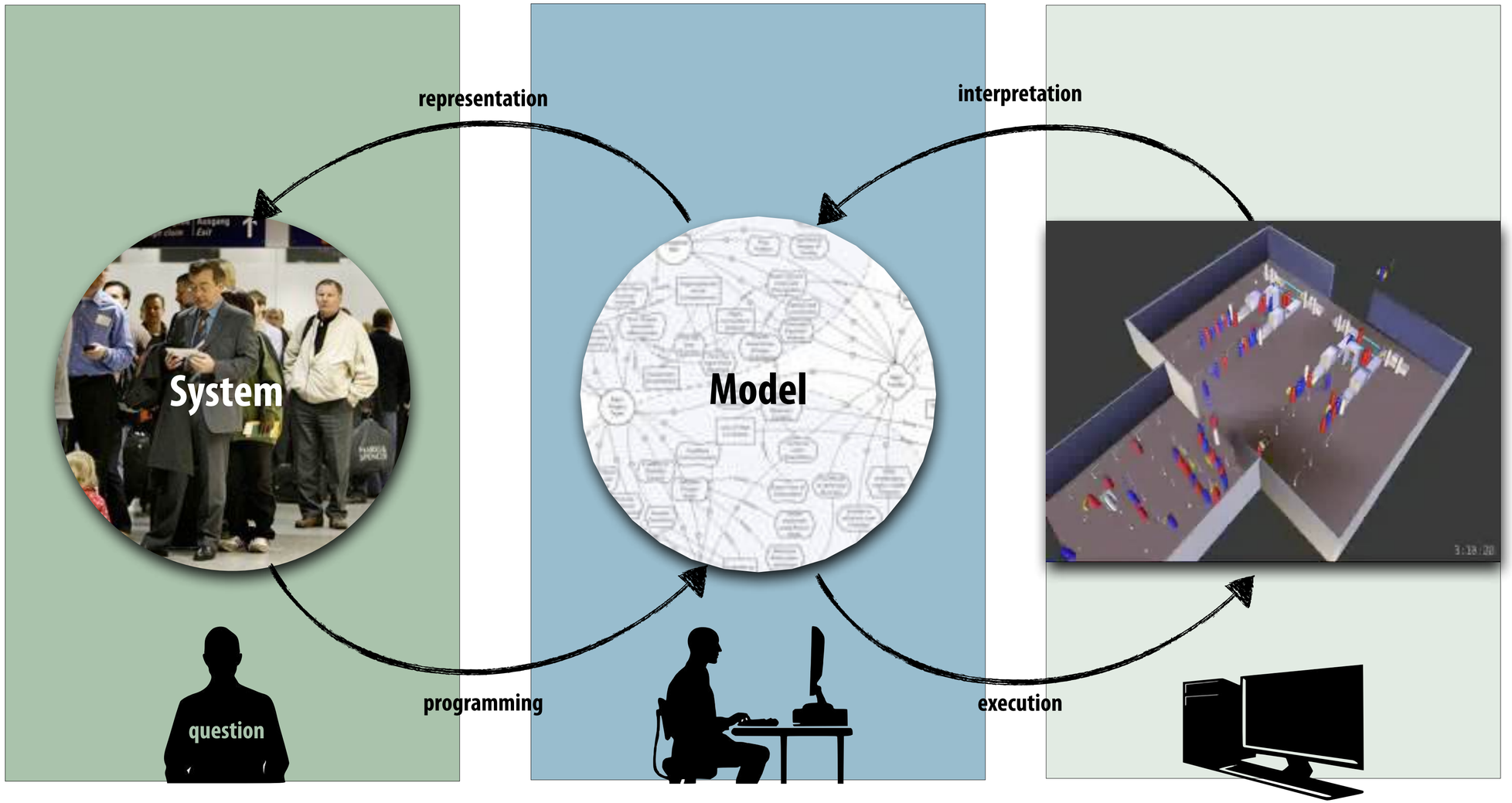
A COMPUTER MODEL USES COMPUTER PROGRAMS AS A REPRESENTATION



THE EXECUTIONS OF A COMPUTER MODEL ARE CALLED <u>SIMULATIONS</u>

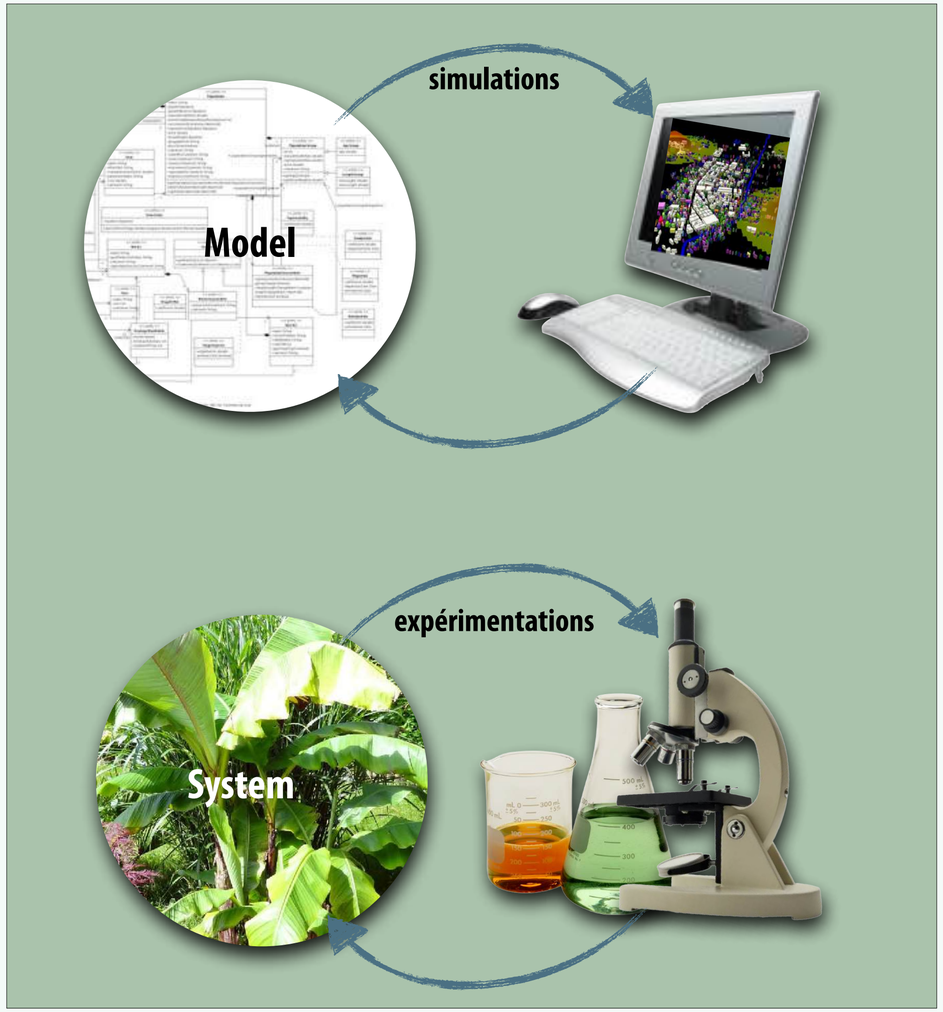


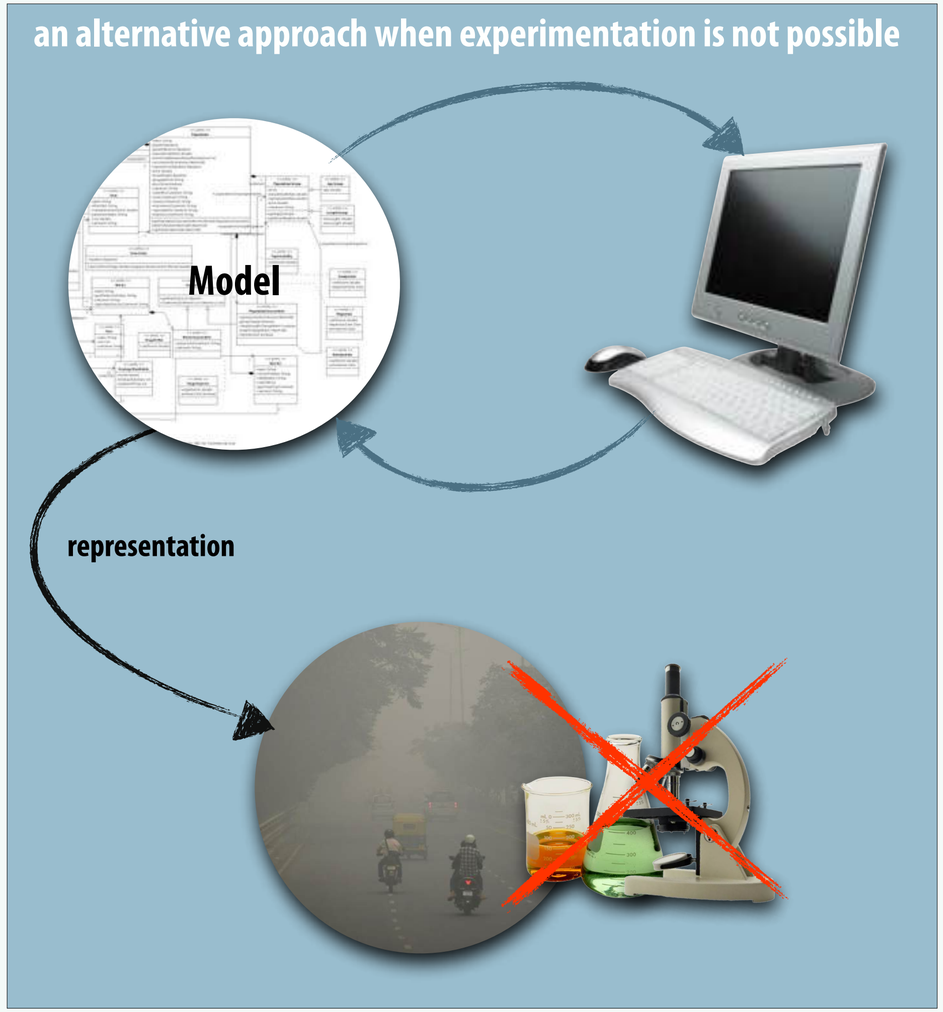
SIMULATIONS CAN SERVE MANY PURPOSES: VISUALIZATION, TRAINING, CONTROL, FORECASTING, DECISION SUPPORT, EVALUATION...



SIMULATIONS ARE TO A MODEL WHAT EXPERIMENTATIONS ARE TO THE REAL SYSTEM: CONTROLLED PERTURBATIONS (CHANGES OF PARAMETERS, INTRODUCTION OF NEW STRUCTURES) TO ANSWER SPECIFIC QUESTIONS

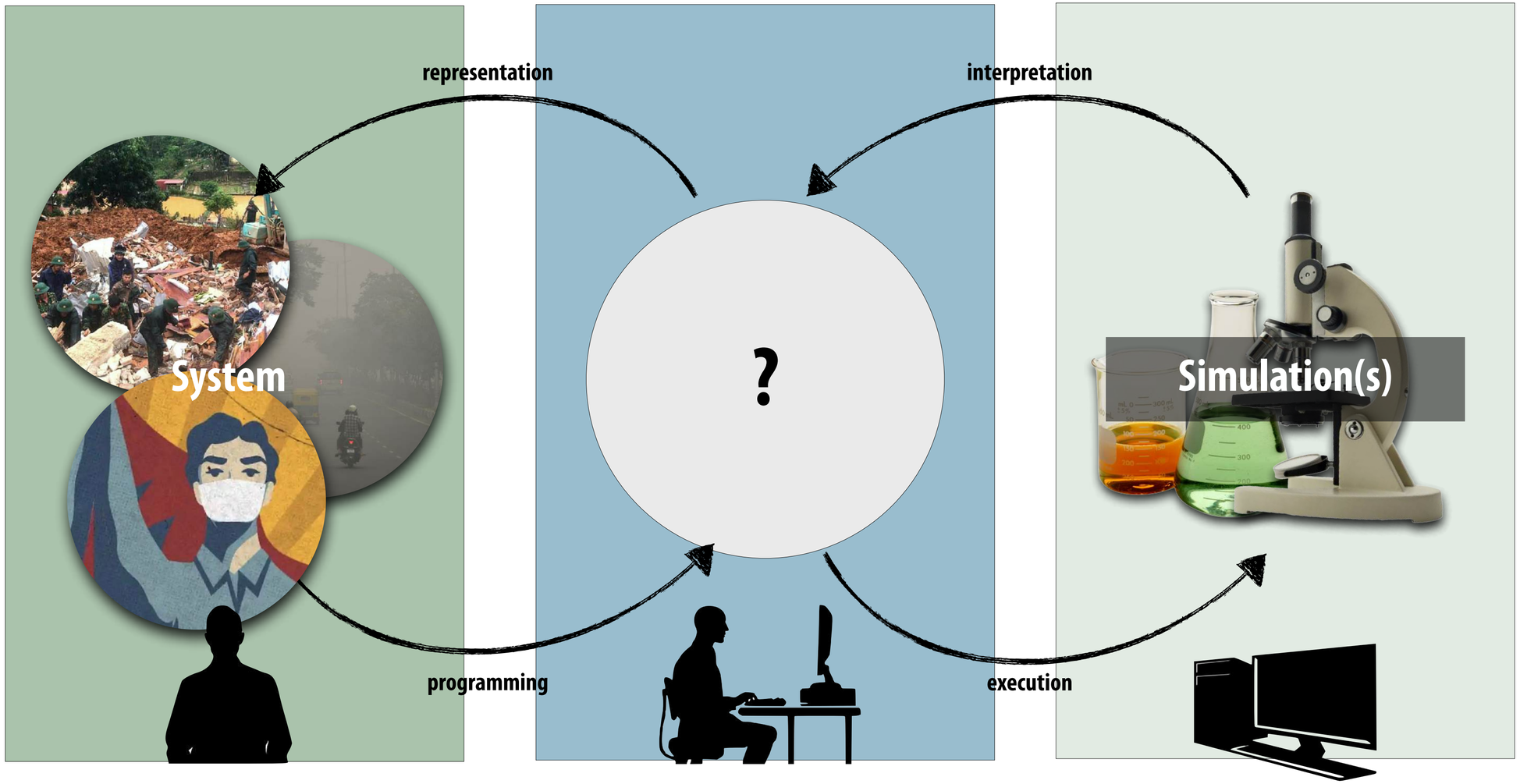
simulation as experimentation



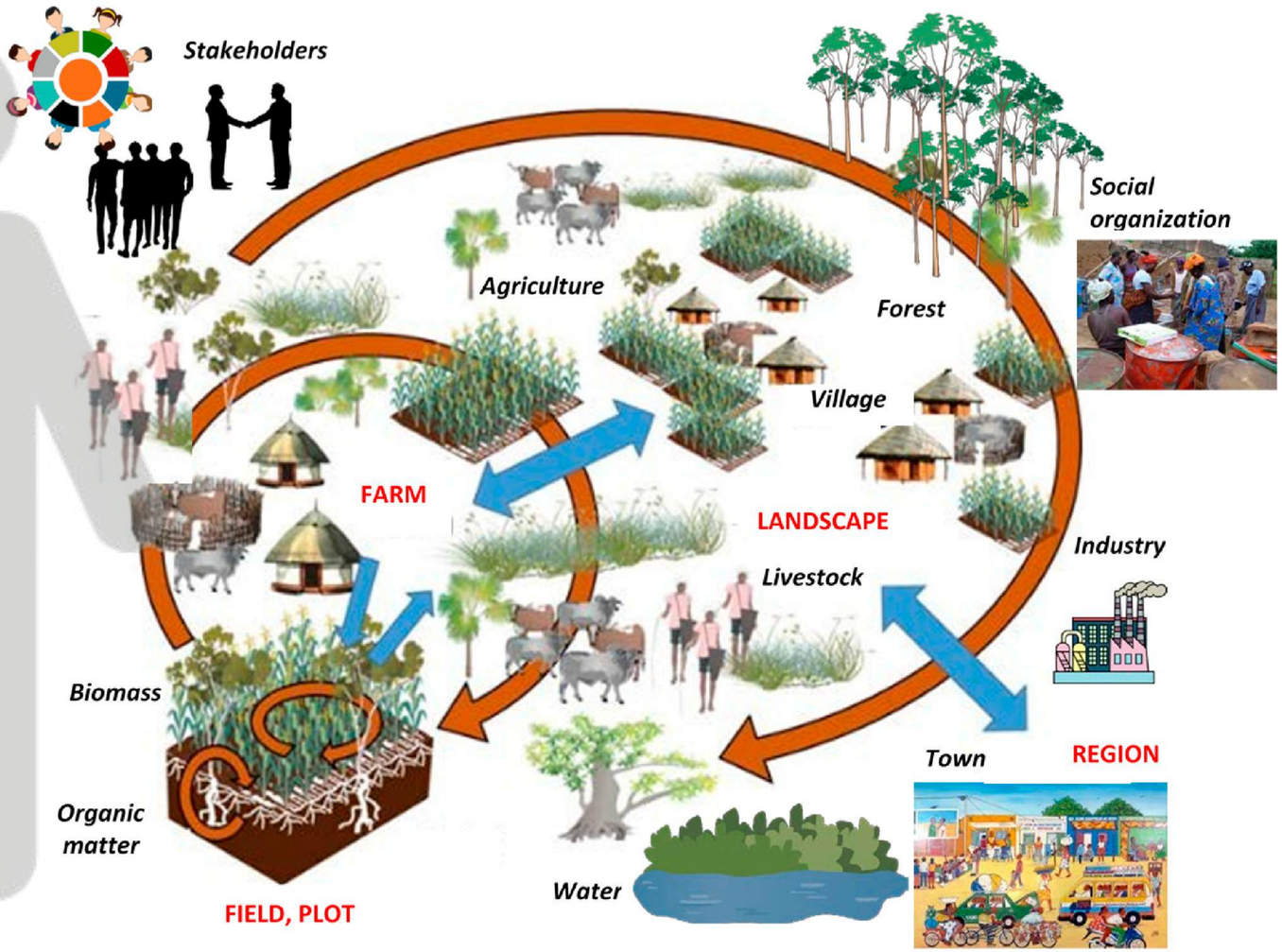


experimentation by simulation

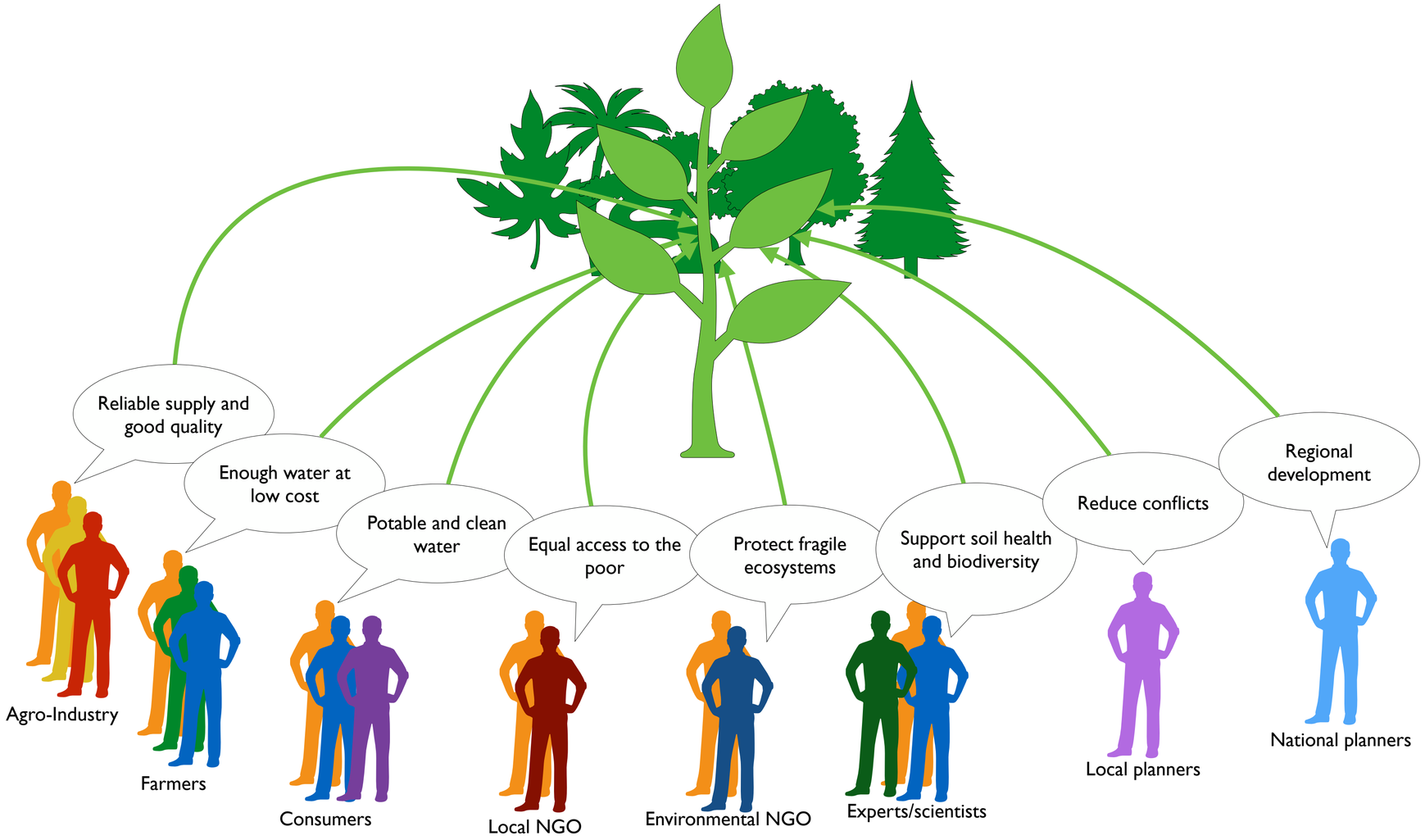
WHAT MODELLING METHODS CAN BE USED TO ANSWER THE QUESTIONS, IN THIS WAY, ABOUT COMPLEX SOCIO-ENVIRONMENTAL SYSTEMS?



THE DIFFICULTY IS THAT STAKEHOLDERS ARE HETEROGENEOUS, AND FORM HETEROGENEOUS GROUPS AT DIFFERENT SCALES



STAKEHOLDERS PURSUE DIFFERENT GOALS, SOME OF WHICH MAY BE CONFLICTING: HOW TO REPRESENT THESE DIFFERENT POINTS OF VIEW AND THEIR INTERACTIONS ?



ALL THESE SYSTEMS ARE DRIVEN BY THE INTERPLAY BETWEEN A MULTITUDE OF PROCESSES, STAKEHOLDERS AND COMMUNITIES, AT DIFFERENT SCALES OF SPACE AND TIME

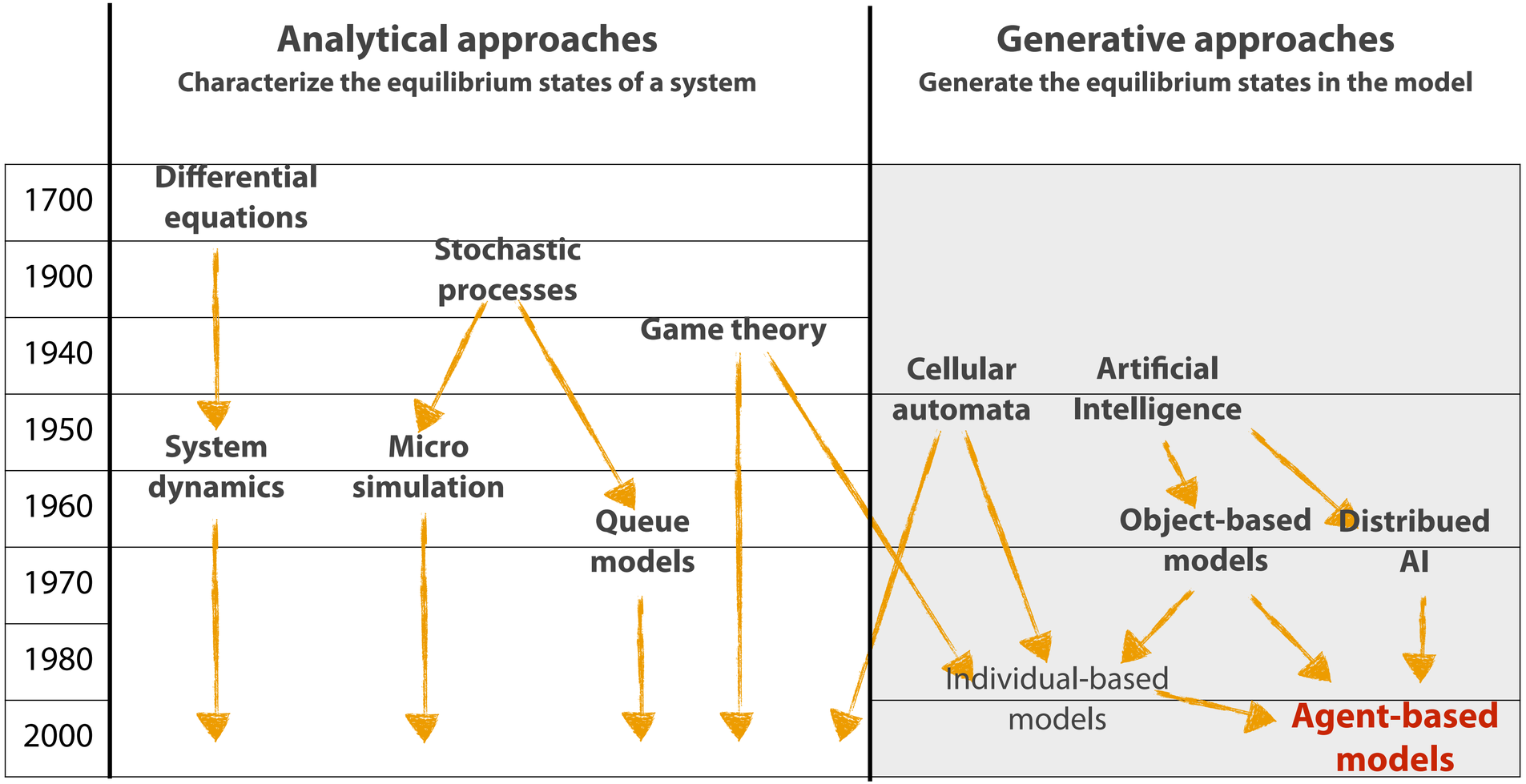
Their complexity creates challenges in terms of understanding & decision-making

- **Counter-intuitive** – outcomes may go against all 'commonsense' expectations
- **Intricate** – the processes are complicated and interact in detailed and complex ways
- **Non-linear** – insignificant changes in conditions can cause unlimited difference in the outcomes
- **Qualitatively changeable** – outcomes may be of a different ***kind***, not just of a different ***amount***
- **Specific** – principles/patterns that hold for one case do not work in an apparently similar case
- **Causally unbounded** – the arrival of new factors may radically change the 'rules of the game'

(adapted from B. Edmonds, « Possibilistic prediction and risk analysis », 2015)

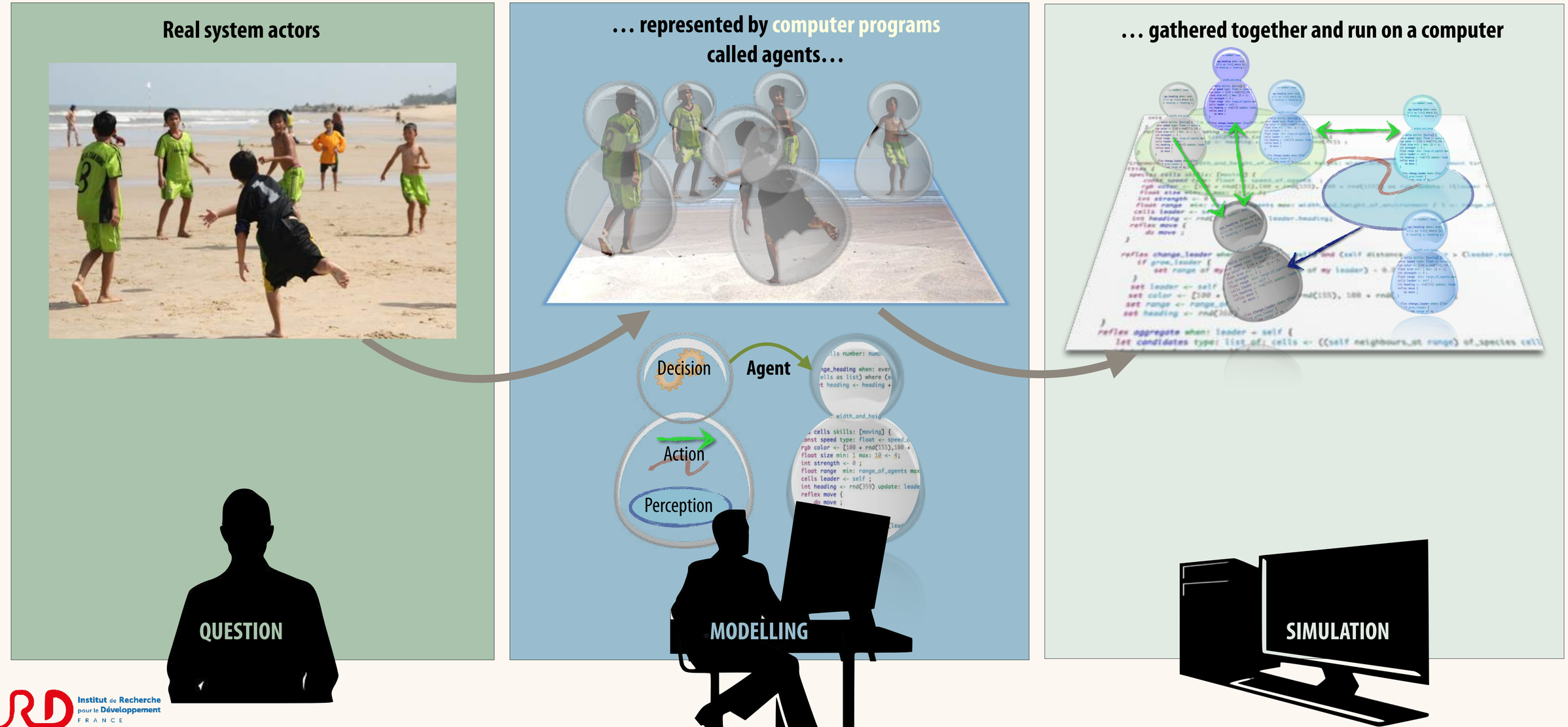
Institut de Recherche pour le Développement FRANCE
French National Research Institute for Sustainable Development

DYNAMIC MODELS AND SIMULATIONS HAVE A LONG HISTORY

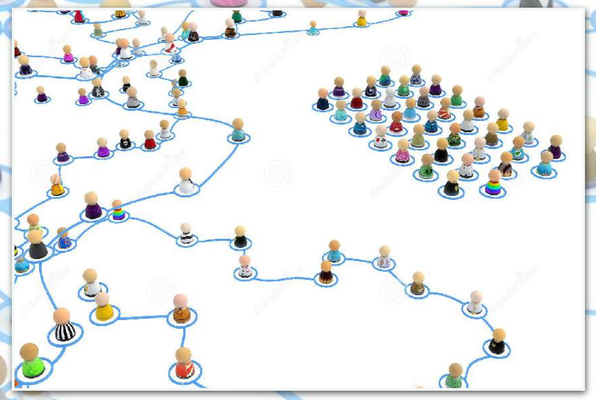


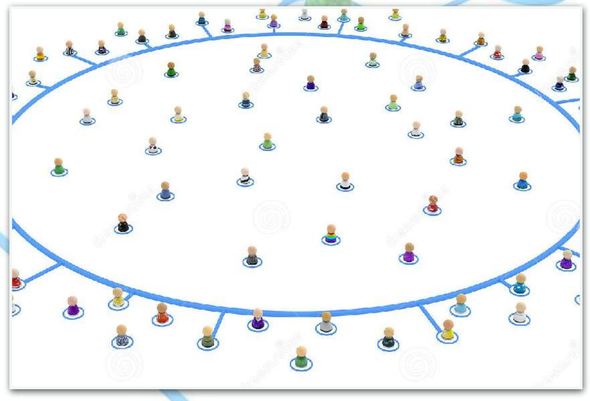
(adapted from Troitzsch & Gilbert 2001)

AGENT-BASED MODELLING: BASED ON AN "INDIVIDUAL-CENTERED" REPRESENTATION THAT ALLOWS TO RECONSTRUCT AND SIMULATE "VIRTUAL WORLDS" ON A COMPUTER.

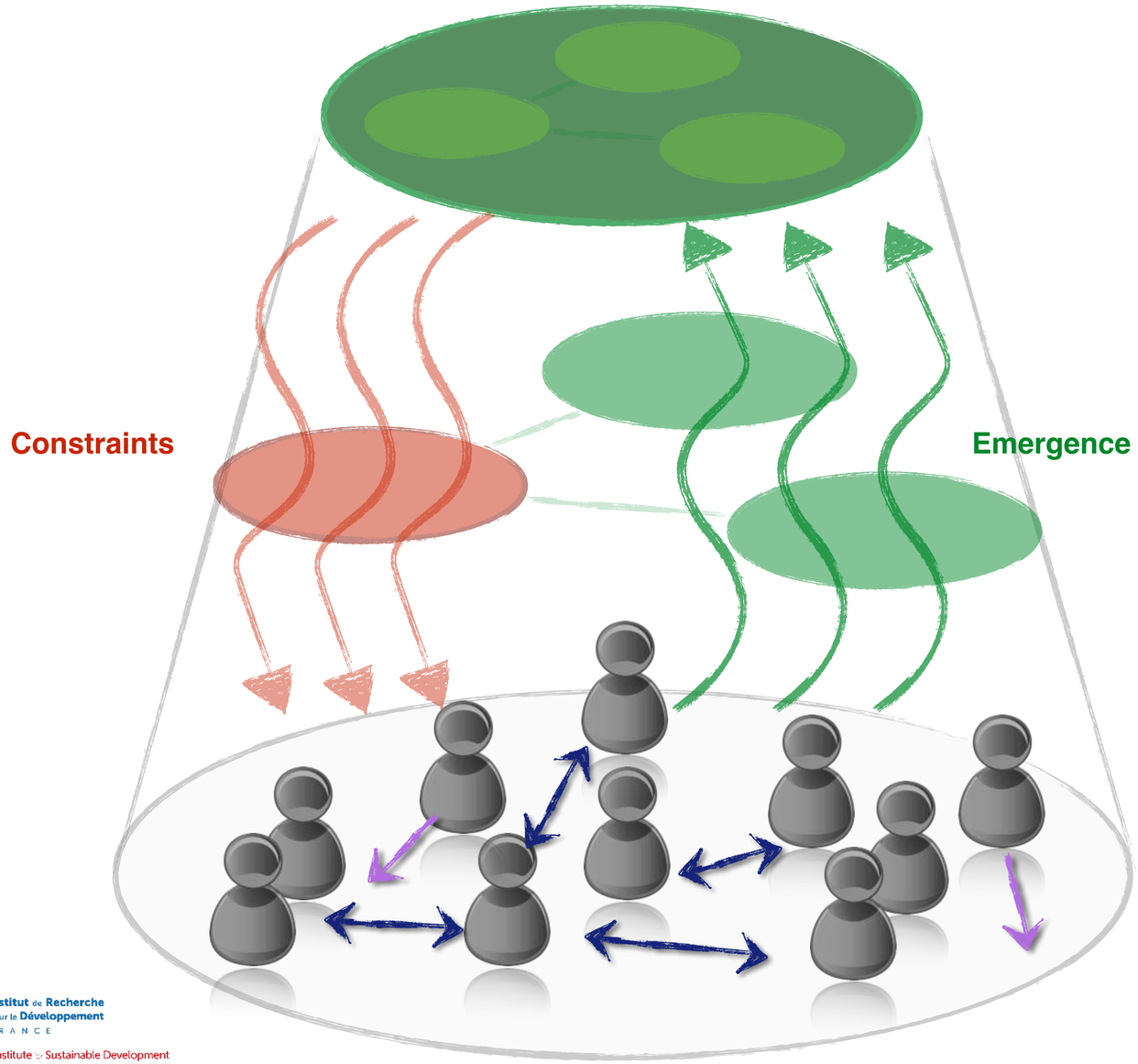


AGENT-BASED SIMULATIONS ARE MINIATURE LABORATORIES THAT SUPPORT EXPERIMENTATION ON THESE "VIRTUAL WORLDS" AND TAKE ADVANTAGE OF THE POWER OF COMPUTERS TO EXPLORE AS MANY SCENARIOS AS NECESSARY.



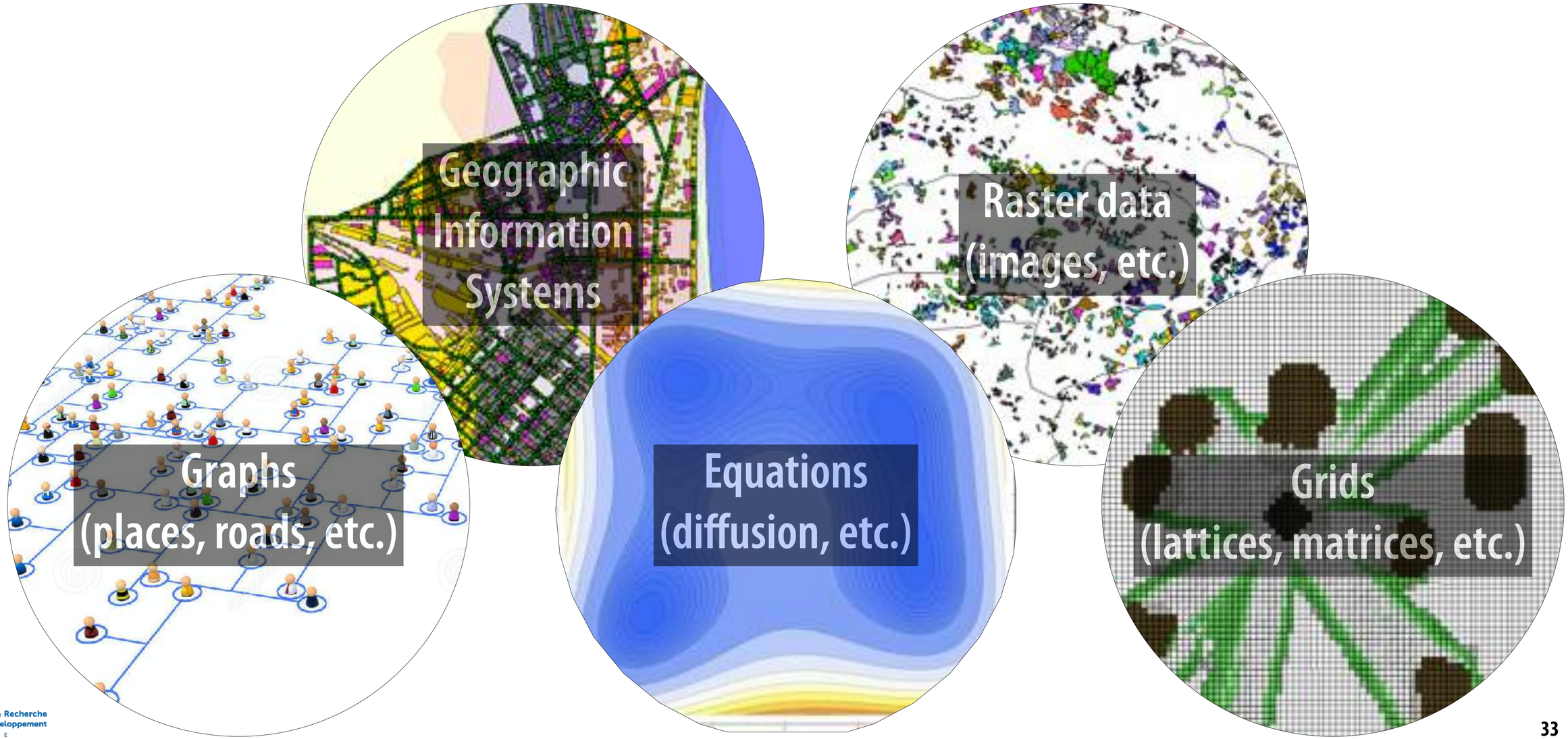


AGENT-BASED MODELS ARE GENERATIVE: THEY REPRESENT BEHAVIORS AT A «MICRO-LEVEL» AND GENERATE OUTCOMES, DURING SIMULATIONS, AT ONE OR SEVERAL «MACRO-LEVEL(S)»

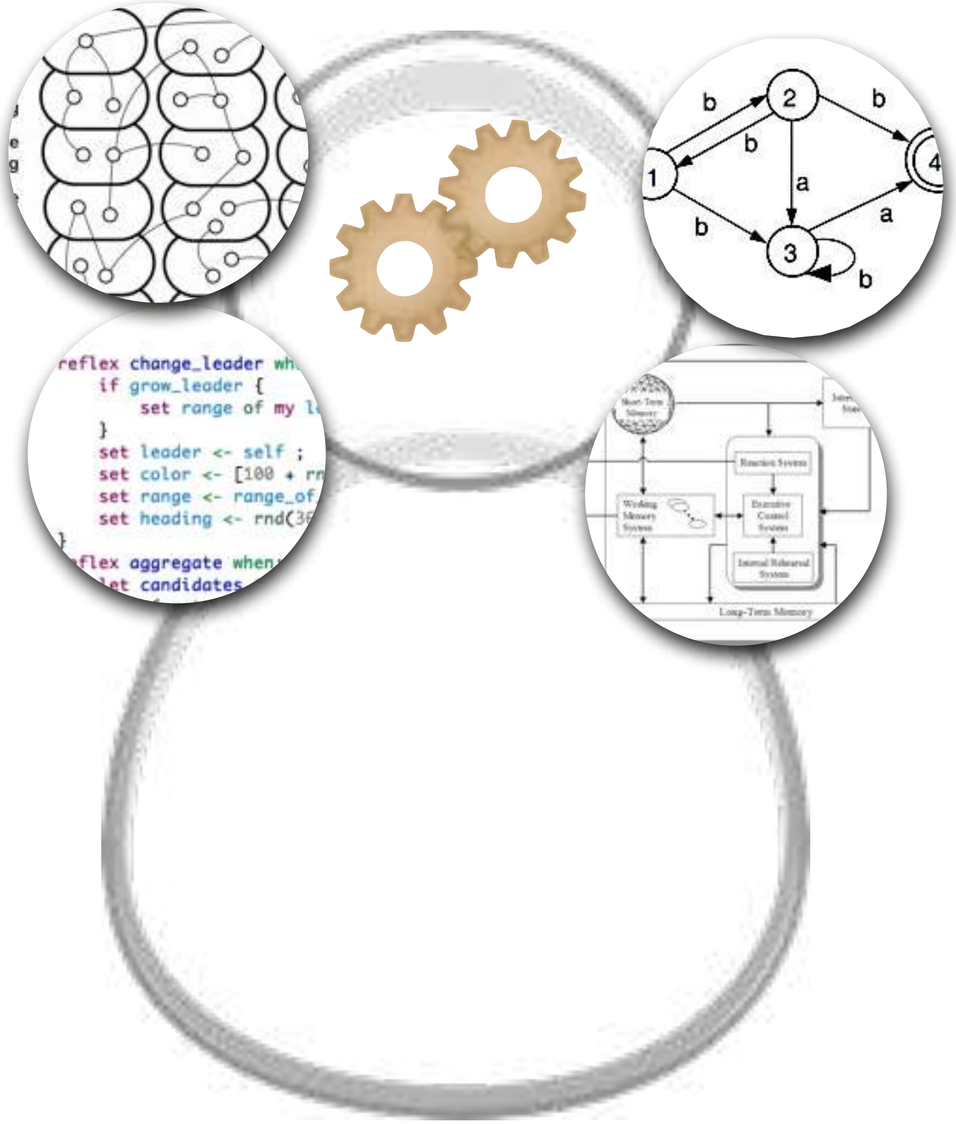


- Agent-based models represent individual behaviours at a "micro" level.
- Simulations run these individual behaviours, their interactions, and produce global results, which can be analysed at different "macro" levels.

AGENT-BASED MODELS CAN BE SPATIALLY EXPLICIT: THE ENVIRONMENT CAN BE VERY DETAILED AND BE MADE UP OF «SPATIAL AGENTS» ITSELF.



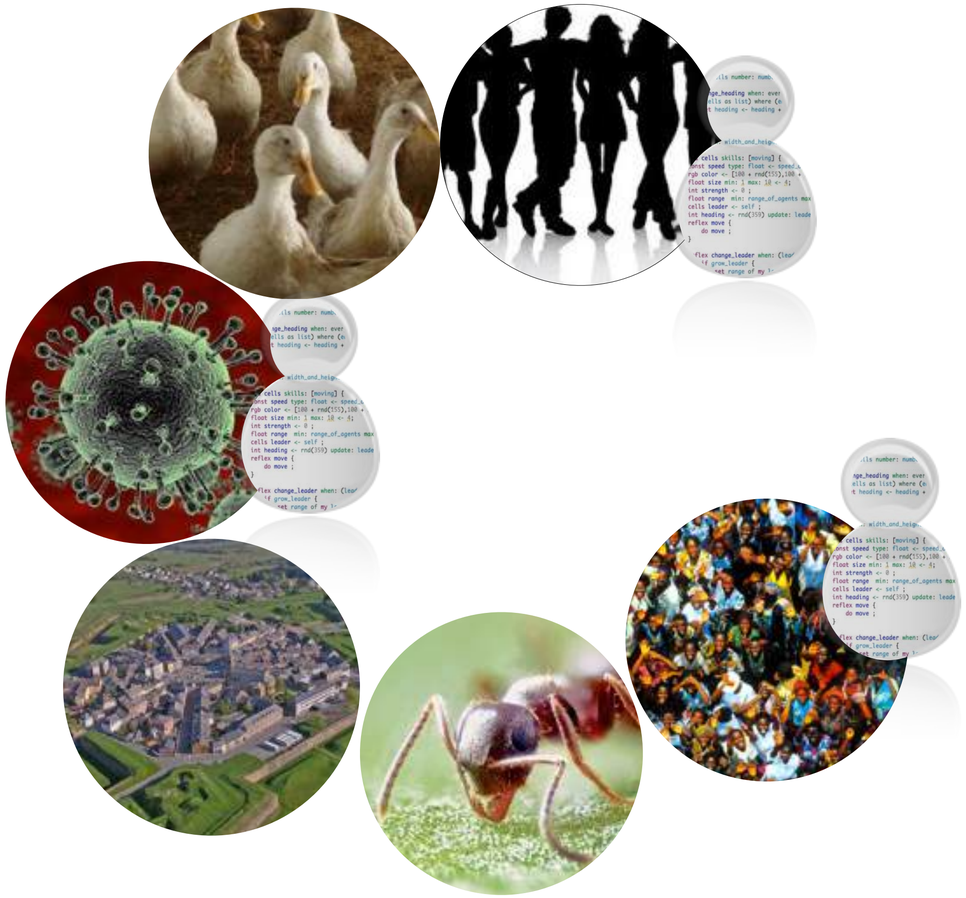
AGENT-BASED MODELS ARE AGNOSTIC : AGENTS CAN BE PROGRAMMED USING ANY LANGUAGE OR DECISION-MAKING ARCHITECTURE



- Any programming language
- Expert systems
- Finite state automata
- Task-based architectures
- Perception-decision-action architectures
- Planning architectures
- Neural networks
- Bayesian networks...

AN ARTIFICIAL AGENT CAN REPRESENT ANY OBJECT OR ACTOR OF THE SYSTEM TO MODEL, AT ANY LEVEL OF ABSTRACTION

THE CHOICE DEPENDS ON THE QUESTION AND DATA AVAILABLE



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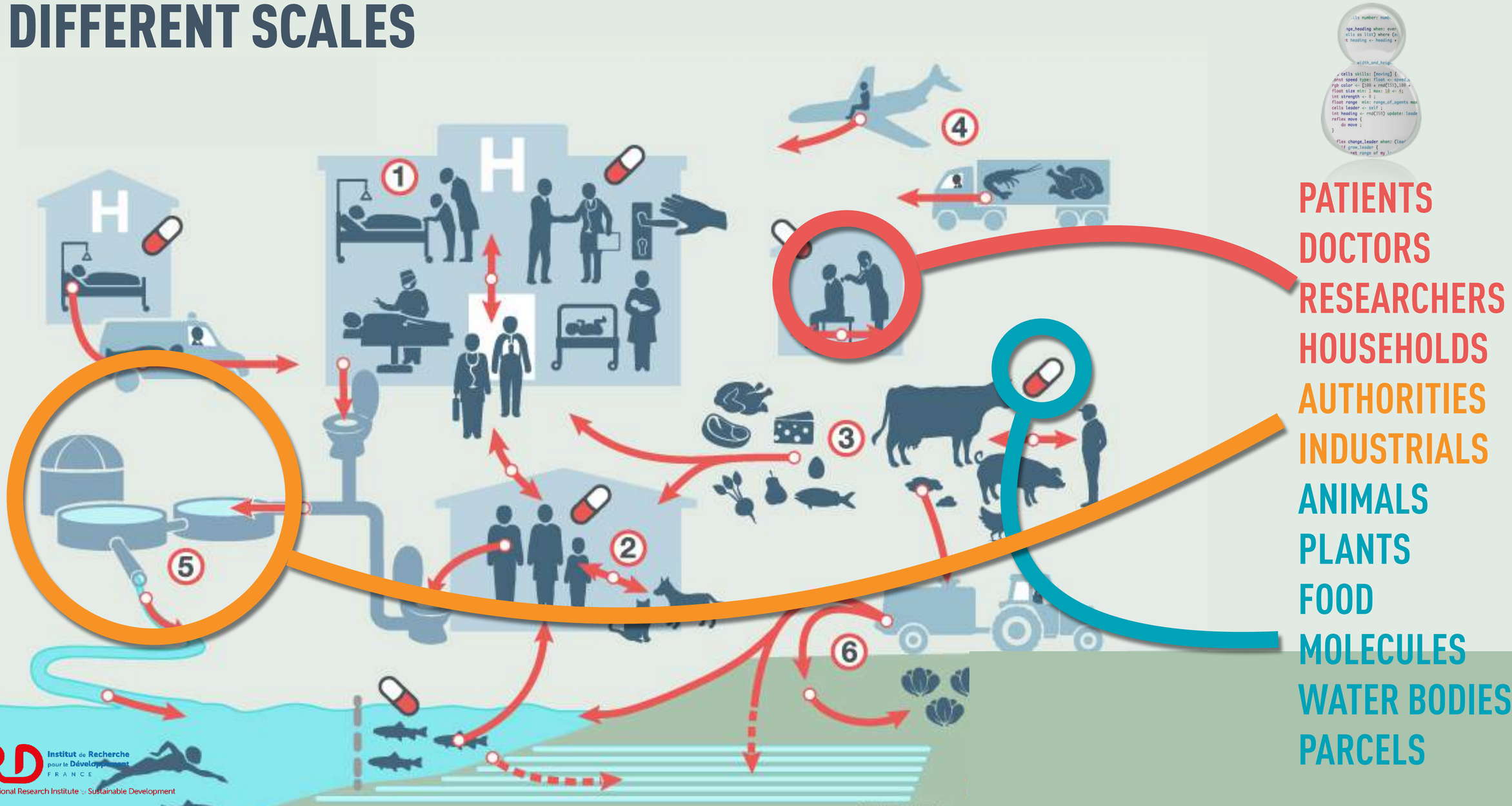
IN AN ABM, AGENTS CAN REPRESENT ANY OBJECT OR ACTOR OF THE REFERENCE SYSTEM. EXAMPLE IN A "SMART CITY"

INHABITANTS
ROBOTS
DRONES
VEHICLES
APPLIANCES
OBJECTS
BUILDING
INFRASTRUCTURES
NETWORKS
....

OR IN A "ONE HEALTH" MODEL, WITH AGENTS POSSIBLY AT COMPLETELY DIFFERENT SCALES



AGENT-BASED MODELLING IS WELL ADAPTED TO SITUATIONS WHERE…

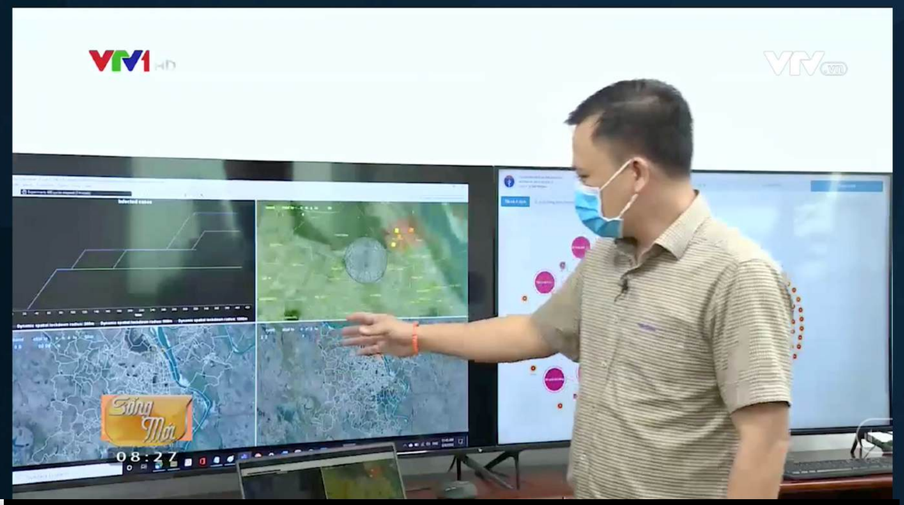
- it is difficult to test hypotheses solely based on observations of the reference system: an (even virtual) experimental approach is necessary.
- the actors are heterogeneous and their behaviours/interactions are suspected to play a role in the outcomes
- the appropriate level of analysis/observation is not fixed and may change dynamically
- changes at the macro-level should be outcomes, and not inputs, of the model

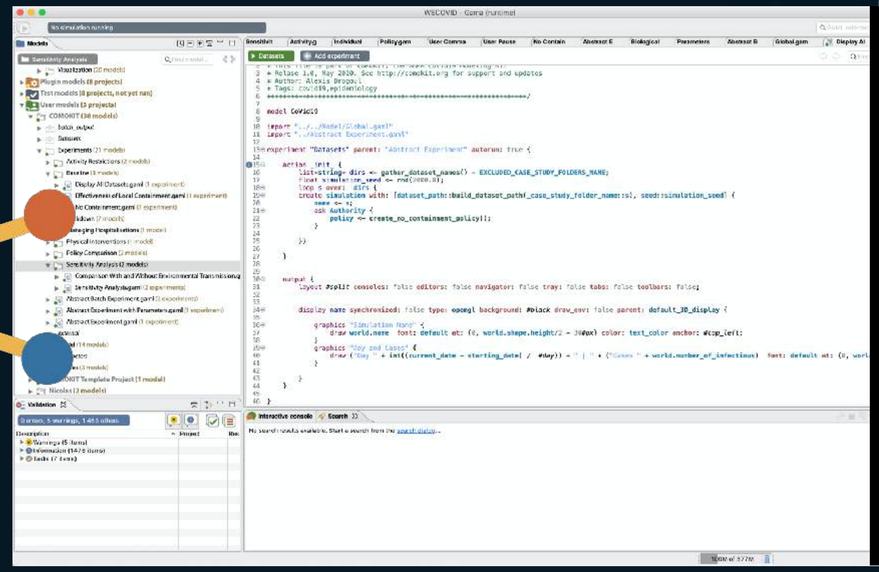
- As such, they represent an invaluable tool for building "SUSTAINABILITY MODELS", i.e. models of complex socio-environmental systems when designing land management policies and agricultural strategies

AN EXAMPLE IS COMOKIT (HTTP://COMOKIT.ORG), WHICH AIMED AT ASSESSING AND COMPARING INTERVENTIONS AGAINST COVID-19 AT THE LEVEL OF COMMUNES

- **Development and provision of a modelling platform to the rapid response team of the national steering committee**

  developed in March/May 2020 by IRD, Thuyloi University, Can Tho University, NIHE (Pasteur Institute), Hong Kong University, Oxford University (OUCRU), Toulouse 1 University, INRAE

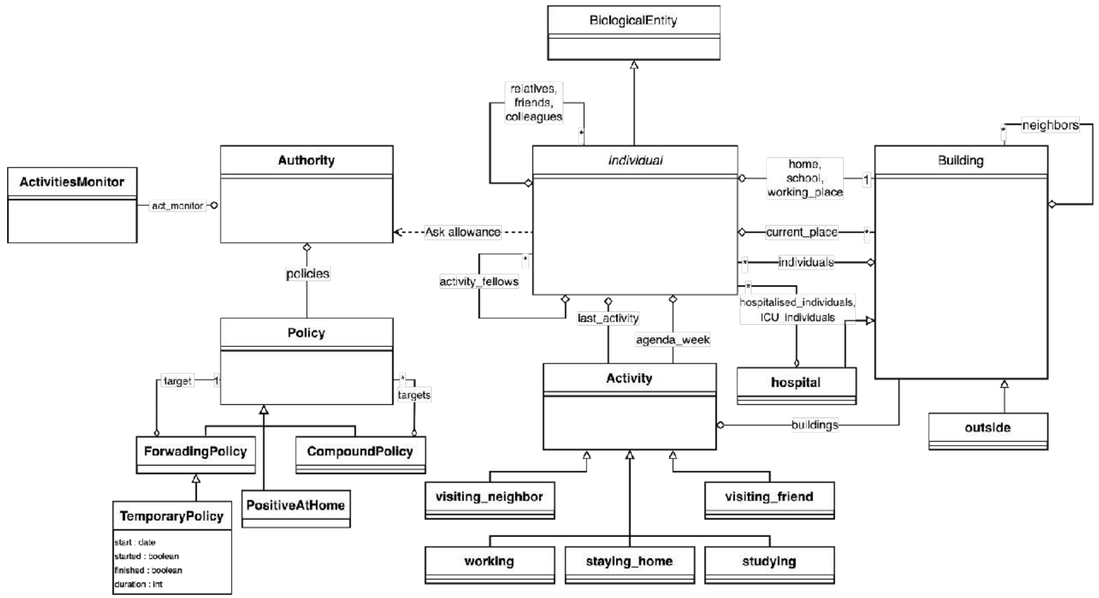


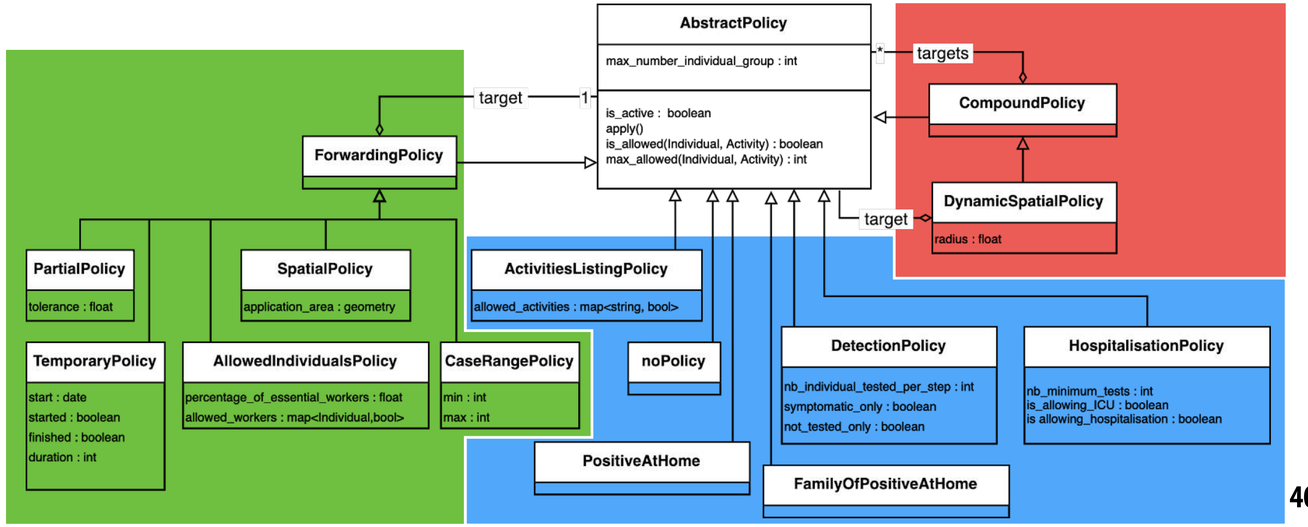


COMOKIT: SCALES AND MODELS

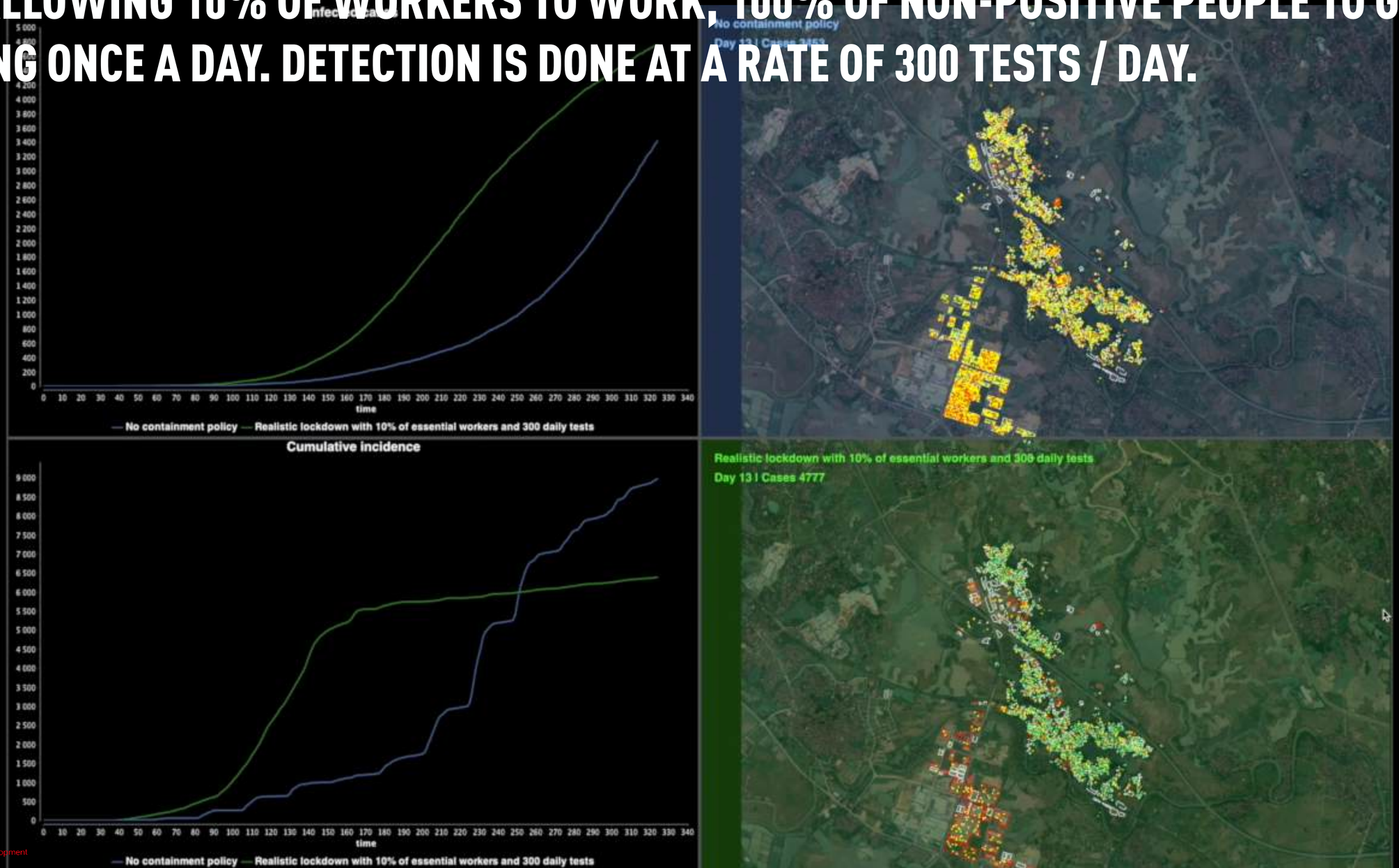
Gaudou, B., Huynh, N. Q., Philippon, D., Brugière, A., Chapuis, K., Taillandier, P., ... & Drogoul, A. (2020). Comokit: A modeling kit to understand, analyze, and compare the impacts of mitigation policies against the covid-19 epidemic at the scale of a city. Frontiers in public health, 8.

- **Spatial scale: commune (~10000 inhabitants, 3000 buildings), temporal scale: 1h.**
- **Main sub-models:**
  - **individual epidemic state evolution (SEIR)**
  - **disease transmission, (person-to-person and environmental transmission through the built environment)**
  - **people mobility based on agendas**
  - **policy design, providing authorities agents with strategies to manage other agents.**

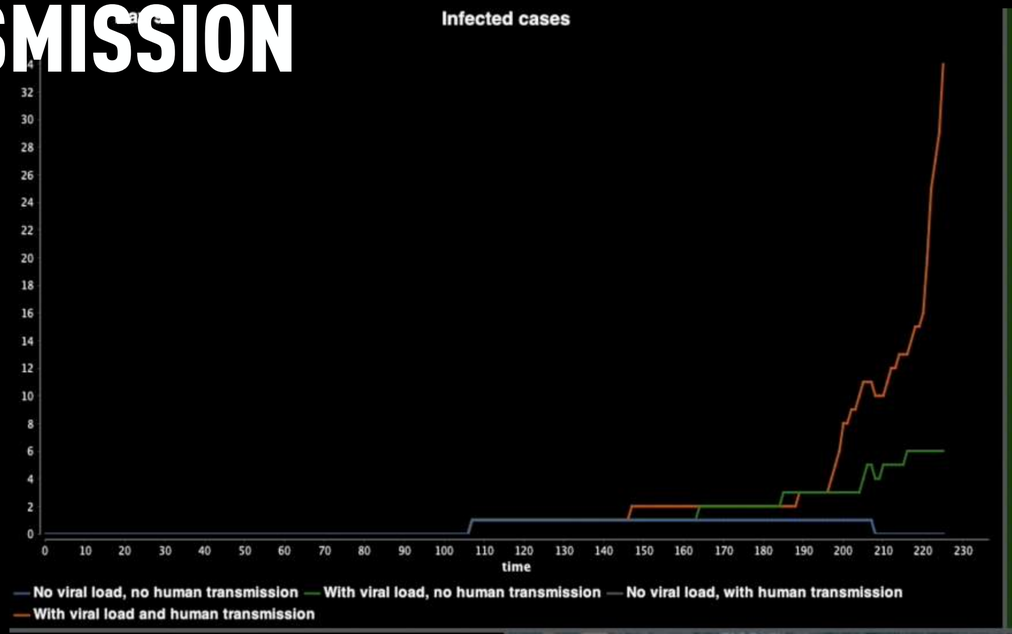


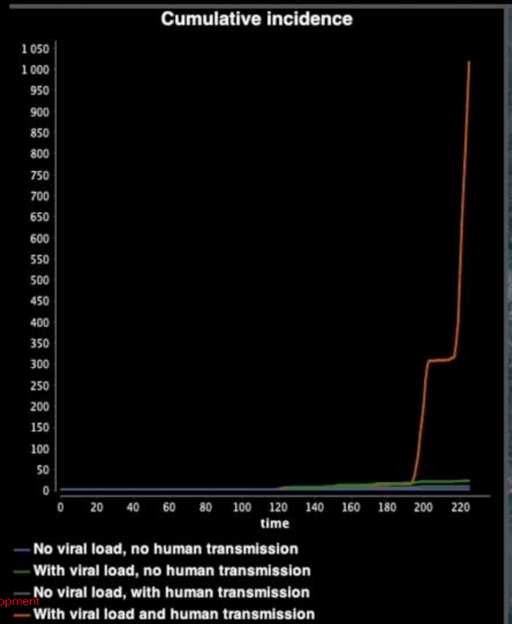


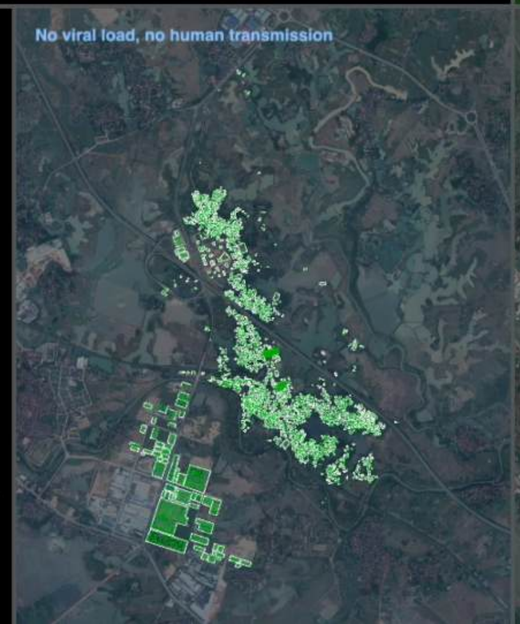
EXAMPLE OF A REALISTIC LOCKDOWN POLICY: CLOSING SCHOOLS, POSITIVE CASES AT HOME, ALLOWING 10% OF WORKERS TO WORK, 100% OF NON-POSITIVE PEOPLE TO GO SHOPPING ONCE A DAY. DETECTION IS DONE AT A RATE OF 300 TESTS / DAY.



MODELS CAN BE USED TO VERIFY HYPOTHESES: HERE, ENVIRONMENTAL TRANSMISSION

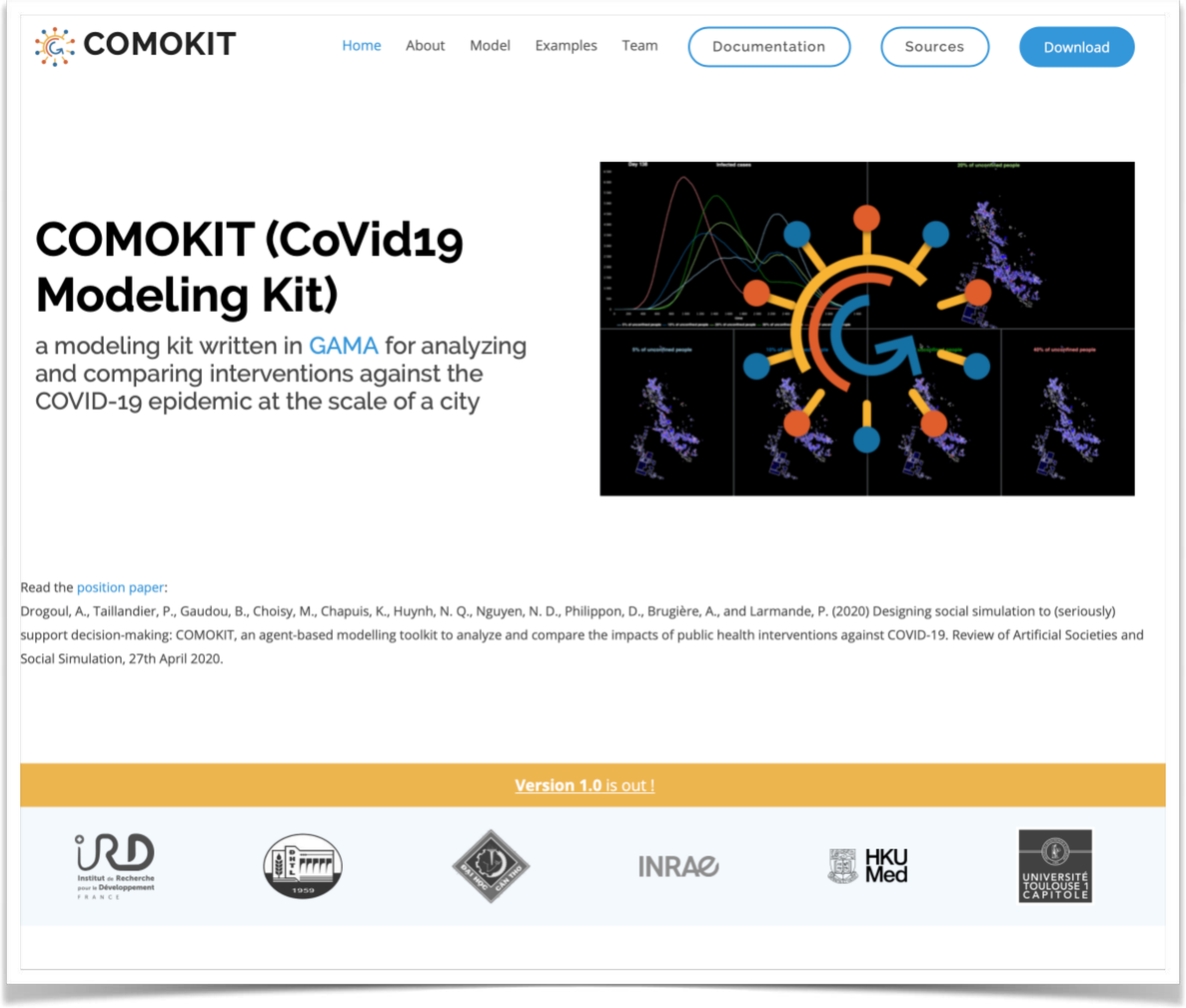






COMOKIT IS AVAILABLE AT HTTP://COMOKIT.ORG. IT CAN BE FORKED AND MODIFIED, OR DIRECTLY APPLIED TO NEW CASE STUDIES

- It is open to contributions and extensions, among which:
  - Upscaling techniques (population size, case study extent, hybridation…)
  - Addition of realistic urban fluxes (transportation, agendas…)
  - Addition of more detailed activities
  - Extension to other infectious diseases
  - Coupling with existing models (urban planning, …)



ANOTHER EXAMPLE: HOAN KIEM AIR

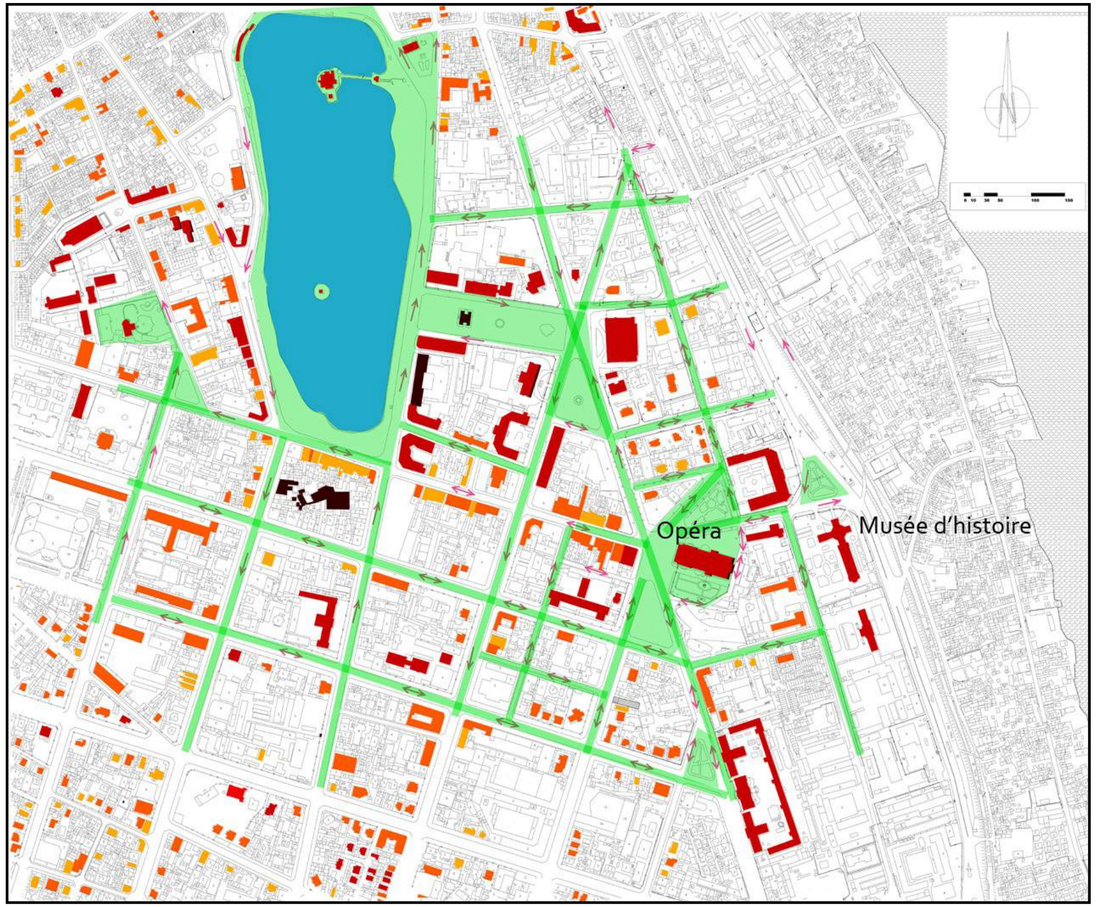
Duc, P. M., Chapuis, K., Drogoul, A., Gaudou, B., Grignard, A., Marilleau, N., & Tri, N. H. (2020, October). HoanKiemAir: simulating impacts of urban management practices on traffic and air pollution using a tangible agent-based model. In 2020 RIVF International Conference on Computing and Communication Technologies (RIVF) (pp. 1-7). IEEE.

HANOI HAS BEEN FACING TWO WORRYING PHENOMENA IN RECENT YEARS: ONE OF THE HIGHEST AIR POLLUTION INDEX IN THE WORLD AND HUGE TRAFFIC JAMS EVERY DAY.

Hoan Kiem People's Committee has experimented Low Emission Zones, transforming streets around Hoan Kiem Lake every weekend into a pedestrian zone. The operation is a great success.

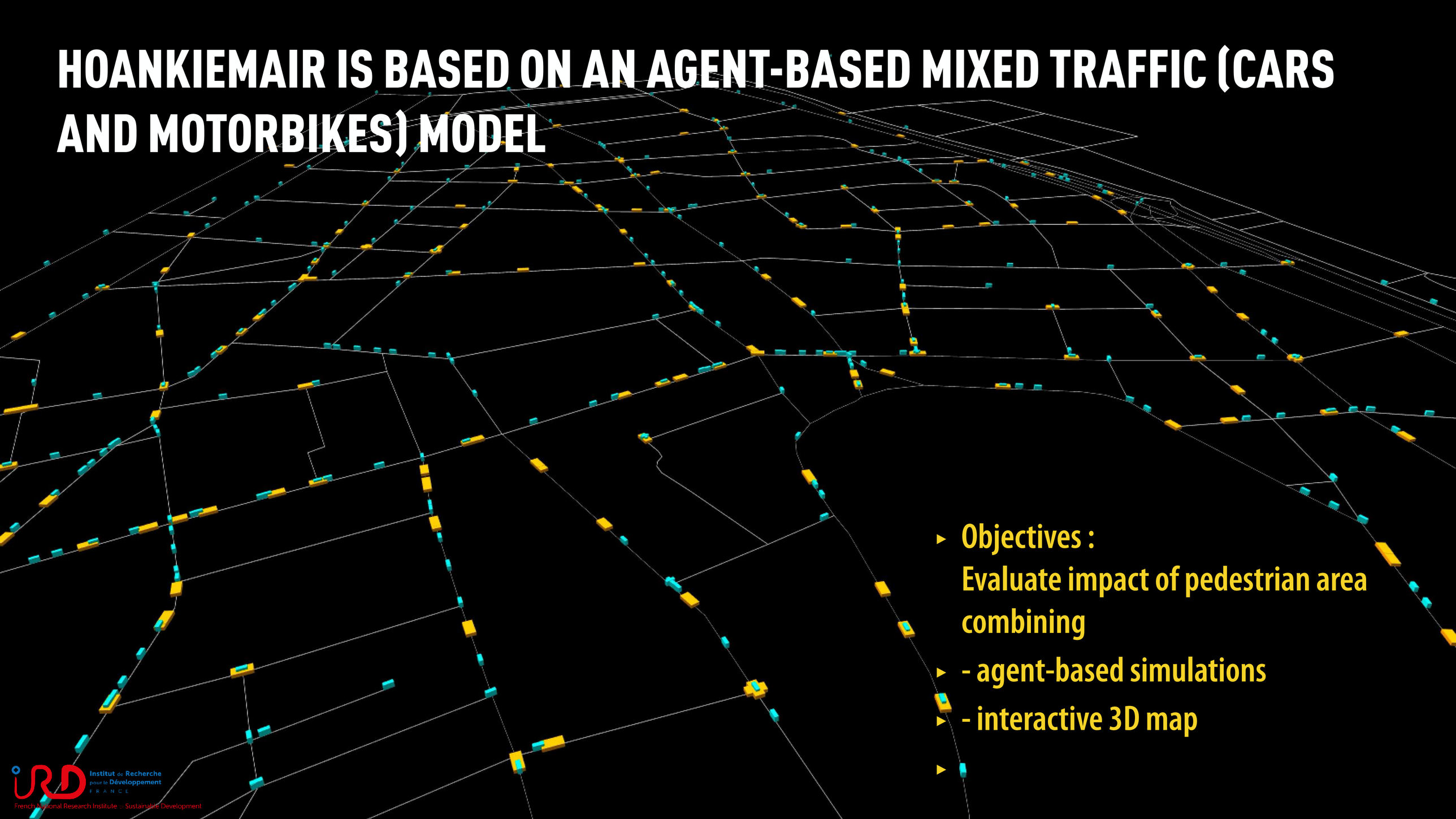
HOWEVER, THERE WAS A NEED TO ASSESS THE IMPACT OF THESE LEZ AND THEIR POSSIBLE EXTENSIONS, IN TERMS OF TRAFFIC, CONGESTION AND EMISSIONS OF AIR POLLUTANTS.

Current LEZ



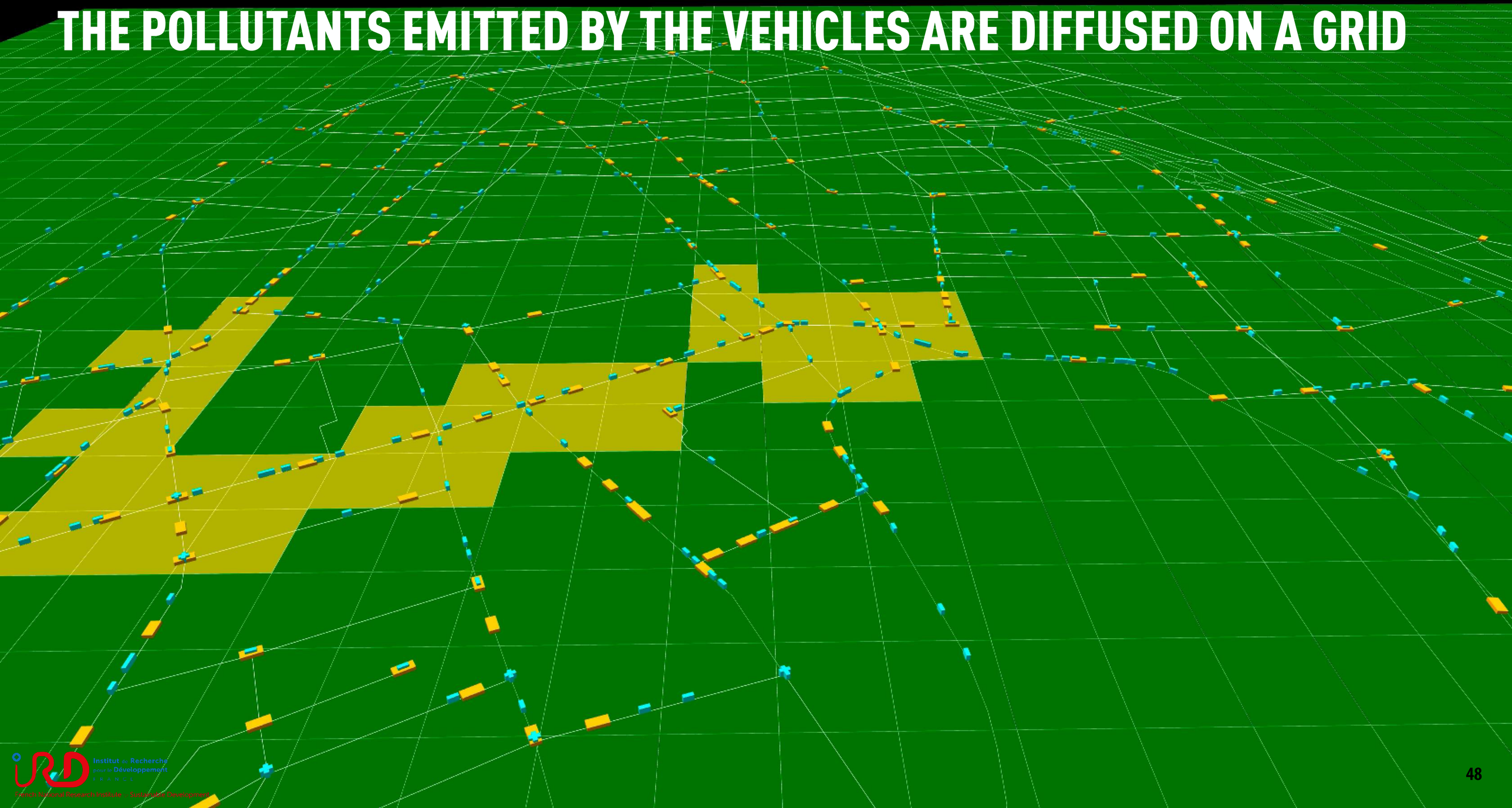
Possible extension

HOANKIEMAIR IS BASED ON AN AGENT-BASED MIXED TRAFFIC (CARS AND MOTORBIKES) MODEL

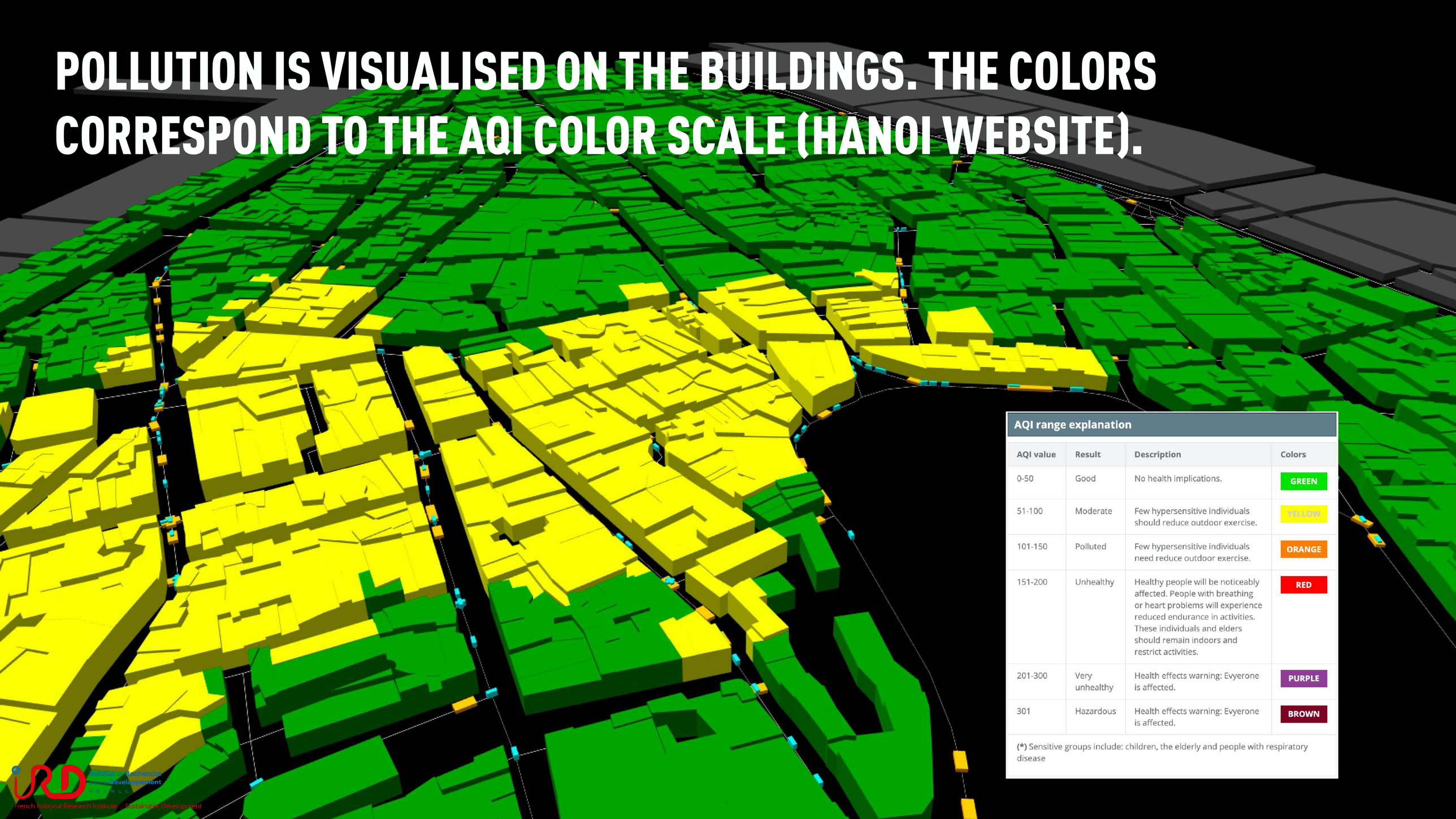


- Objectives :
  Evaluate impact of pedestrian area combining
- - agent-based simulations
- - interactive 3D map
-

THE POLLUTANTS EMITTED BY THE VEHICLES ARE DIFFUSED ON A GRID



POLLUTION IS VISUALISED ON THE BUILDINGS. THE COLORS CORRESPOND TO THE AQI COLOR SCALE (HANOI WEBSITE).



AQI range explanation

AQI value	Result	Description	Colors
0-50	Good	No health implications.	GREEN
51-100	Moderate	Few hypersensitive individuals should reduce outdoor exercise.	YELLOW
101-150	Polluted	Few hypersensitive individuals need reduce outdoor exercise.	ORANGE
151-200	Unhealthy	Healthy people will be noticeably affected. People with breathing or heart problems will experience reduced endurance in activities. These individuals and elders should remain indoors and restrict activities.	RED
201-300	Very unhealthy	Health effects warning: Evyerone is affected.	PURPLE
301	Hazardous	Health effects warning: Evyerone is affected.	BROWN

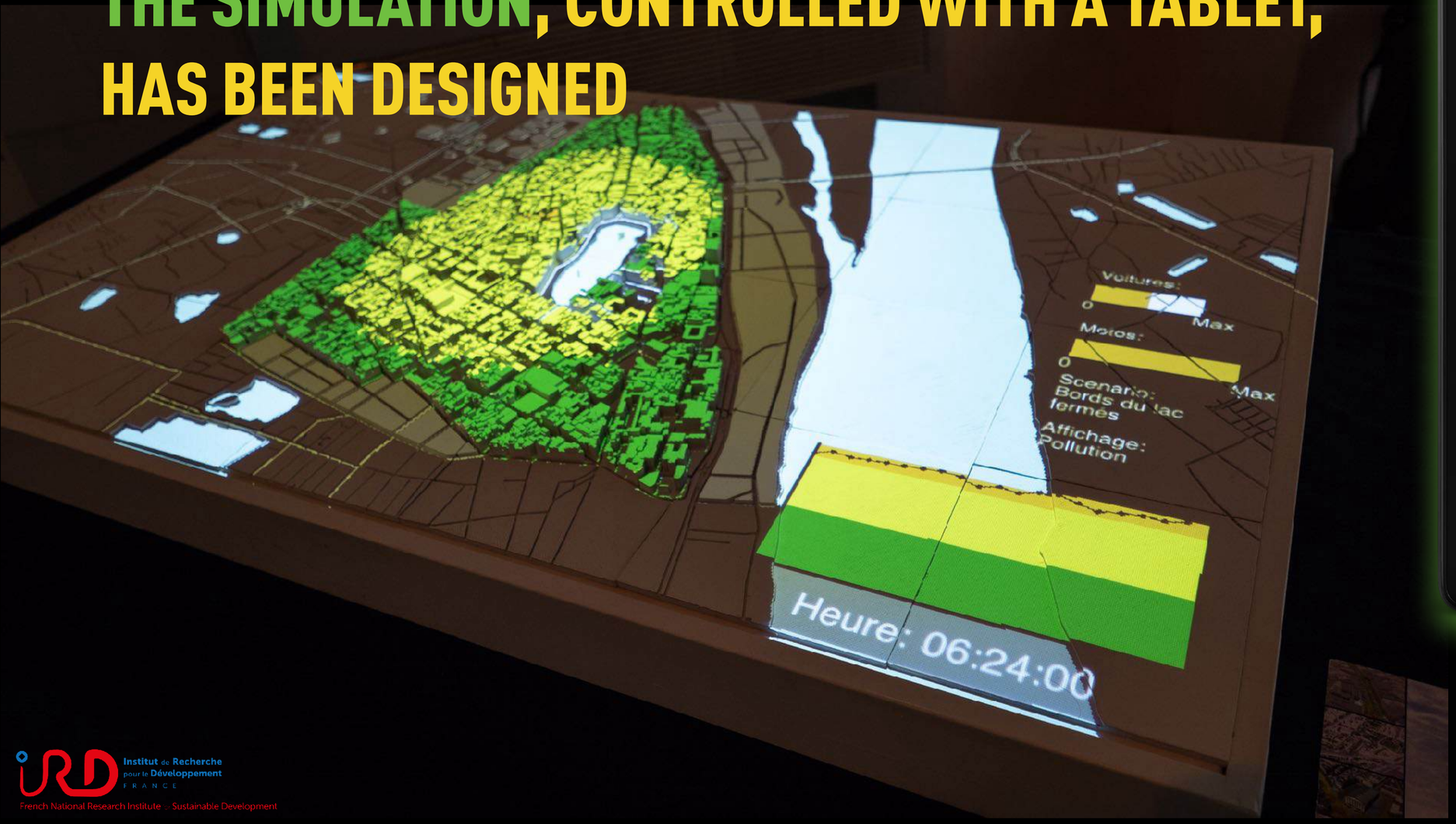
(*) Sensitive groups include: children, the elderly and people with respiratory disease

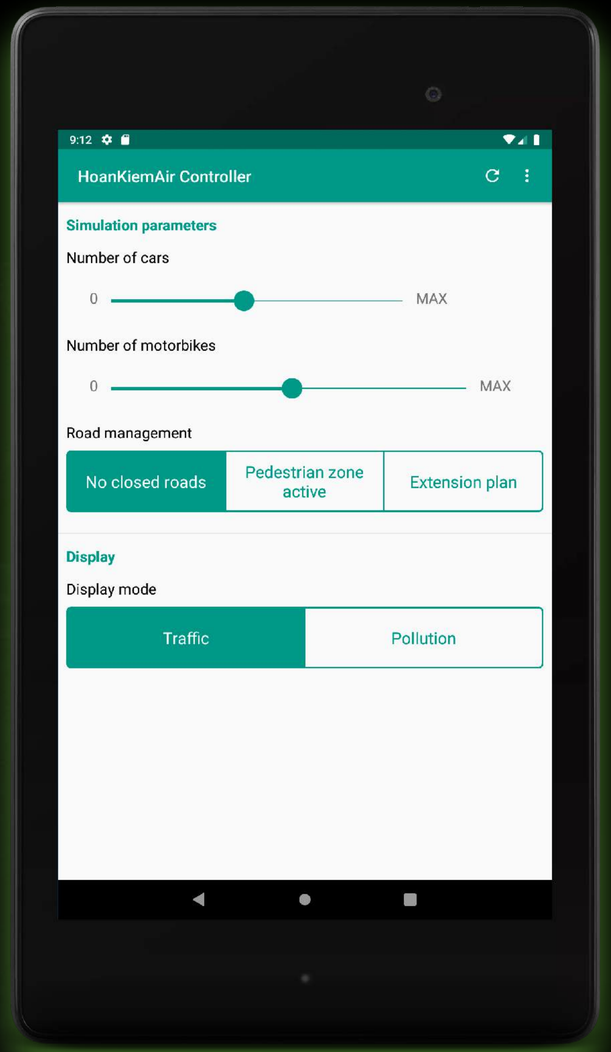
THIS ALLOWS, FOR INSTANCE, TO TEST THE IMPACTS OF URBAN CHOICES ON THE RESULTING TRAFFIC AND THE AIR POLLUTION

EXTENDED ZONE

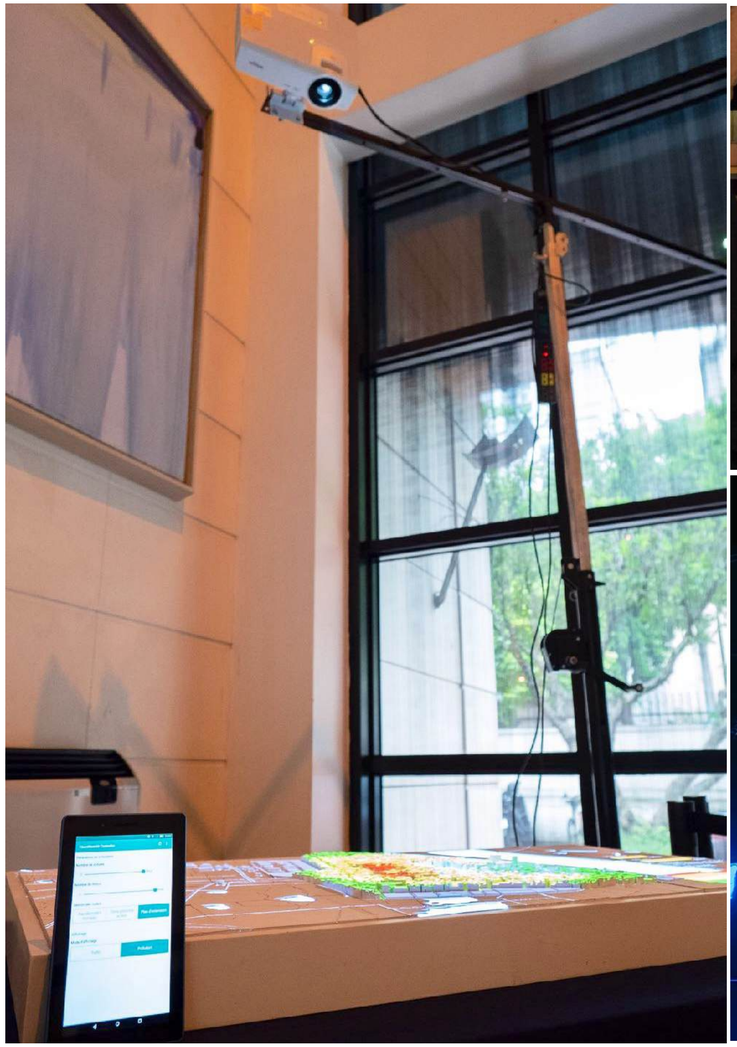
CURRENT ZONE

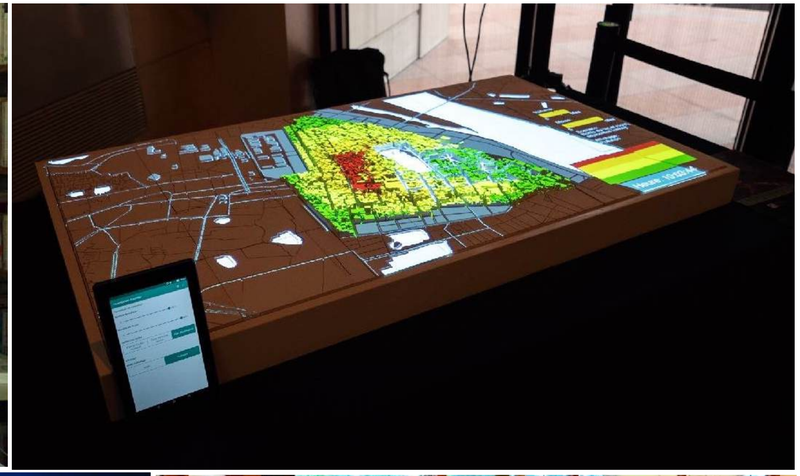
IN ORDER TO ALLOW CITIZENS TO EXPERIMENT OPTIONS, A 3D PHYSICAL REPRESENTATION OF THE SIMULATION, CONTROLLED WITH A TABLET, HAS BEEN DESIGNED



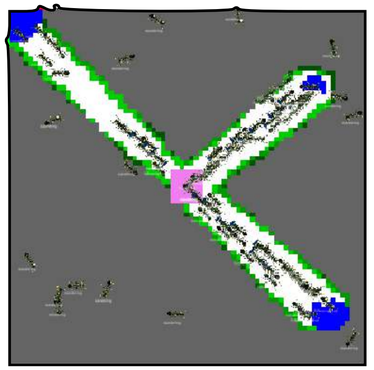
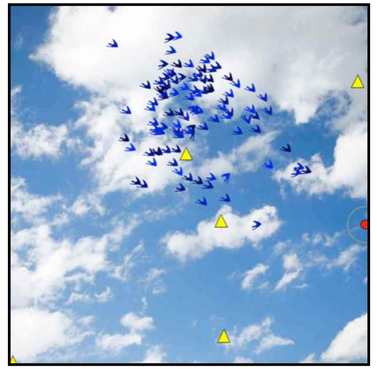


THE INSTALLATION HAS BEEN DEMONSTRATED TO DIFFERENT AUDIENCES





Agent, Multi-Agent Systems and Agent-based Modelling and Simulation

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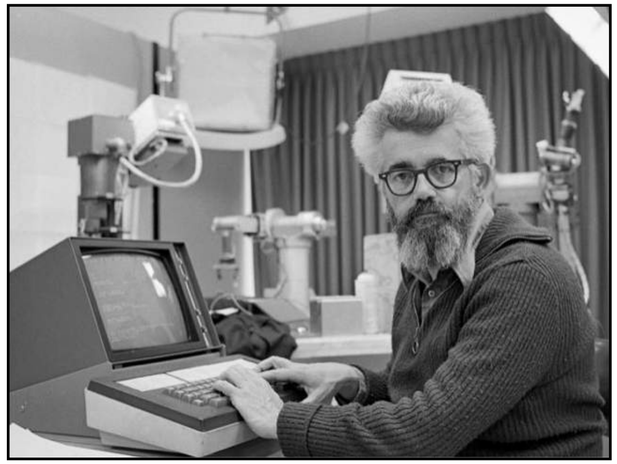
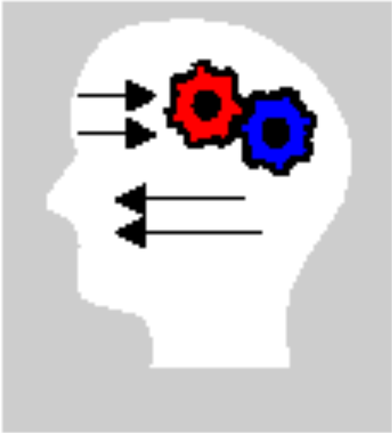
In 1956, John MacCarthy organized the first workshop about Artificial Intelligence.

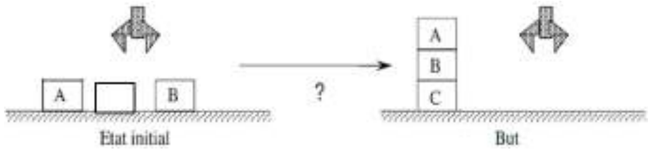
- In ”Classical AI”, the basic model is the **individual intelligence**. E.g.:
  - Planner (STRIPS 1971)
  - Expert systems.





The expert

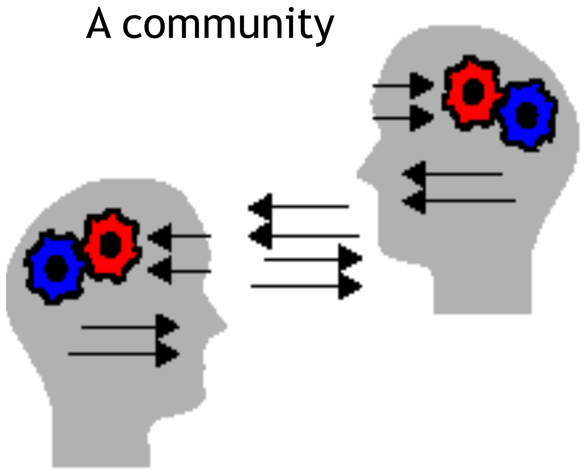
STRIPS planner




```
(:action stack
   :parameters (?x – block ?y - block)
   :precondition (and (holding ?x) (clear ?y))
   :effects (and (not (holding ?x)) (not (clear ?y))
                 (on ?x ?y) (clear ?x) (handempty))
```

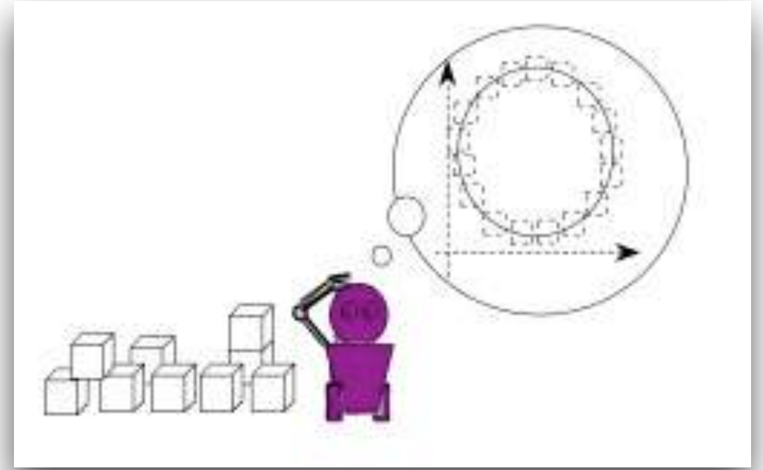
In 80's, Distributed AI and Multi-Agent Systems (DAI/MAS) (among others) appear in opposition to Classical AI.

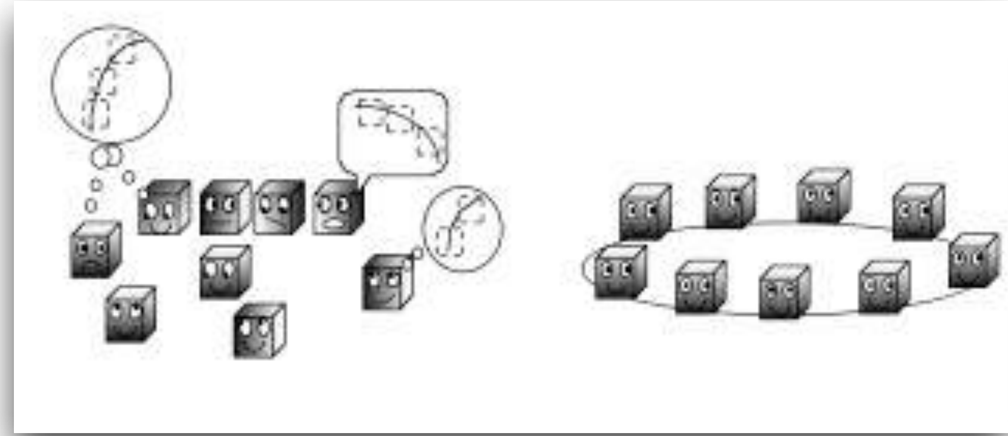
- Instead of considering only cognitive faculties of an individual, **DAI/MAS** postulates that intelligence "**emerges**" from the interactions between agents and between agents and environment.



- Other approaches:
  - Artificial Life (1984): adaptation vs intelligence
  - Connectionism(1987): numerical vs symbolical (which gave birth to Generative AI)

AI vs DAI/MAS on a problem:
How to draw a circle with boxes ?

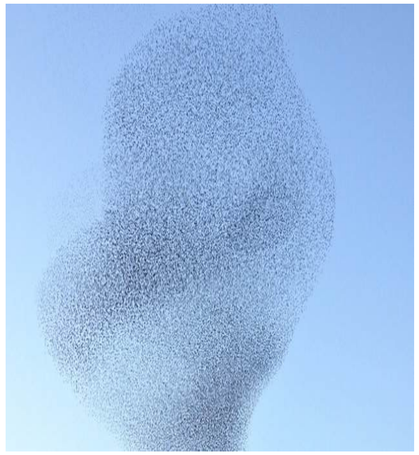


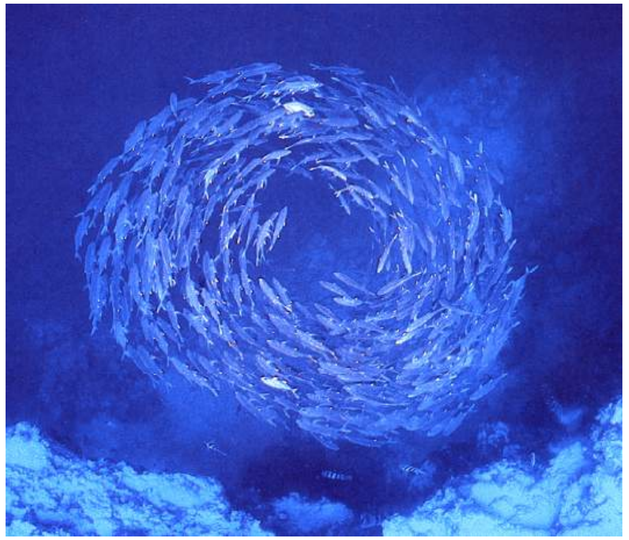


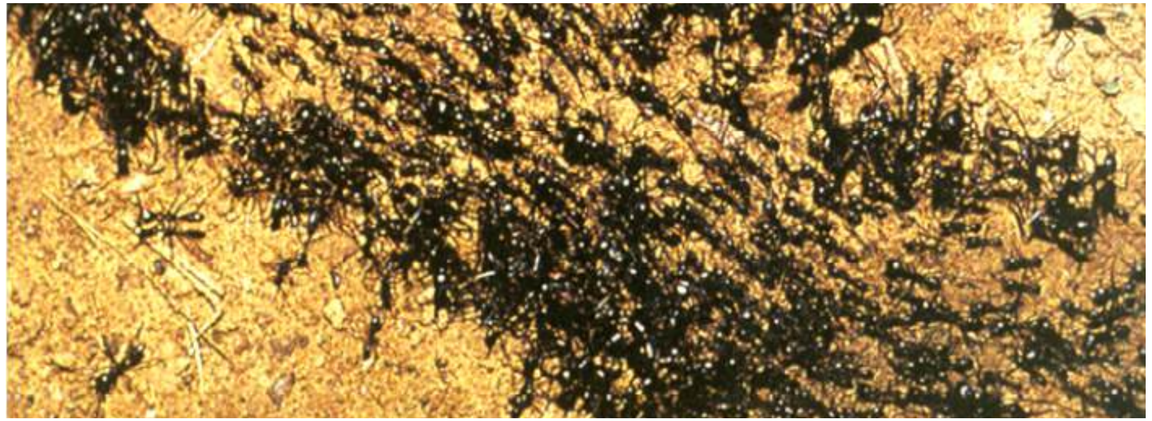
Example of M.Huhns (96)

Multi-Agent Systems are interested in complex systems where artificial and/or natural entities interact to produce collective behaviors.

- MAS is interested in complex systems where artificial and/or natural entities interact to produce collective behaviours.

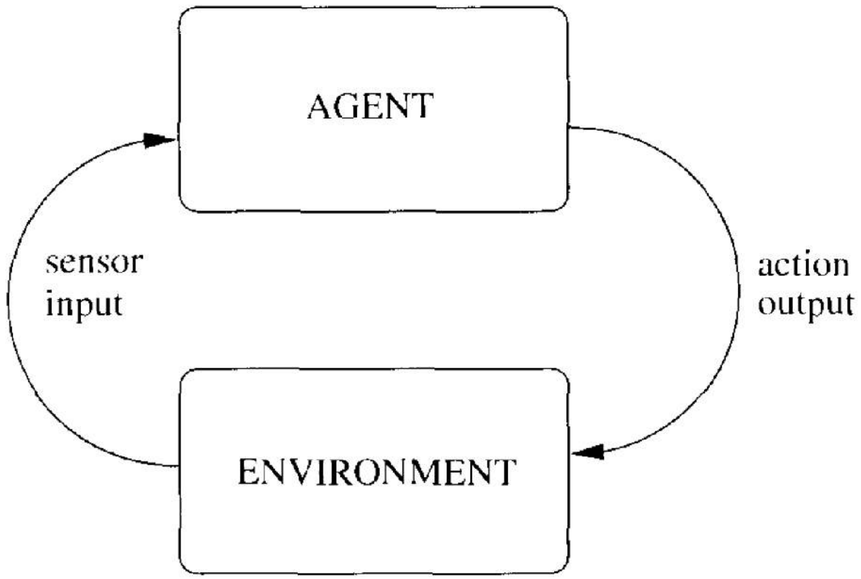






What is an agent?

- An agent is a computer system that is situated in some **environment**, and that is capable of **<u>autonomous</u> action** in this environment in order to meet its **design objectives**. (Wooldridge, 2008)



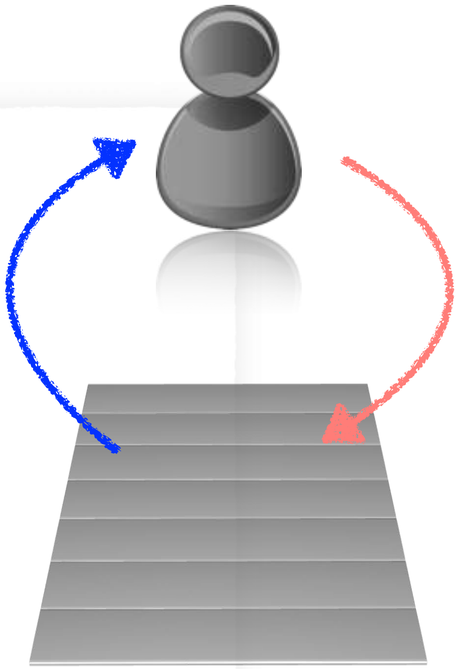


Figure 2.1 An agent in its environment. The agent takes sensory input from the environment, and produces as output actions that affect it. The interaction is usually an ongoing, non-terminating one.

What is an agent?

(Ferber, 95) names **agent** a **physical or virtual entity** which:

a. can **act** in its **environment**,

b. can **communicate** with other agents

c. has its own set of **individual objectives**

d. has its own **ressources**

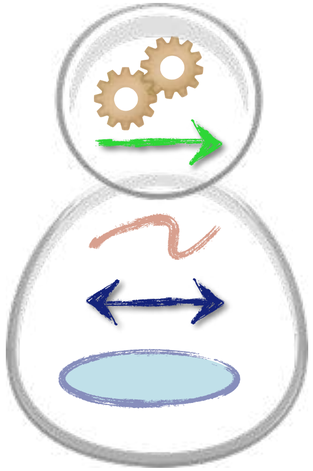
e. can **perceive** (**partially**) its environment

f. has a partial **representation** of its environment (or even no representation)

g. has **skills** and can **offer services**

h. can (eventually) reproduce

i. has a behavior tending to **satisfy its own objectives**, **taking into account** its ressources and skills, its perception, representations and communication it gets.



Agent

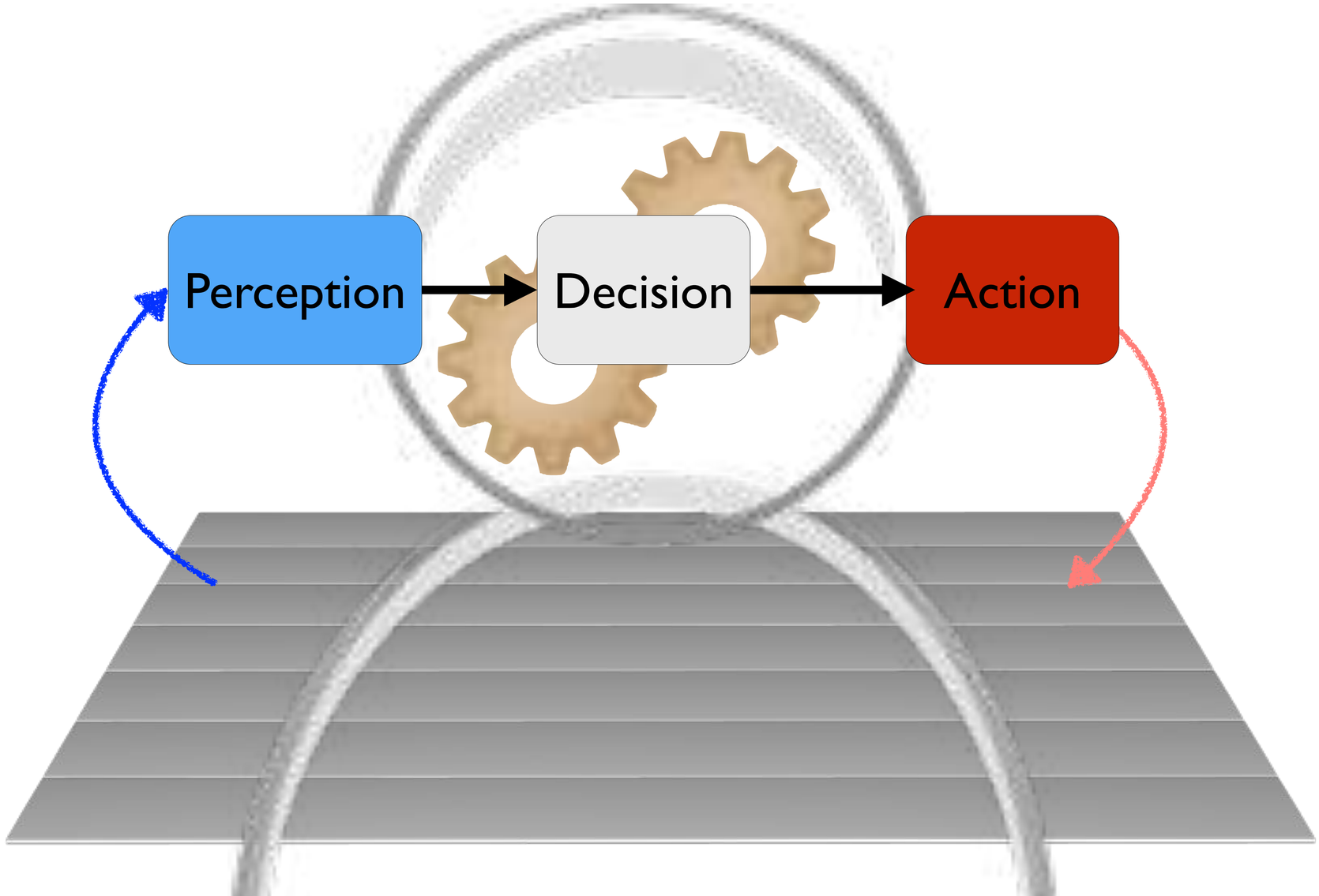
Decision-making
Behavior
Communication

Actions

Interactions

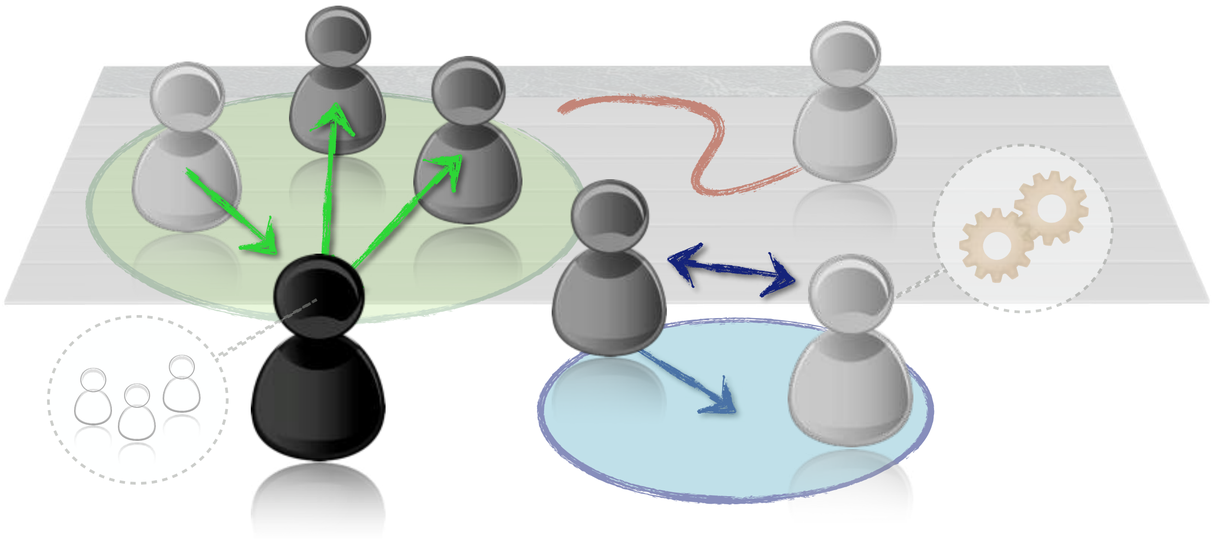
Perception

The basic agent life-cycle has 3 steps.
Agents can be <u>reactive</u> or <u>cognitive</u> depending on the decision complexity.



What is a Multi-Agent System ?

- A Multi-Agent System is a **set of agents acting and communicating in an environment.**

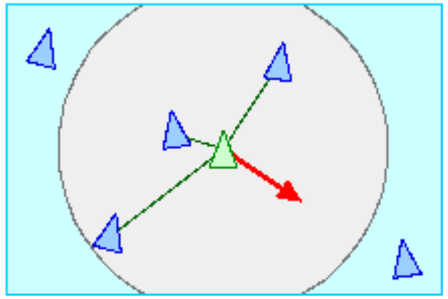


- In addition some authors add:
  Passive objects and **an organization or coordination mode.**

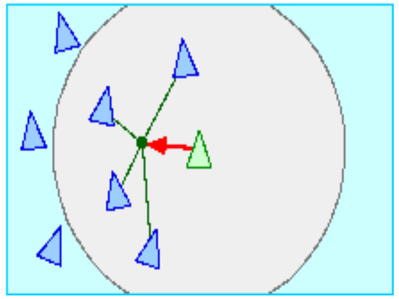
Example of reactive agents: Reynolds' Boids to model swarms/flocks (Craig Reynolds (1987)

Boids: Interactions by field of forces

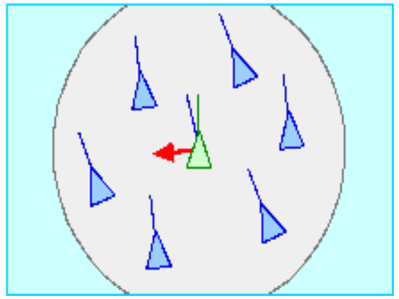
- **Separation**: the force is calculated so as to push back the Boid from its close neighbours.



- The purpose of **cohesion** is to bring the Boid closer to the gravity center of the group.



- The force of **alignment** is calculated as being an average between speeds of the neighbours.

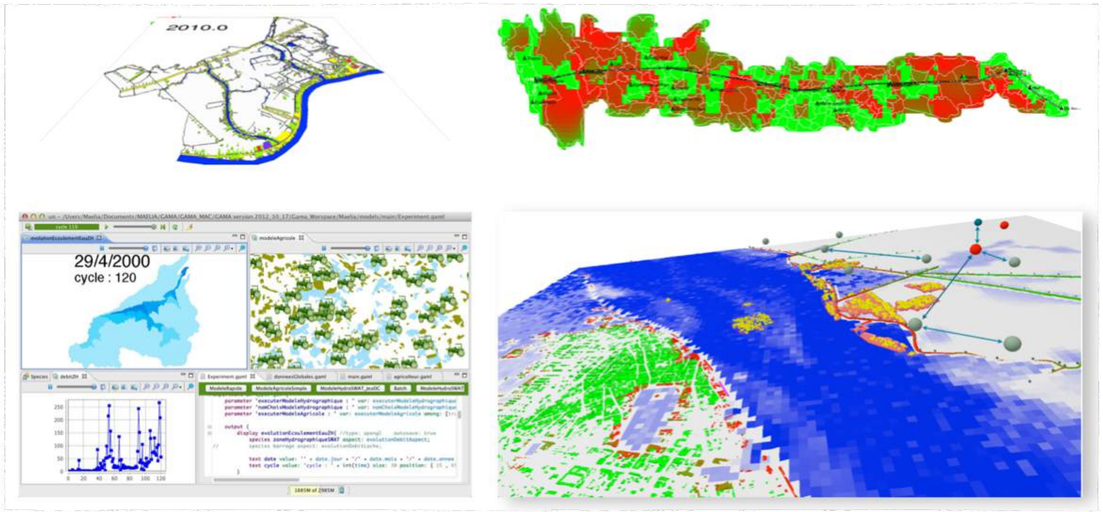


Application: crowd animation (movie !)

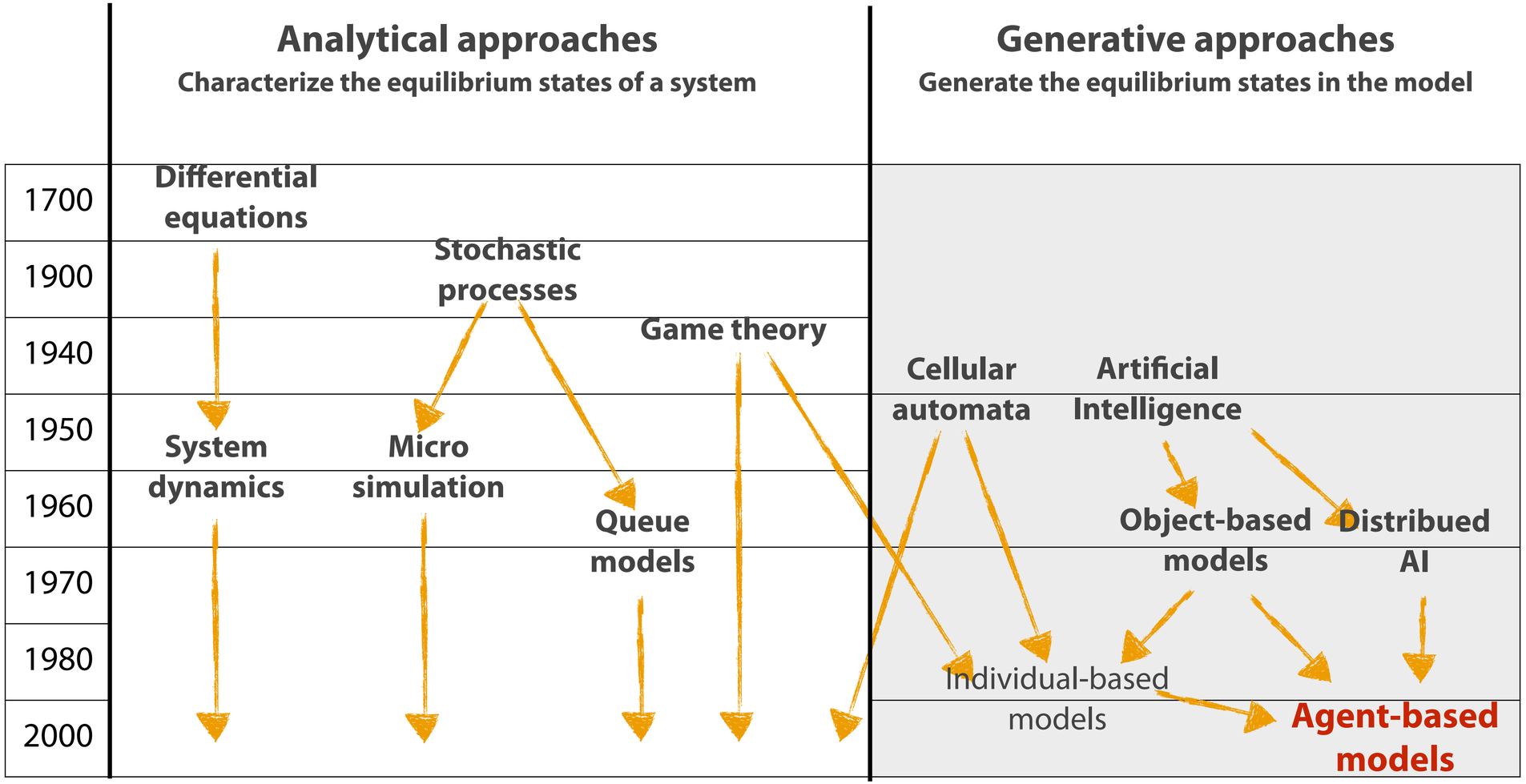
- Objective:
  short-term individual
  and collective realism

http://www.massivesoftware.com/index.html

Agent-Based Modelling and Simulation



REMINDER: DYNAMIC MODELS AND SIMULATIONS HAVE A LONG HISTORY



(adapted from Troitzsch & Gilbert 2001)

Illustration: road traffic

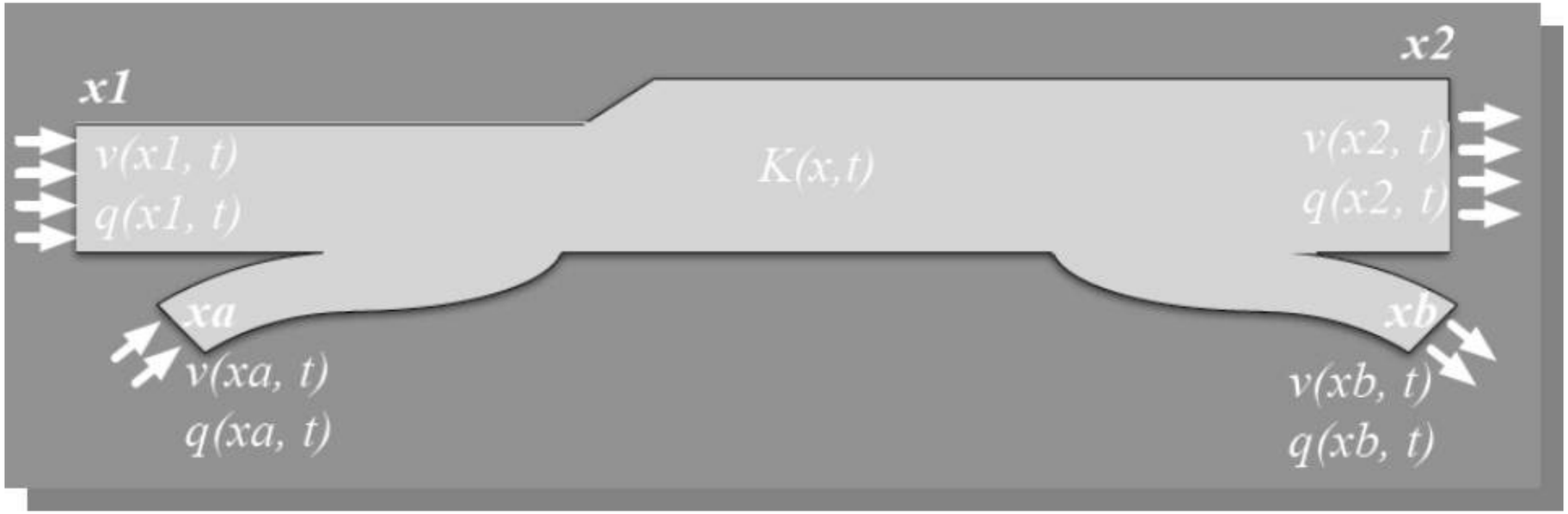
- Traffic jams, delays
  - How to understand them?
  - How to anticipate them?
  - How to control them?
- Difficulties
  - « Experiments » are difficult
  - Reproduction is impossible
- Simulation is the only way

Classical macroscopic models

$$\begin{cases} Q(\Delta x, \Delta t) = K(\Delta x, t) V(\Delta x, \Delta t) \\ V(\Delta x, \Delta t) = V_e\left(K(\Delta x, t)\right) \\ \dfrac{\partial Q(\Delta x, \Delta t)}{\partial x} + \dfrac{\partial K(\Delta x, t)}{\partial t} = 0 \end{cases}$$

LWR macroscopic model

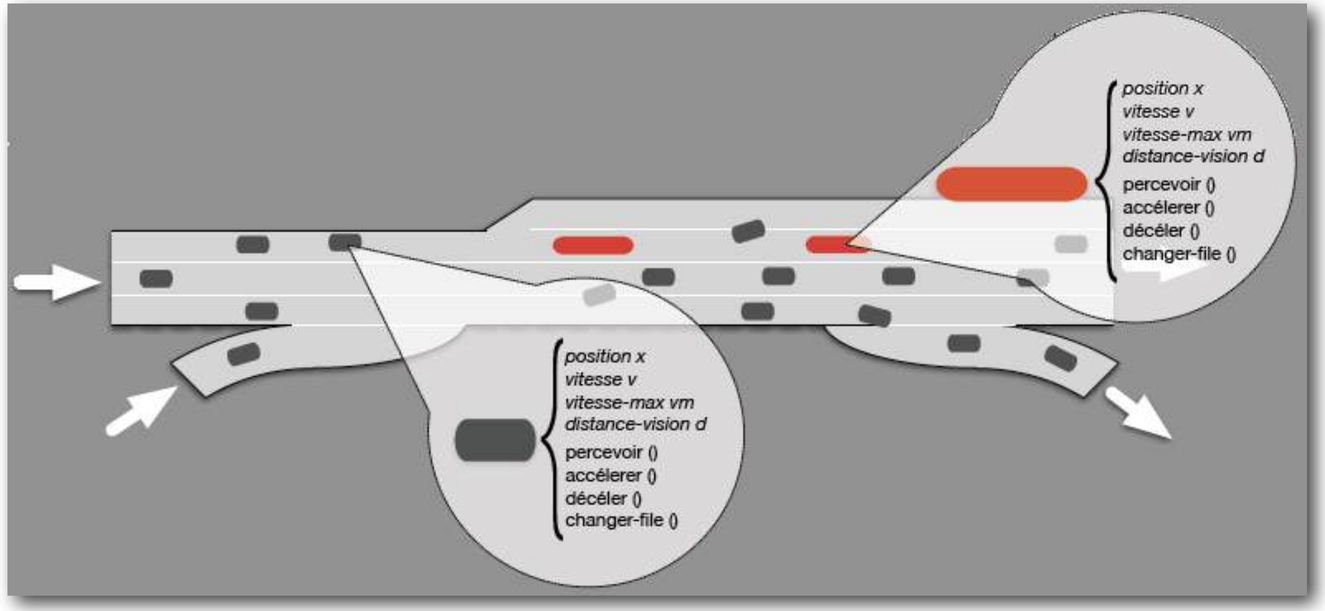
- based on a (physical) analogy between the flow of traffic and the flow of a fluid in a pipe.



- Flow of vehicles characterised by macroscopic attributes, behaviours averaged in global equations.

Agent-based models

- Attributes and behaviours (ou equations, rules …) are “attached” to individuals.



- Allow for heterogeneous vehicles and behaviours and stochasticity.
- Analytical results impossible to obtain: simulation is the only possibility.

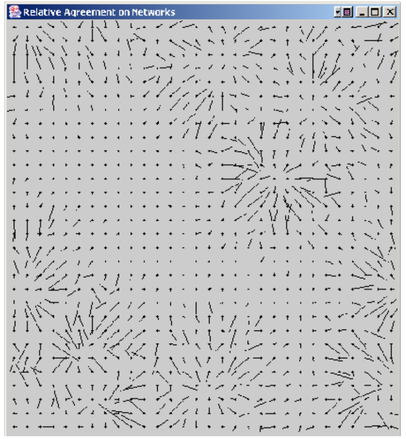
Some remarks concerning Agent-Based Modelling

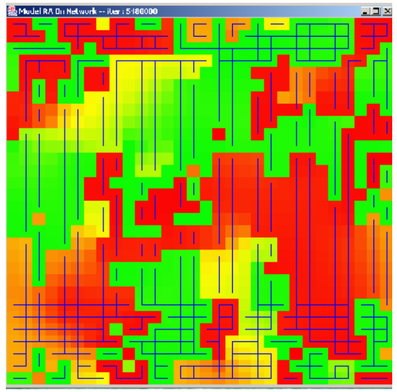
- **Advantages**
  - Hypotheses expressed at the individual level
  - Modelling the dynamics
  - Models are experimental objects (simulation)

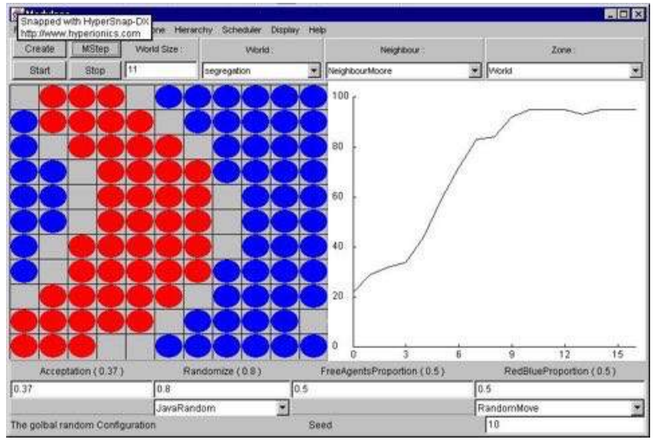
- **Drawbacks**
  - Reproduction of the complexity of the real system (micro/macro link)
  - Difficulty to understand how the results are produced
  - Validation

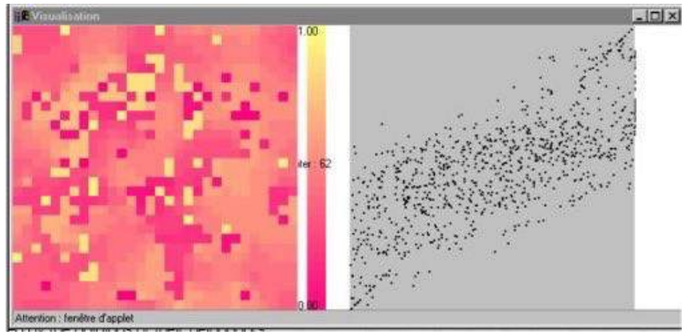
Use of modelling

- **To understand**
  - Test/elaboration of hypotheses, prospective simulation
  - Formalization/verification of sociological theories



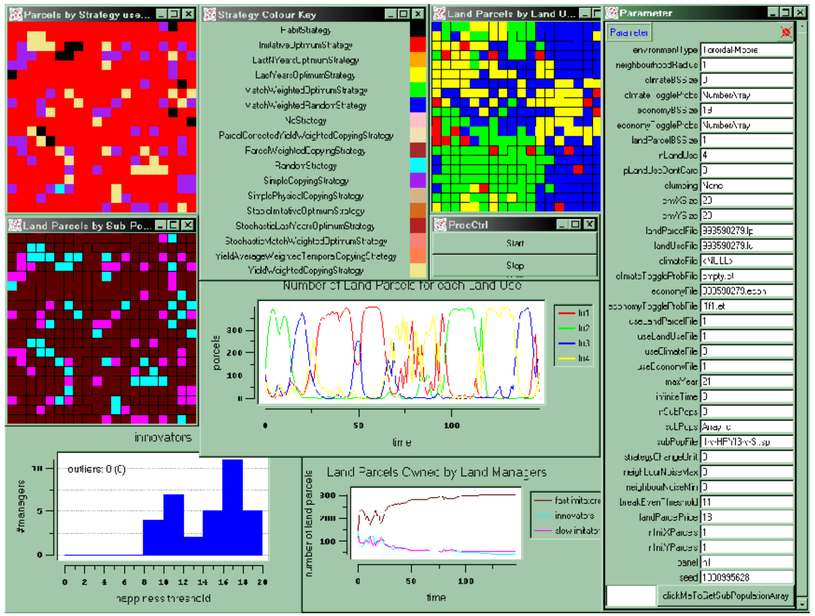






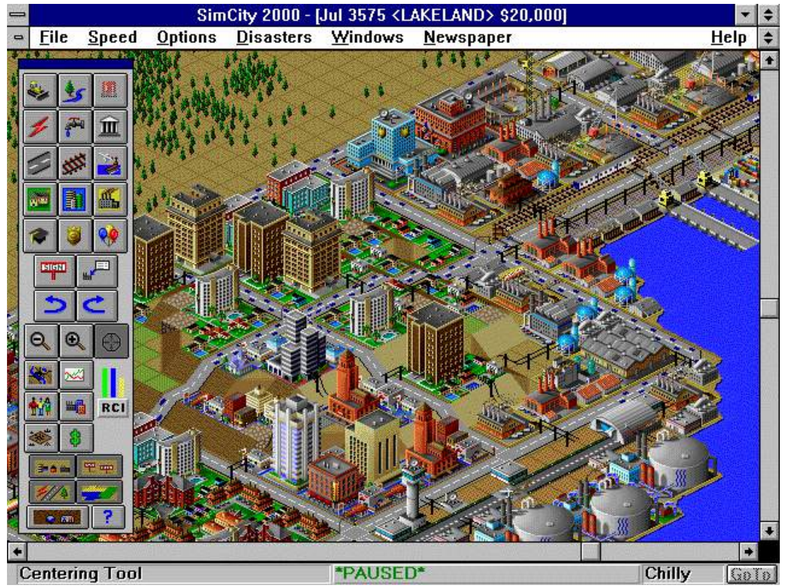
Use of modelling

- To understand
- **To decide**
  - Predictive simulation for decision-making
  - Test of scenarios through simulation
  - Artefacts for helping negotiation and/or coordinated management



Use of modelling

- To understand
- To decide
- **Interactive simulation**
  - « Serious » Gaming (SimCity)
  - Training, teaching



Rebuild phenomena to understand them : learning !

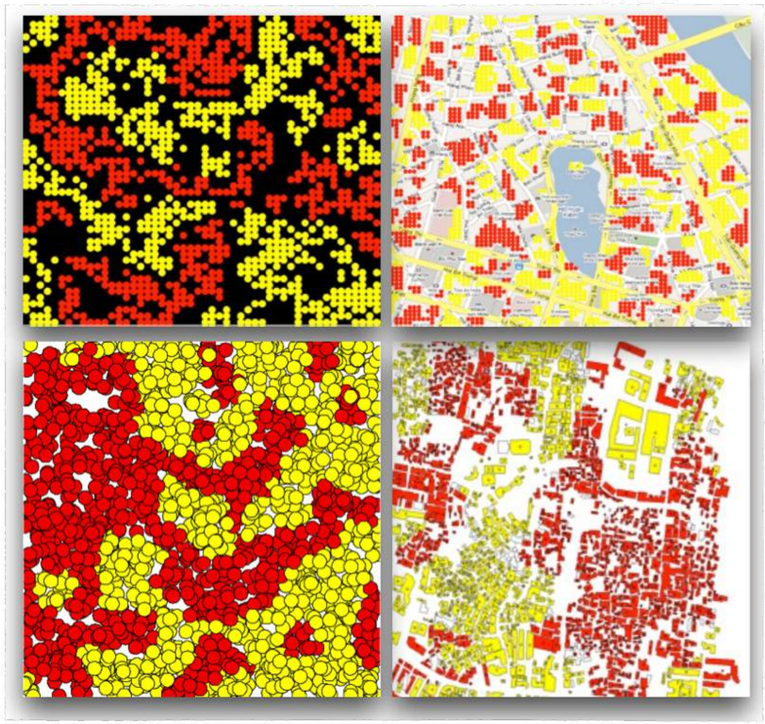
- Use Modelling not Models !!!

- **Rebuilding phenomena enable to better understand them**
  - Pappert (Logo), Resnick (NetLogo)

- What could be the individual behaviours producing a given collective phenomenon?
  - Experimental approach by trial and errors
  - ex: Regroupment of ants dead bodies outside of the anthill

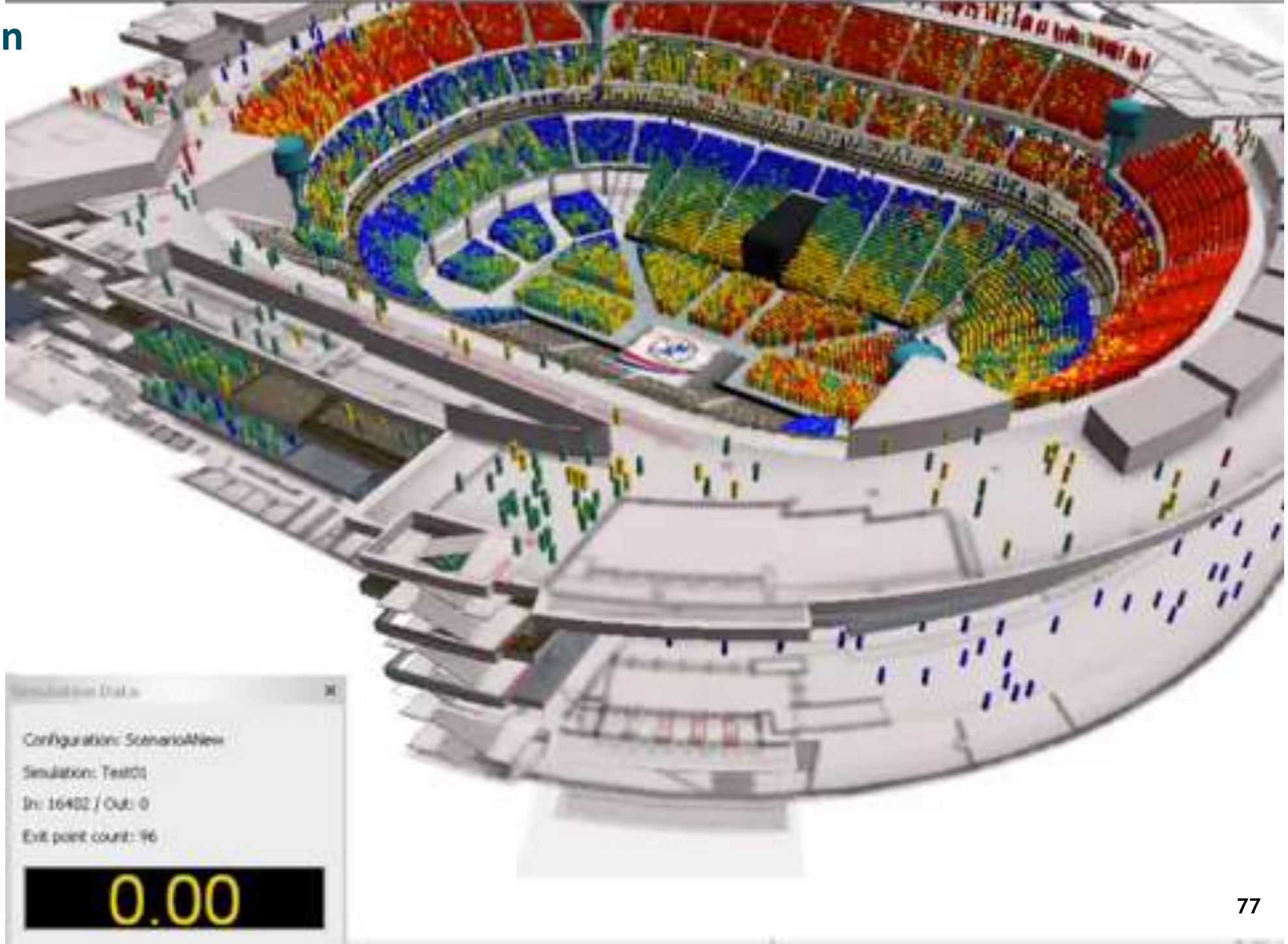
Agent-Based Modelling and Simulation

Some examples



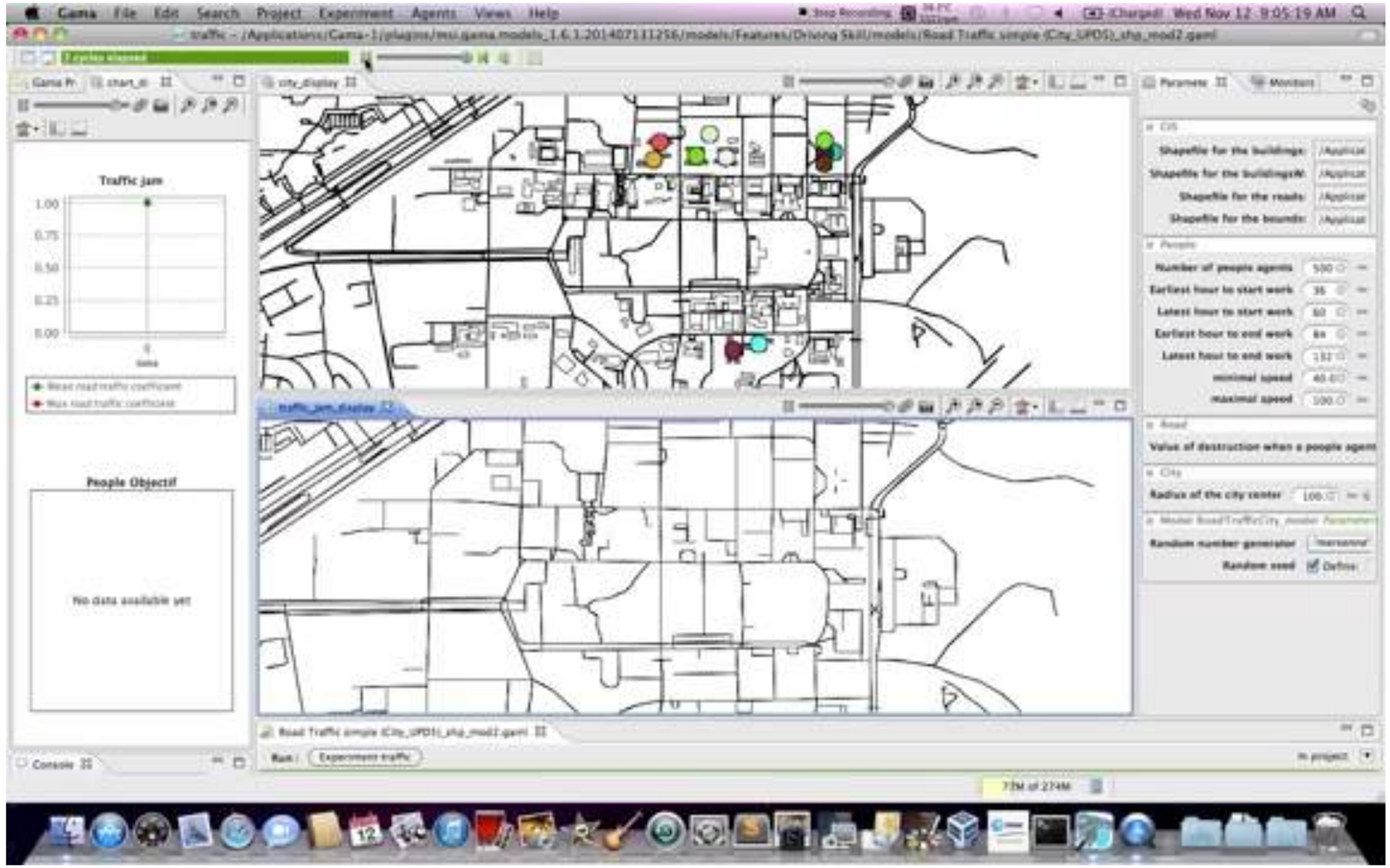
Crowd dynamics

Evacuation

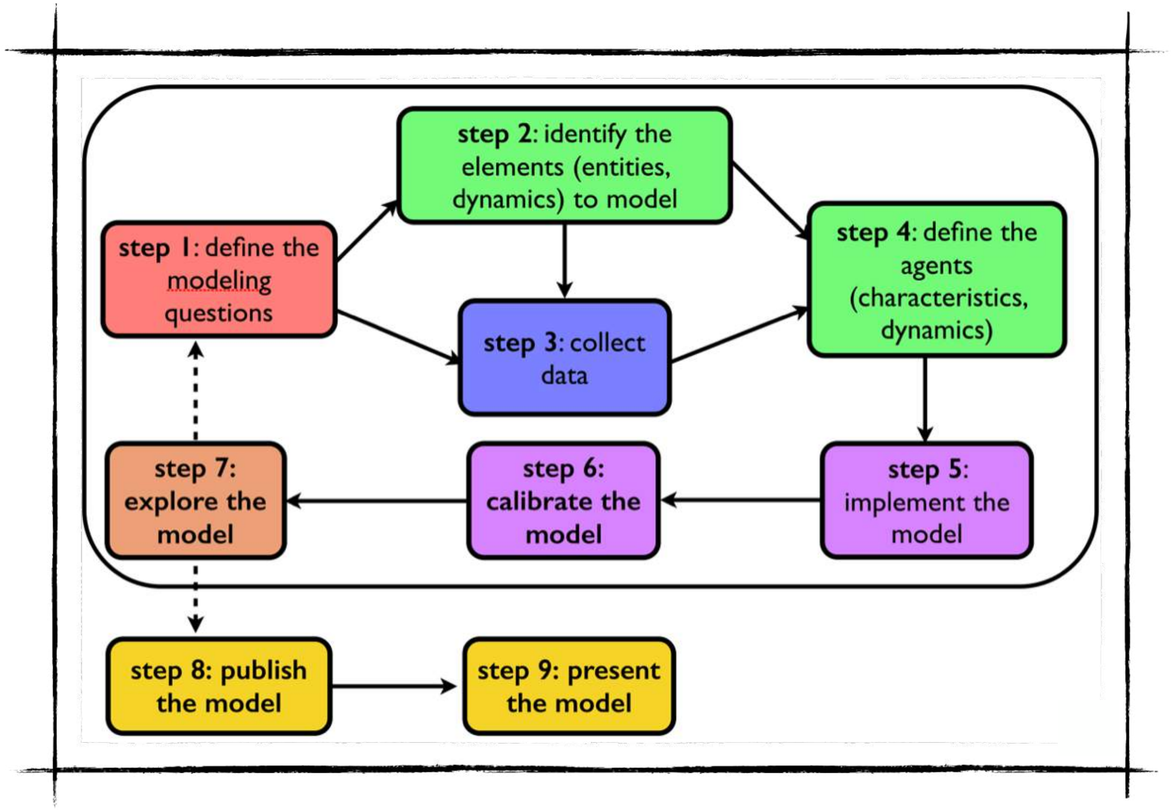

Configuration: ScenarioAllview
Simulation: Test01
In: 16402 / Out: 0
Exit point count: 96
0.00

Epidemics

Traffic



Modelling is a multi-step cycle.



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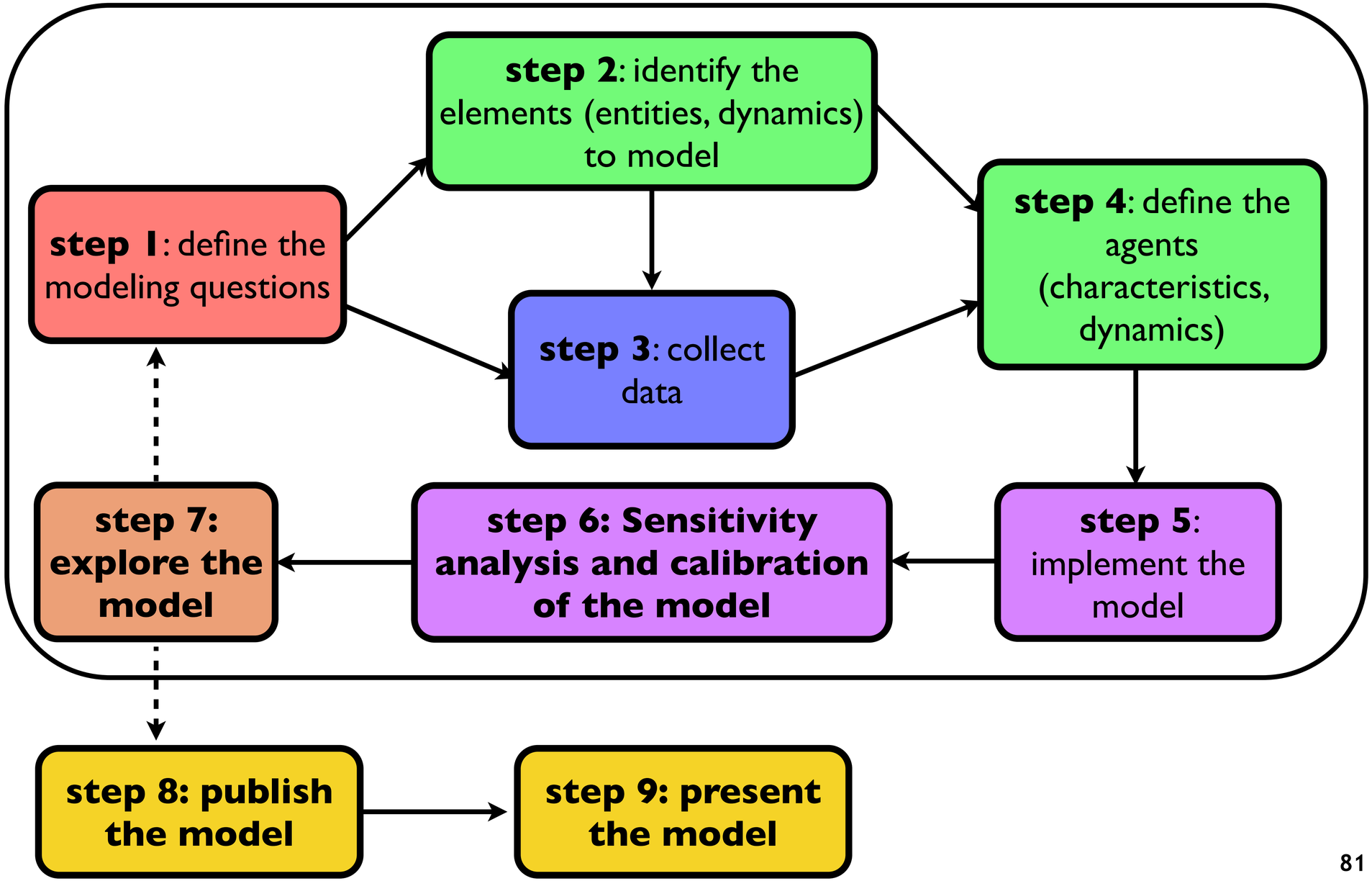
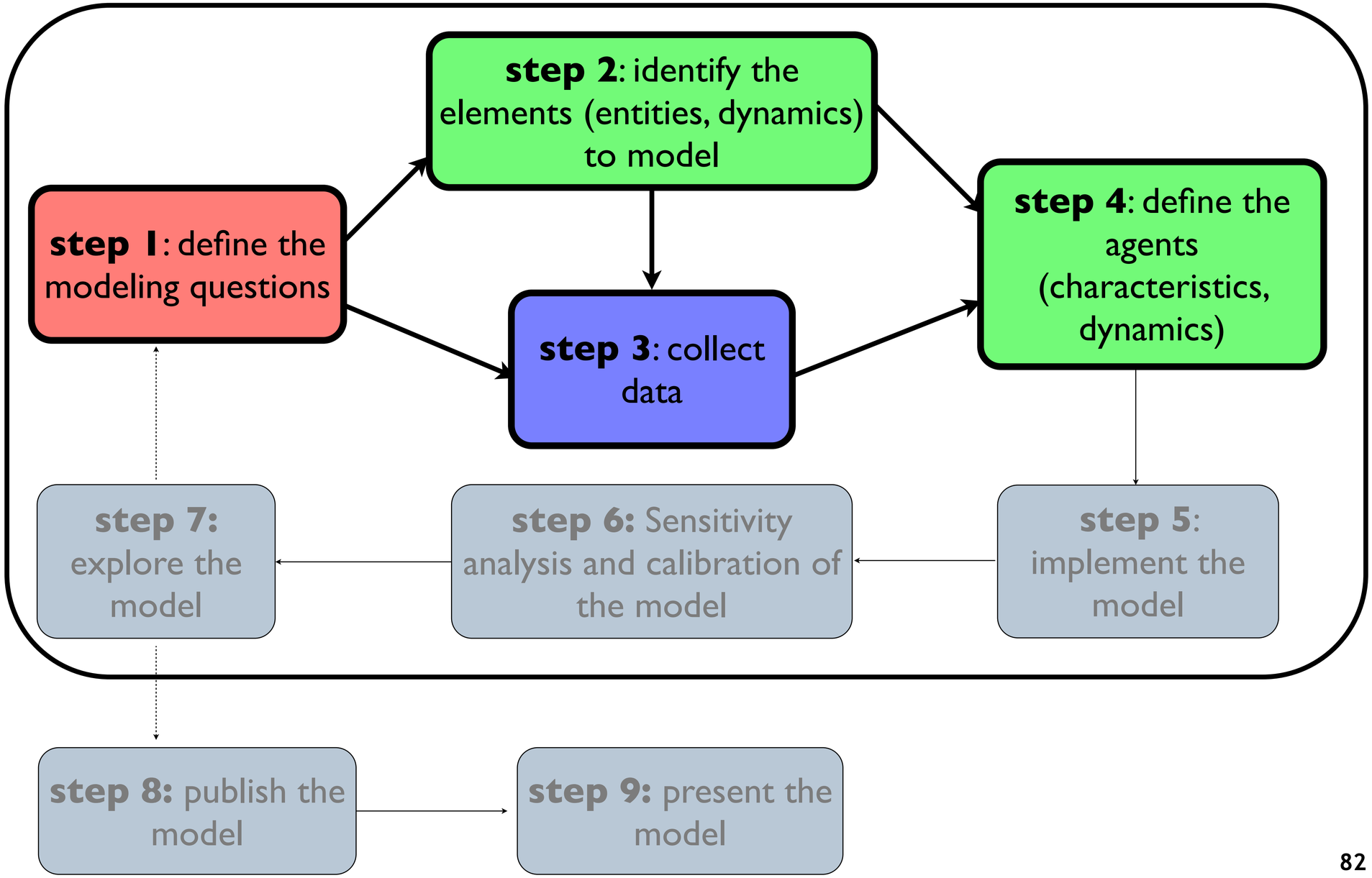
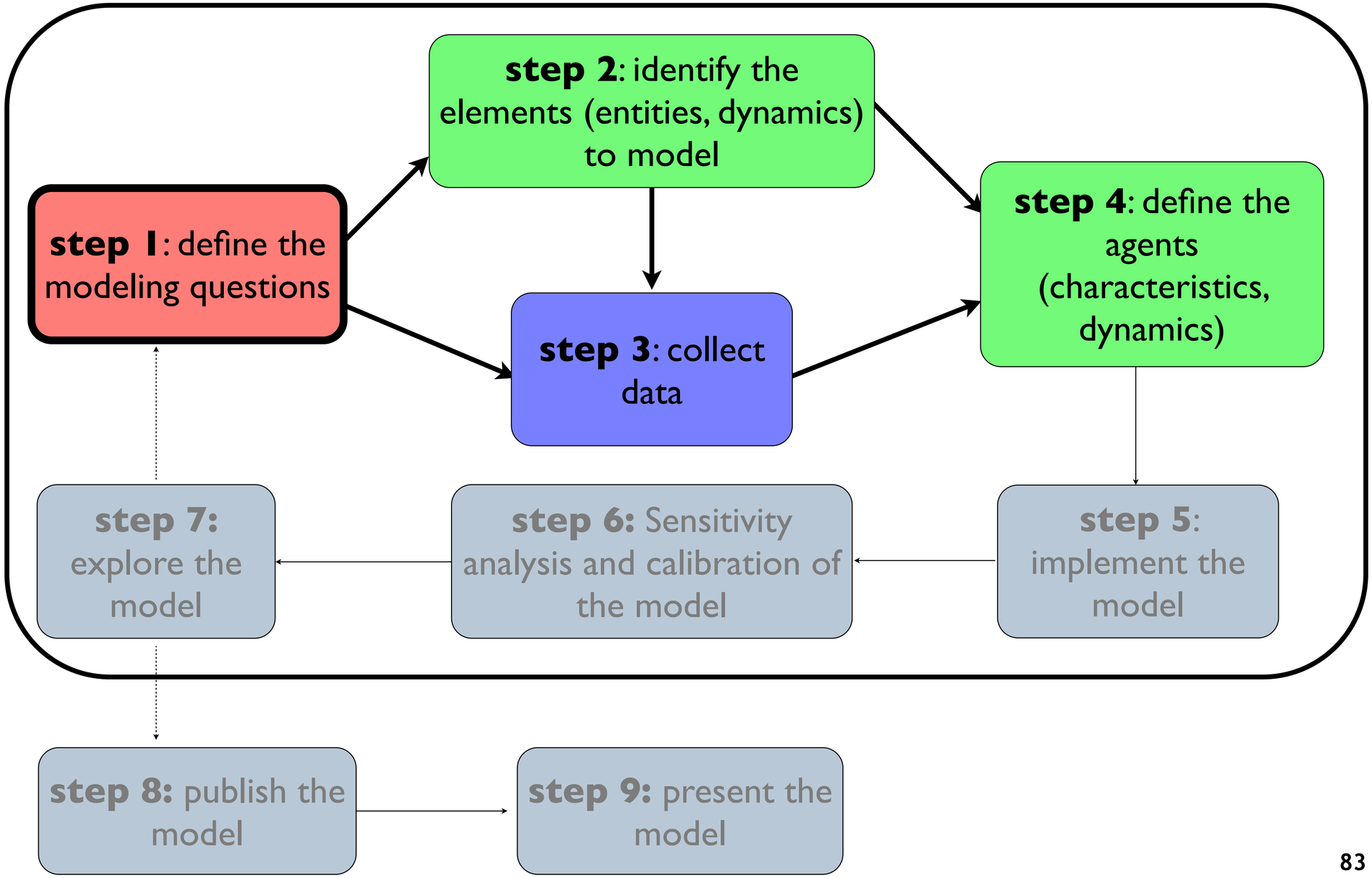


Modelling is a multi-step cycle.



«Every model has to start from a clear question, problem, or hypothesis.» [Grimm, et al. 2010]



Which questions for which models ?

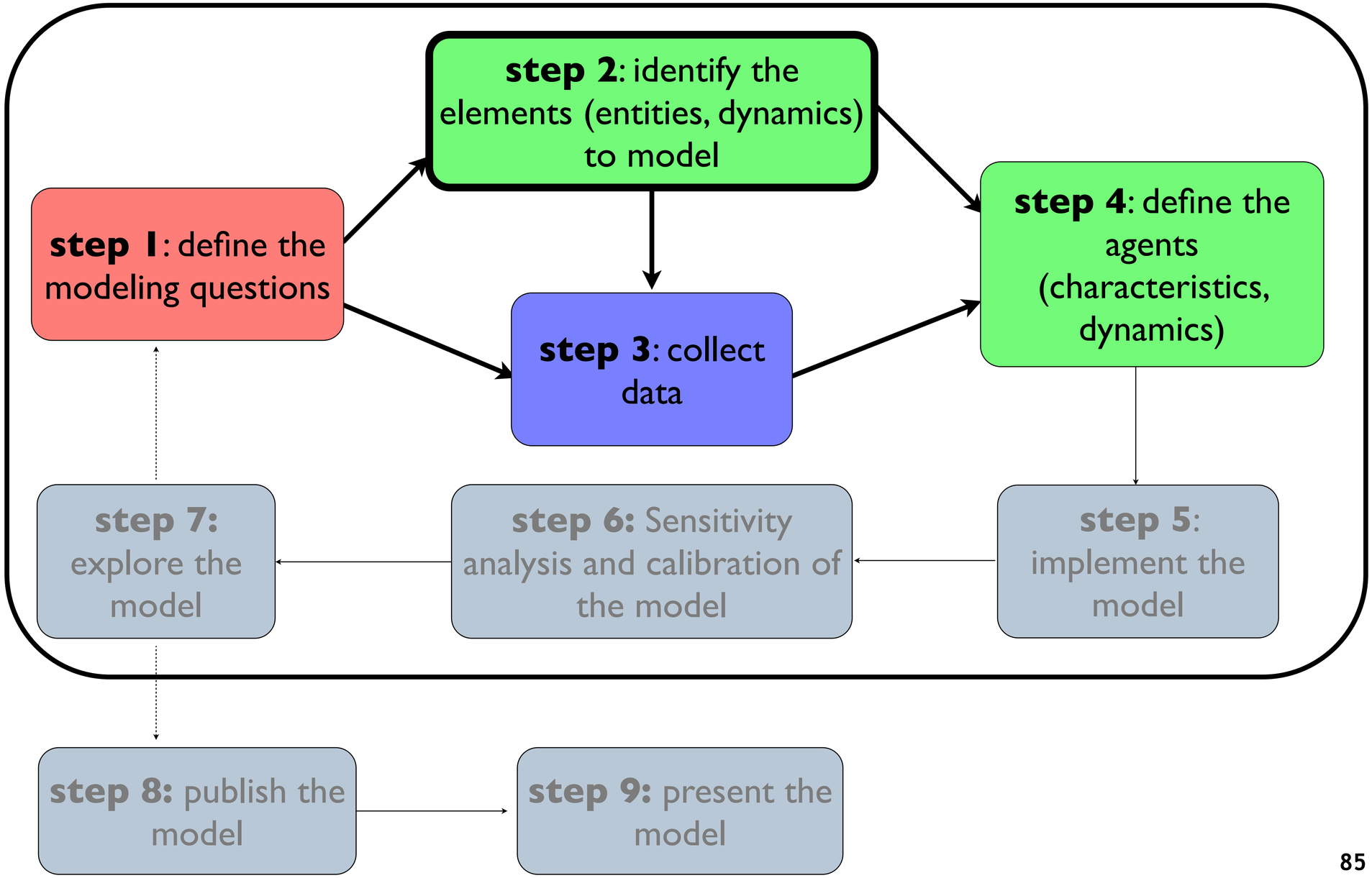
- Among dynamic models we can distinguish:
  - **Reproduction models**: that try, given data, to reproduce as precisely as possible these data by simulation.
    ---> we cannot understand the way the phenomenon is generated.
    But it could «**predict the future**», e.g. weather forecast.

  - **Understanding models**: that try to understand processes that generate phenomena. They are focused on the processes and try to get the phenomenon by simulation.
    ---> allow to understand, explain and generate the phenomenon.

    Consequence: we can « **ask questions to the model**» via What-If scenario.

- **We cannot tackle the same questions with all kinds of models.**

Modelling is a multi-step cycle.

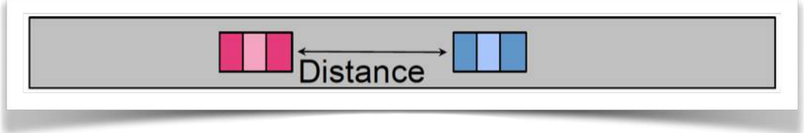


There is a huge number of languages to write a dynamic model.

- Consider 2 main approaches:
  - **equation-based models**: describe the evolution at macroscopic level
  - **agent-based models**: describe microscopic entities, their behaviors and interactions between these entities and generate a macroscopic behavior
- **Example:** traffic
- We focus on **agent-based model** here.

$$\begin{cases} Q(\Delta x, \Delta t) = K(\Delta x, t) V(\Delta x, \Delta t) \\ V(\Delta x, \Delta t) = V_e\left(K(\Delta x, t)\right) \\ \dfrac{\partial Q(\Delta x, \Delta t)}{\partial x} + \dfrac{\partial K(\Delta x, t)}{\partial t} = 0 \end{cases}$$

LWR macroscopic model

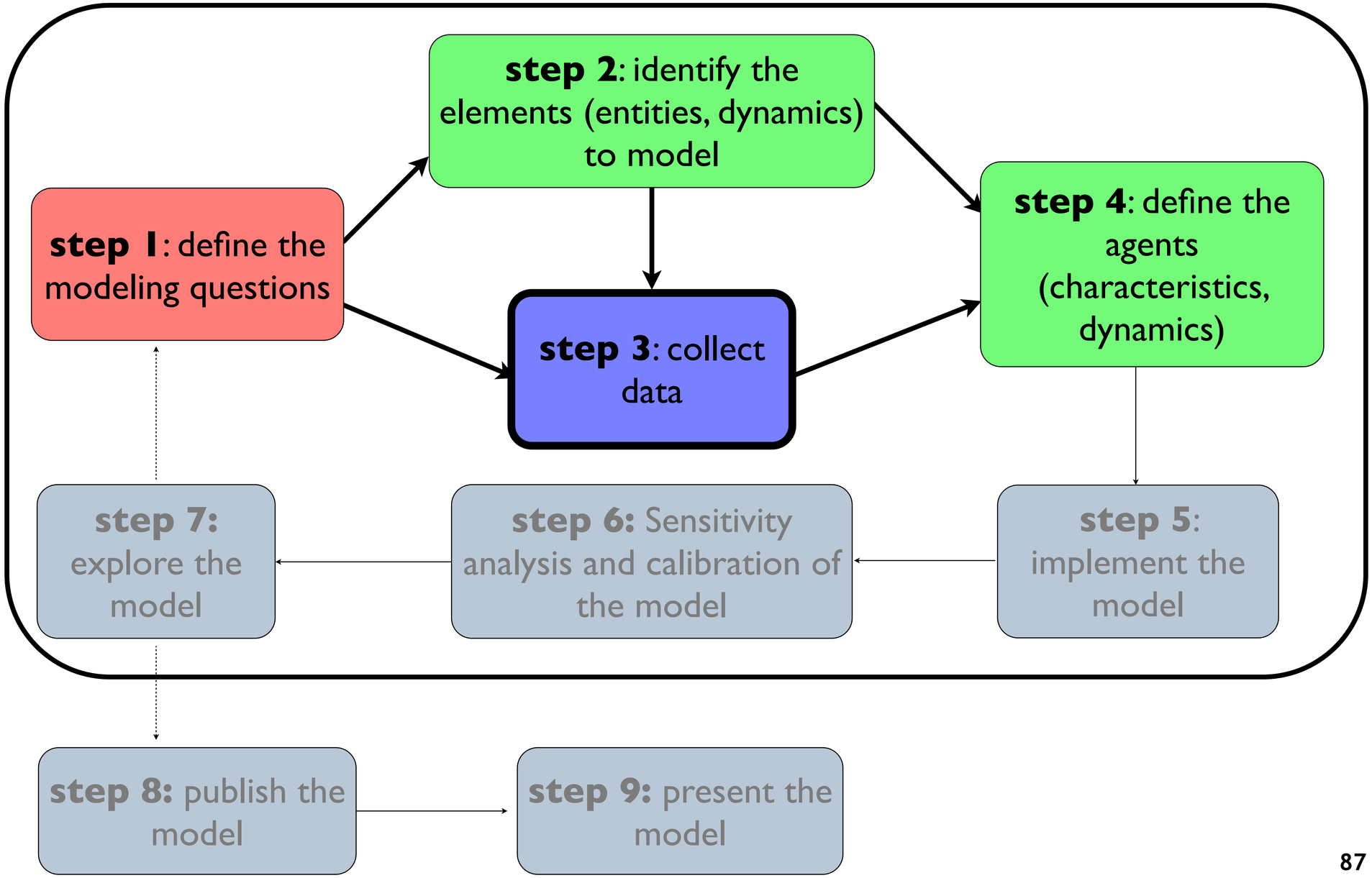


NaSch microscopic model

$$\begin{cases} \dfrac{dS}{dt} = -\beta I S \\ \dfrac{dI}{dt} = \beta I S - \alpha I \\ \dfrac{dR}{dt} = \alpha I \end{cases}$$

Example of epidemic equation-based model

Modelling is a multi-step cycle.



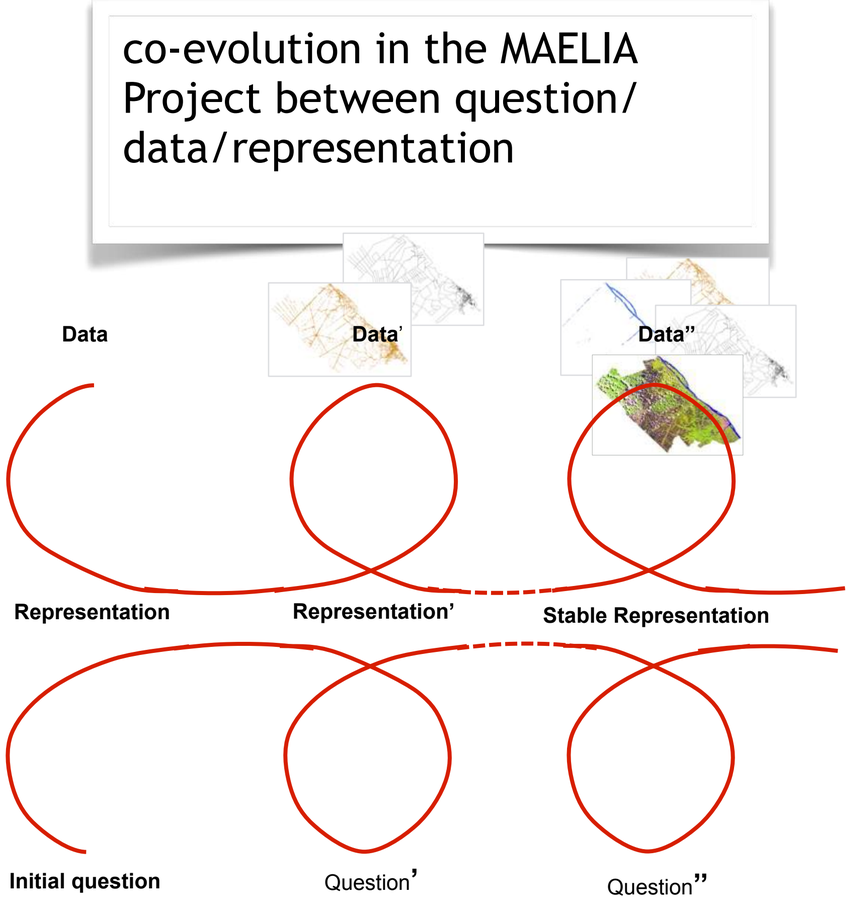
Data collection, cleaning and management are a huge and hard work in a modelling and simulation project!

- **<u>First</u>: Get data**
  - collect yourself,
  - ask/buy from government agency,
  - get open source data (Open Data), e.g. OpenStreetMap, IGN (France) -> unequal quality

- **E.g. :** to get data from Can Tho, we need to ask the Department for Natural Ressources and Environment (*Sở tài nguyên môi trường Cần Thơ*)

- **E.g. :** in France, IGN, INSEE, Water Agency...

- **<u>Then</u>**: process and clean them.

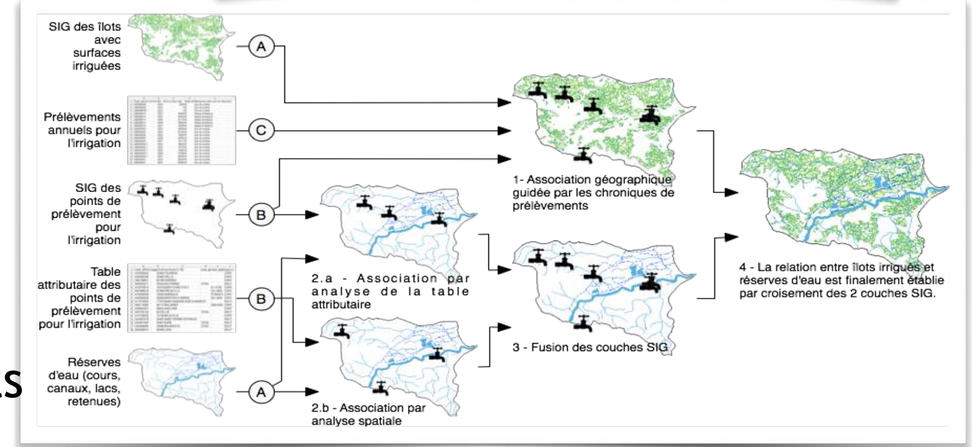


Data need to be cleaned and processed, depending on the aim and need of the model.

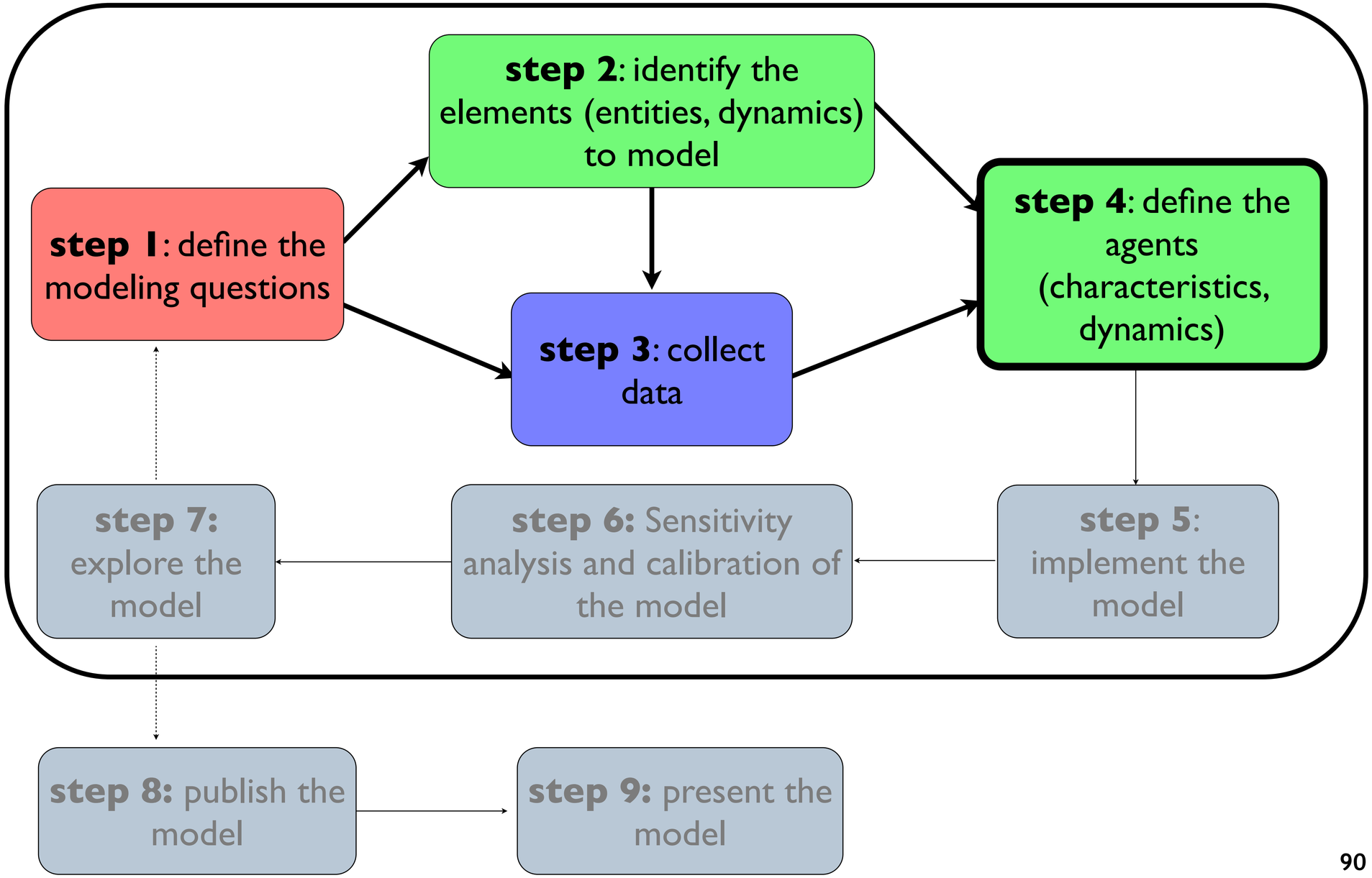
- **Aim:** building of a common GIS merging data from all the various sources.

- <u>Example of issues to tackle:</u>
  - **convert** all the **data formats** in a common one
  - **clean data** (e.g. correct invalid polygons, overlapping or disjoints polygons...)
  - **transform data** to be used in the model (e.g. , switch from polygons to polylines for roads...)
  - correct/create **attribute table** for each geographic objects
  - **integrate / cross** various data sources

Example on the MAELIA project of data integration.



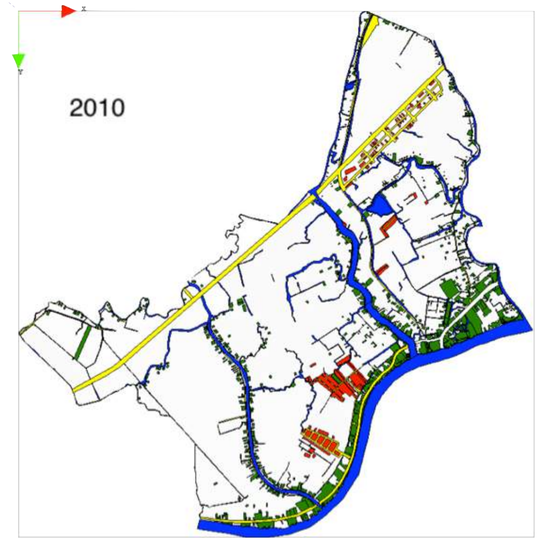
Modelling is a multi-step cycle.



Given the chosen entities and the data collected, we have to choose what will be an agent in our model (i.e. an entity with a behaviour)

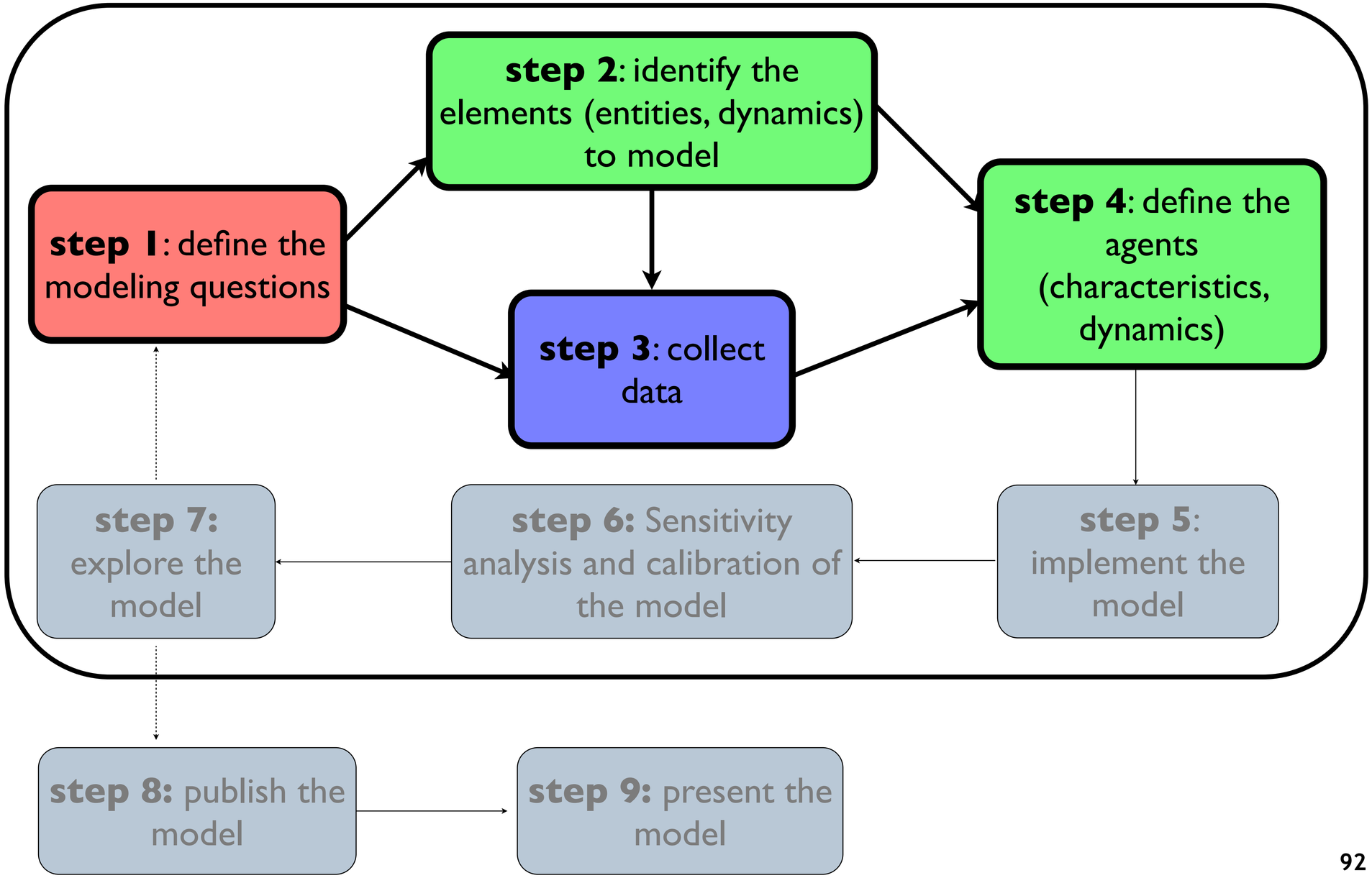
What will be an agent depends mainly on the chosen scale (and data & question).

- If we want to simulate a city, do we need to take into account each inhabitant, each household, each building ... ?



Can Tho - Ninh Kieu - 2010

Example of modelling steps



Current changes in worldwide urbanization patterns at all geographic scales are quite likely the most significant since the advent of humanity.

To address the challenges raised by these changes, there is a need for **tools and models that can support deciders** in:

Providing knowledge on and understanding the dynamics of the urban system,

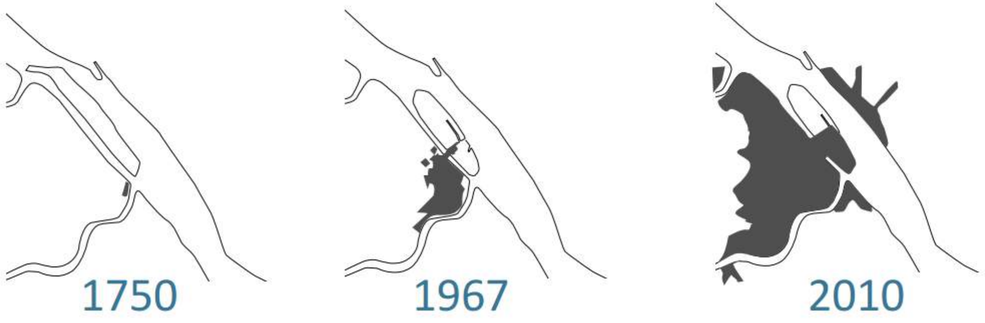
Anticipating and forecasting future changes or trends of development,

Describing and assessing impacts of future development,

Exploring different policies and **optimising** planning and management of sustainable urban areas.

The model is focus on designing and exploiting **urban morphogenesis (or growth) mo**
models that represent the evolution(s) of the spatial inscription of the city.

Example 1: What are the mechanisms allowing a modeler to reproduce the urban growth in Can Tho ?

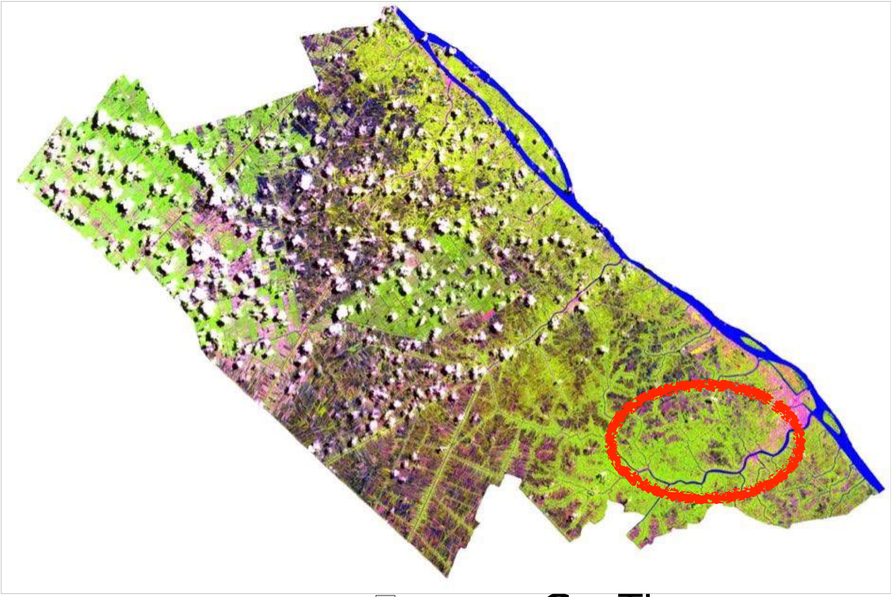


- Application: urban planning

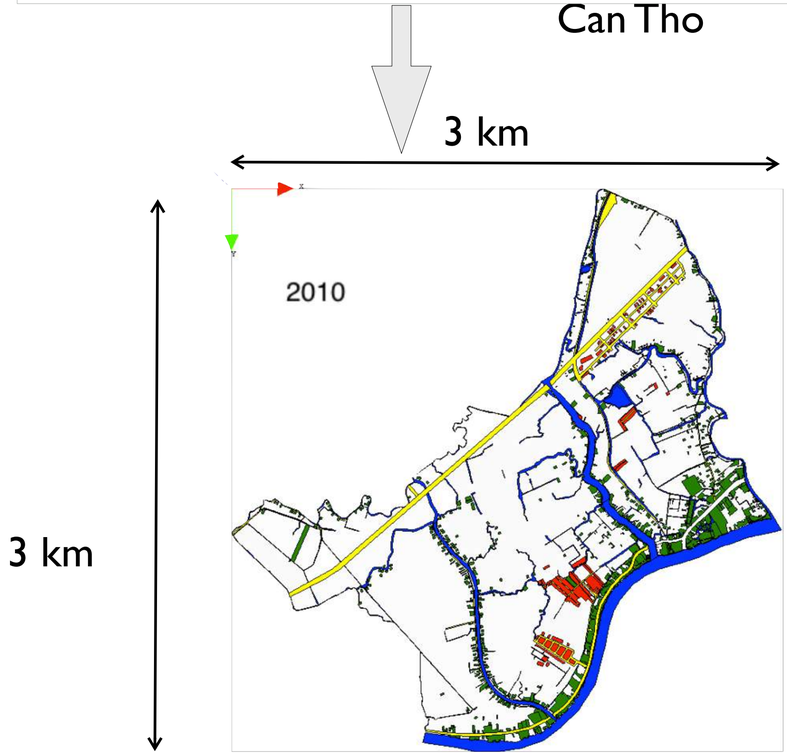
Slide by Alexis Drogoul

Model 1: entities, dynamic and scales

- **Spatial scale**
  - <u>The An Binh ward of Can Tho</u>
- **Time scale**
  - Duration : 5 years from 2005 to 2010
- **Dynamic to take into account**
  - The construction of buildings
- **Entities to take into account**
  - Buildings
  - Roads
  - Rivers



Can Tho



Considered area

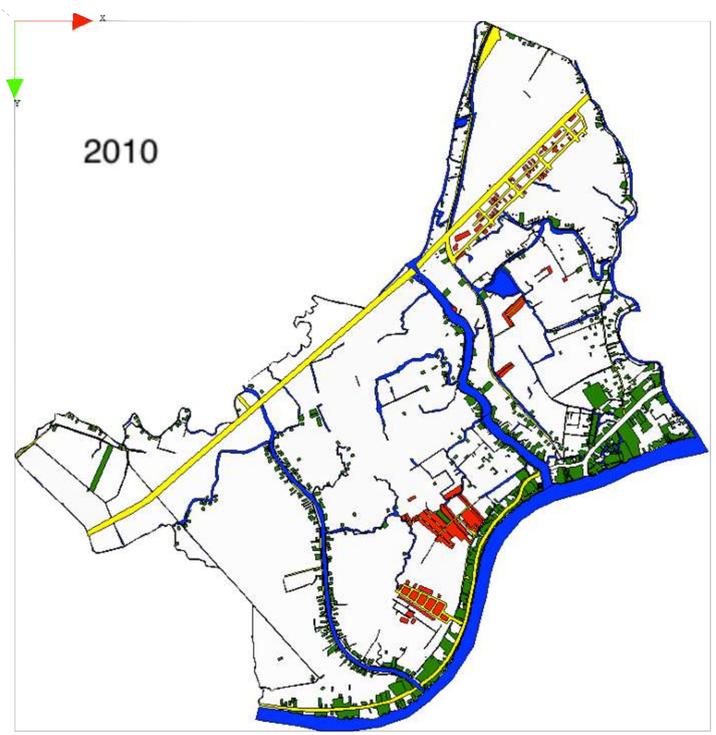
Given the chosen entities and the data collected, we have to choose what will be an agent in our model

- **First attempt**
  - as we are interested in the new buildings, we can chose to make buildings as agents.
  - They have a shape, location and type as attributes.

- We have ***concrete agents***:
  1 agent = 1 physical entity (building, road)

- **Dynamics** should then be described at the **level of the building**.

Can Tho - Ninh Kieu - 2010



Model 2: entities, dynamic and scales

Spatial scale

- <u>Area that covers Can Tho city and the nearby suburbs</u>

Time scale

- Duration : 15 years from 1999 to 2014

Dynamic to take into account

- The construction of buildings

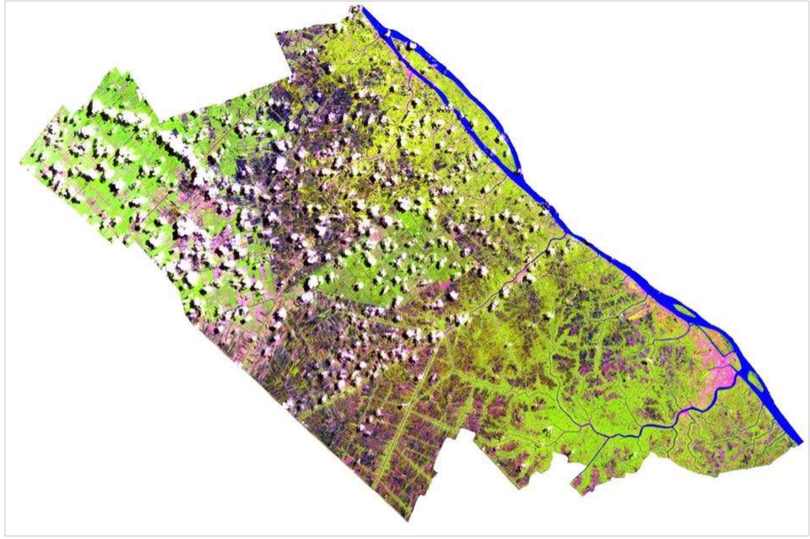
Entities to take into account

- Buildings
- Roads
- Rivers

MeKong Delta

70 km

45 km

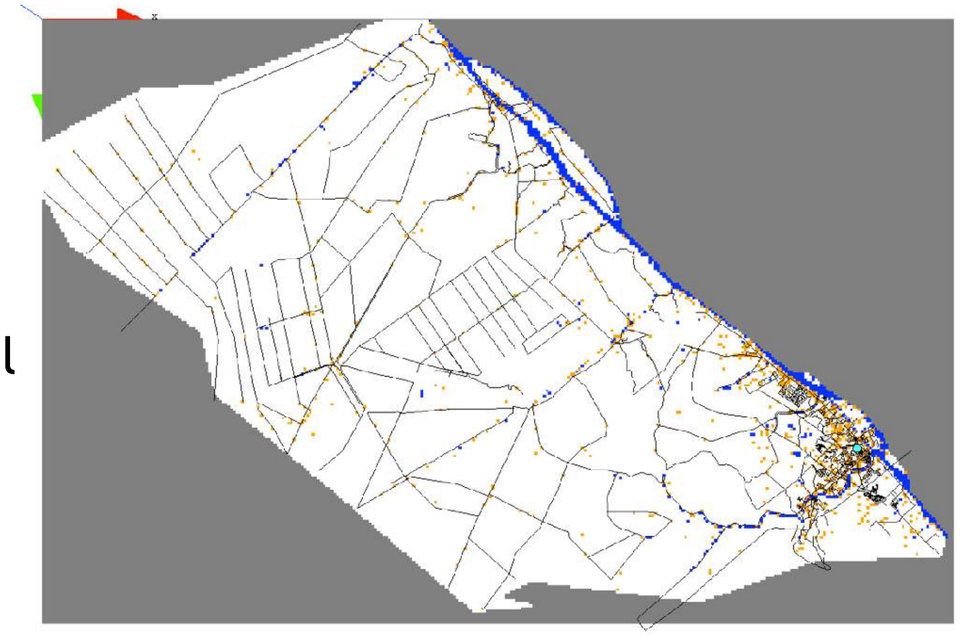


Considered area

Given the chosen entities and the data collected, we have to choose what will be an agent in our model

- To deal with the whole city, we have to switch to something else...
- **Second attempt**
  - we choose to discretise to whole space on a regular grid. Agents will be the cells.
  - they are characterised by a rate of building on the cell area.

Can Tho 1999



- We have ***abstract agents***:
  1 agent = 1 entity aggregating buildings.
- We can choose the number of cells, so the discretisation rate, and so the precision.

Can Tho Case study

- Objective: reproduce the urban growth of the agglomeration of Can Tho from 1999 to 2014

Empty space

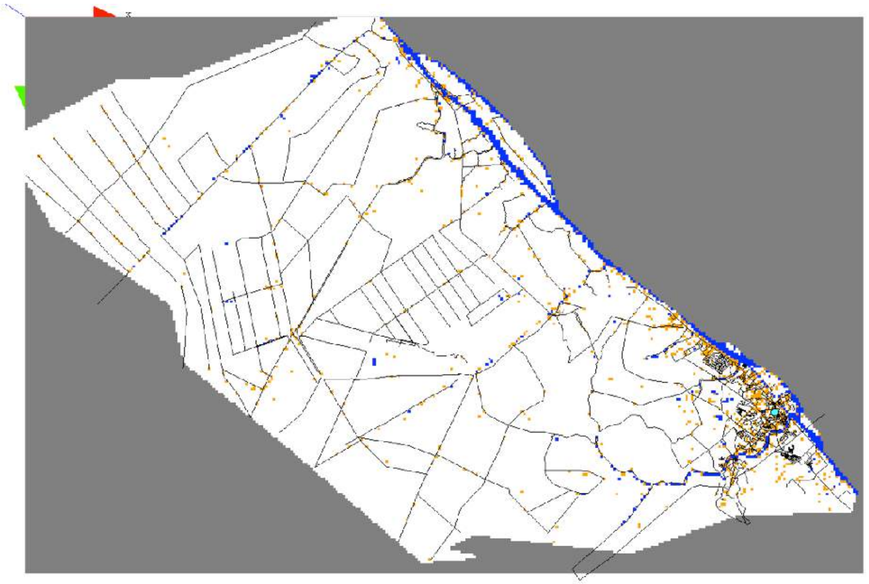
Water space

Built space

Road

City center

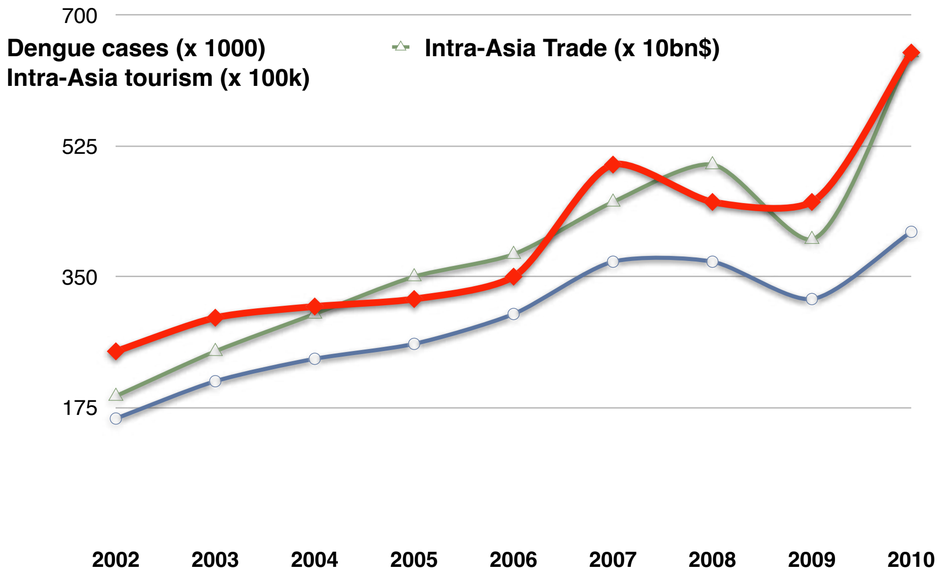
Can Tho 1999



For each free cell (empty space): evaluation of their constructability value based on 3 criteria:
- density (C1)
- distance to road (C2)
- distance to city center (C3)

The decision is made using multi-criteria (**weighted mean**) decision-making process, with 3 weights (w1, w2, w3) associated to each criteria.

Example 2: What incidence do the economic exchanges between ASEAN countries have on the dengue spread?



- Impact of country control policies ?

Model: entities, dynamic and scales

Spatial scale

- Area that covers the ASEAN corridor from Myanmar to Vietnam (200 000km2)

Time scale

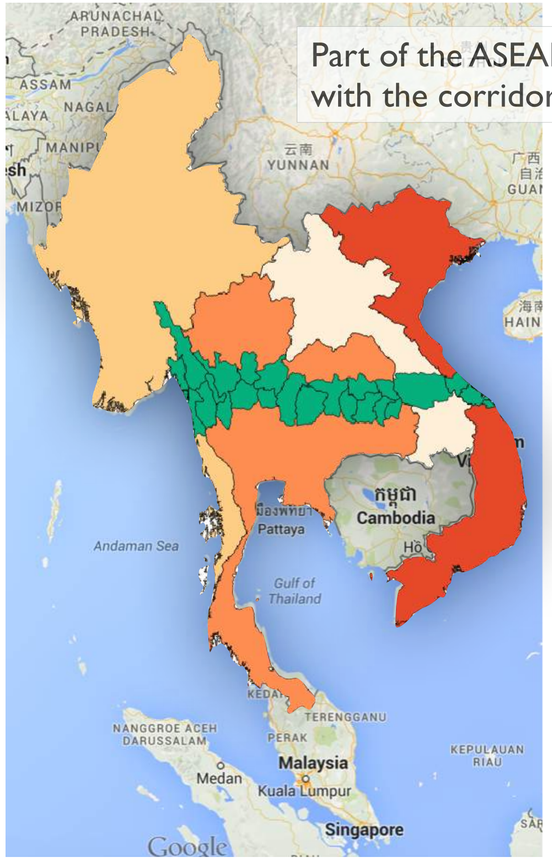
- Duration : from 2004
- Time step = 12 hours

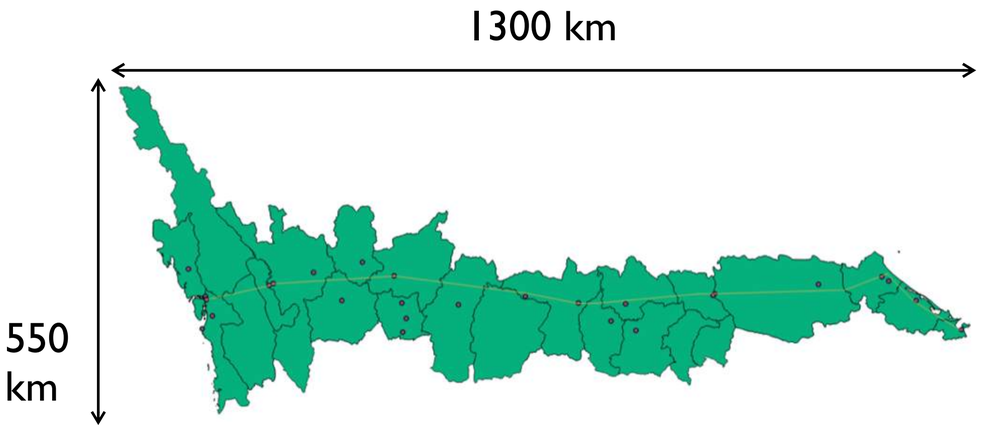
Dynamic to take into account

- Epidemic spread
- Weather
- Mobility

Entities which may be taken into account

- <u>Mosquitoes, humans</u>
- Meteo Station
- <u>trucks, roads</u>, cities

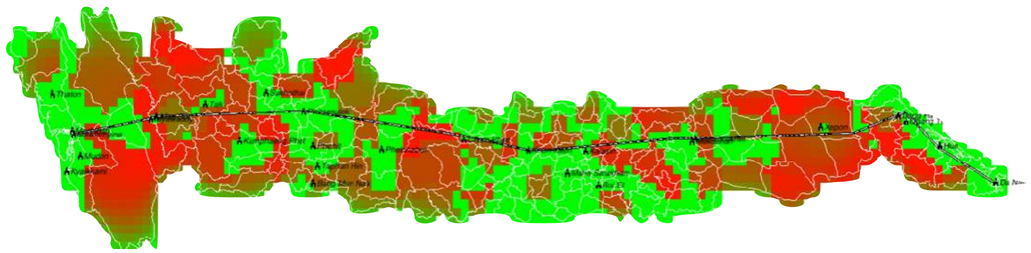




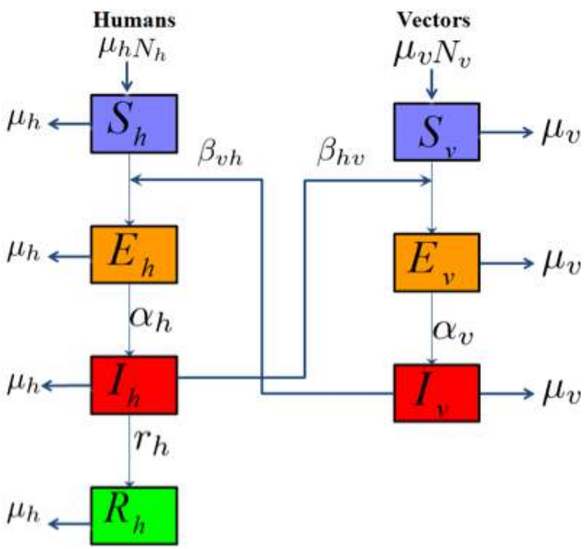
Considered area

What will be the agents in this case ?

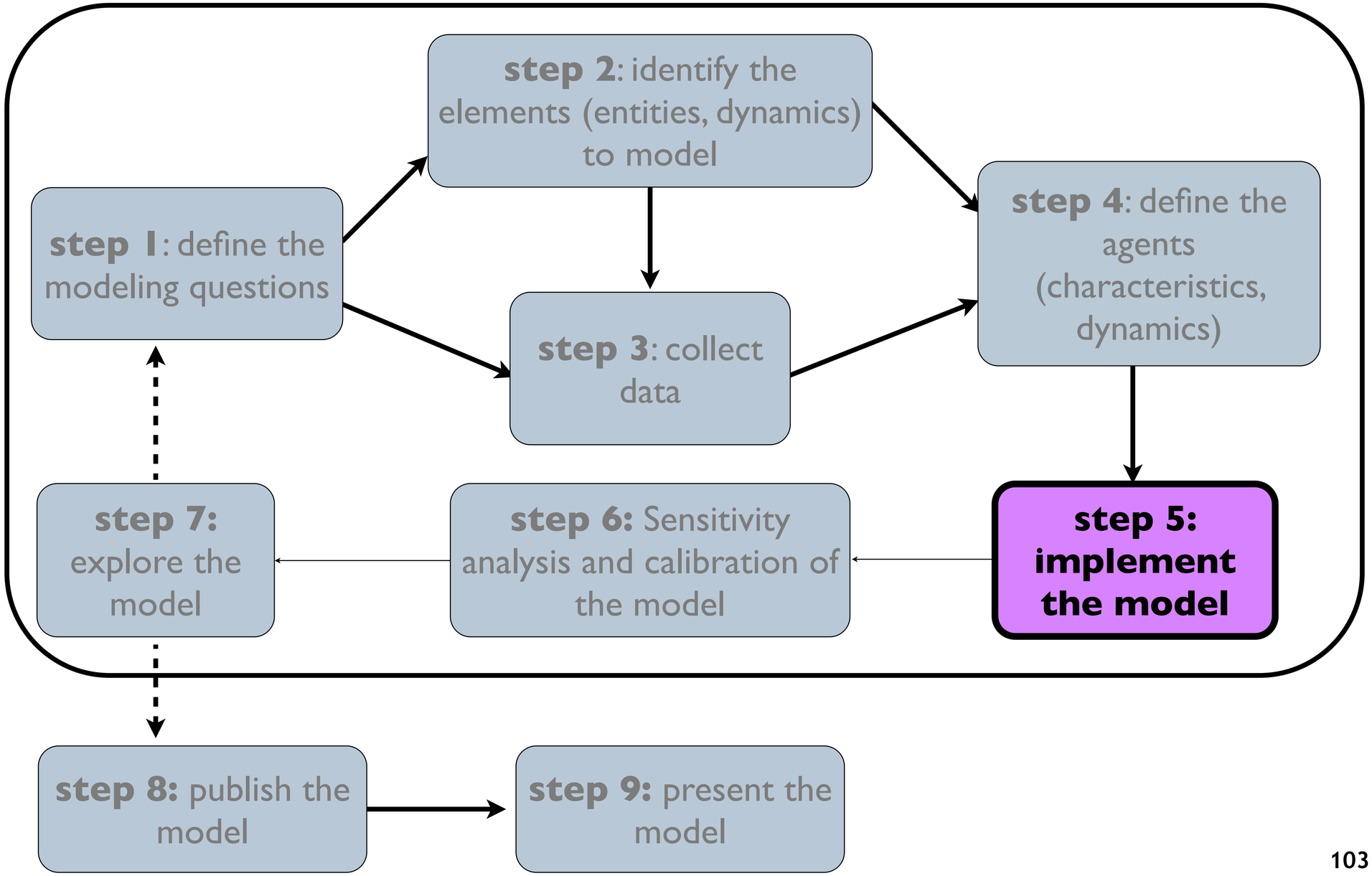
- **Issue:**
  - **#humans = 15 000 000,**
  - **#mosquitos = unknown (a lot !)**
    => We cannot simulate each individual.



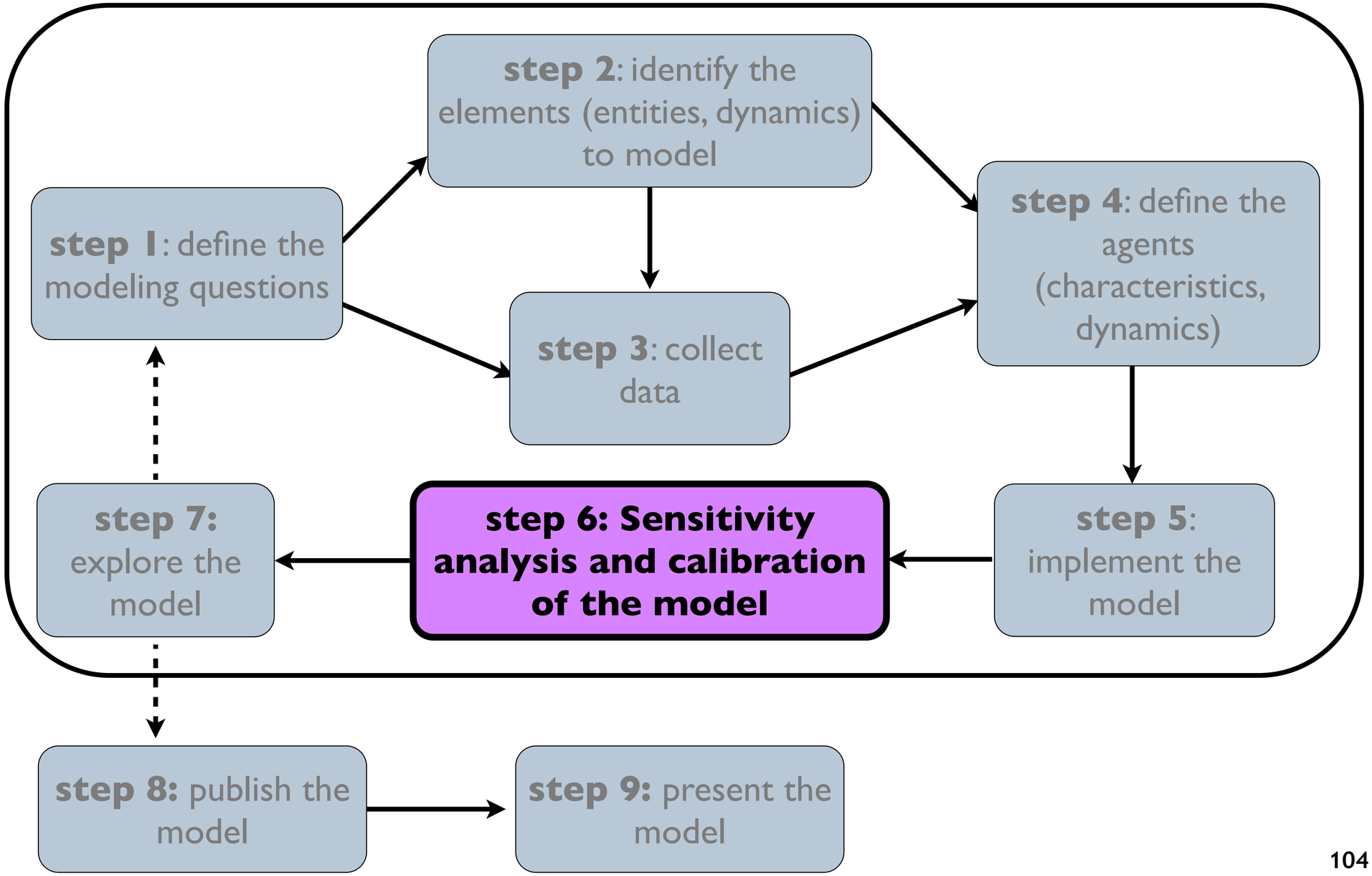
- **Hypothesis & Choice:**
  - we choose to discretise to whole space on a regular grid. Agents will be the cells.
  - they are characterised by populations of mosquitos and human beings in each epidemic state.
- **Dynamics:**
  - disease spread : mathematical equation-based model (SEIRS + SEI model on each cell).



Modelling is a multi-step cycle.



Modelling is a multi-step cycle.



A model is an object that can be manipulated or explored via simulation and on which we can launch experiments.

Parameters

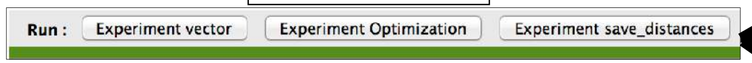
w1
between 0 and 1

w2
between 0 and 1

w3
between 0 and 1

Inputs Data

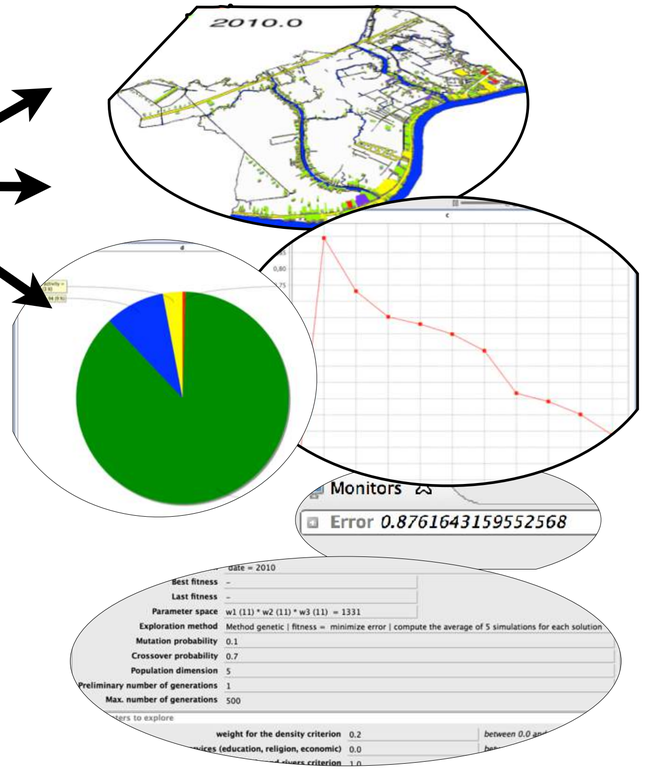
Experiments



Model

```
282  float limit <- world.shape.area;
283  list<building> possible_buildings <- (buildings + (neigbours_blocks accumulate each.buildings)) where (each.ty
284  if empty(possible_buildings) {
285      possible_construction<- false;
286      write name;
287      return;
288  }
289  bool bd_built <- false;
290  building bd <- nil;
291
292  loop while: true {
293      building one_building <- one_of (possible_buildings where (envelope(each.shape).area < limit));
294      if (one_building = nil) {
295          break;
296      }
297      geometry new_building <- copy(one_building.shape);
298      float size <- max([new_building.width,new_building.height]) ;
299
300      geometry space2 <- nil;
301      geometry space <- empty_space reduced_by size;
302      if ((space != nil) and (space.area > 0.0)) {
303          agent closest_road_river <- (road) closest_to space;
304          create building with:[ shape:: new_building, location::((closest_road_river closest_points_with space)
305              texture :: "../includes/texture.jpg",type::one_building.type] {
306              myself.buildings << self;
307              bd <- self;
308              switch type {
309                  match "Education" {myself.has_education <- true;}
310                  match "Religion" {myself.has_religious <- true;}
311                  match "Economic activity" {myself.has_economic <- true;}
312              }
313          }
314          bd_built <- true;
```

Outputs



Often there are at least 2 ways to run simulations.

GUI experiment:

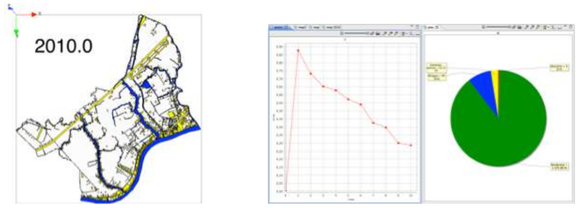
Gui experiments allow the modeler to observe indicators evolution during a simulation

batch experiment:

batch experiments allow model to observe the evolution of indicators of the simulation (computed at the end of the simulation) over the change of parameters.

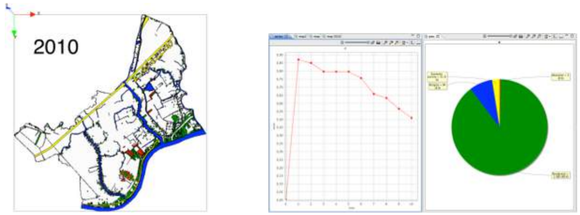
GUI experiments allow to test various parameters values and observe the output.... which can be long and fastidious at hand ...

w1 = 0.2
w2 = 0.0
w3 = 1.0



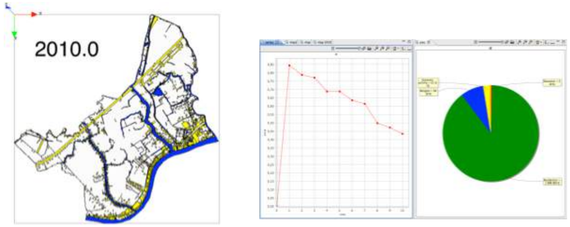
Error = 0.2869

w1 = 0.7
w2 = 0.5
w3 = 0.2



Error = 0.5093

w1 = 0.5
w2 = 0.3
w3 = 0.8



Error = 0.4344

.....

The batch mode allows to automatically execute parameter space exploration.

- Exploring the parameters space of a model can be used to:
  - Correct the model,
  - Do sensibility analysis,
  - Calibrate it,
  - Discover emerging properties,
  - …

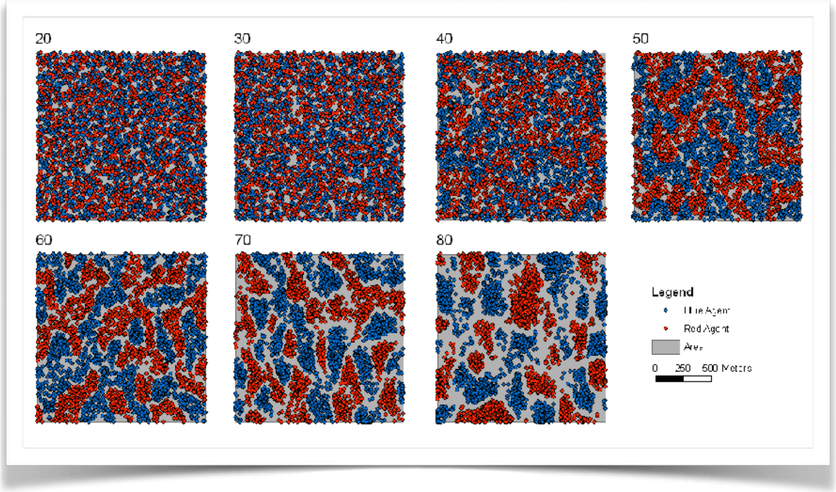
➡ **A necessary step!**

Explore the model behaviour through the exploration of the parameters space.

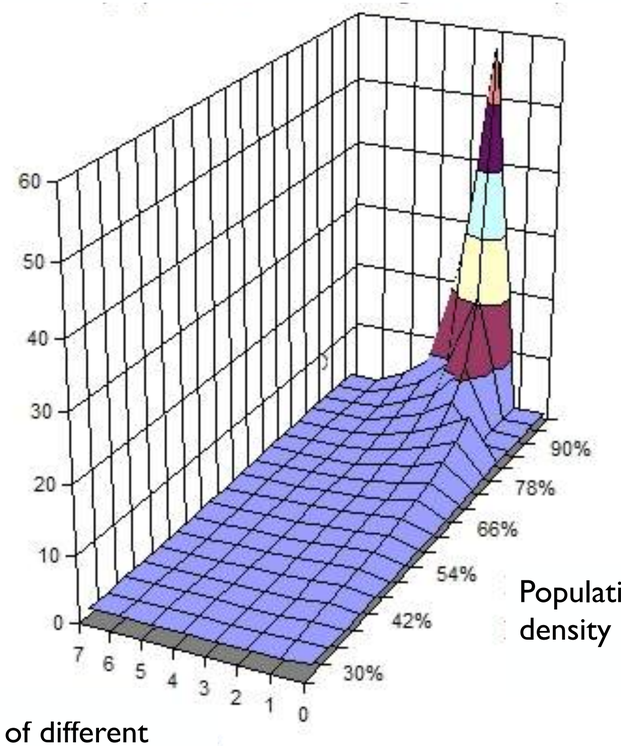
Aim: to have a deep knowledge of the behaviour of the model (and in particular its **sensitivity to parameters variations**)

==> the range of values to which the simulation is very sensitive -> discretisation need (step= 1, 0.1 or 0.0001 ...)

Example on the Schelling's model:



Mean size of aggregates depending on the 2 parameters:
- number of different neighbours accepted
- population density
(Daudé E. & Langlois P. 2006)



Population density

Number of different neighbours that can be accepted by an agent

«Exhaustive» exploration of the Schelling's model

The calibration allows to find parameters values making the simulation results fitting to real data.

Objective:

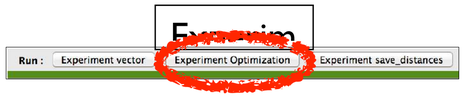
What are the values of parameters:

- that allow to obtain a «realist» model ?
- **that minimise the difference between real and simulated data ?**

Real data (at the time of the simulation end)

error = difference between simulated data and real data

w1 = ??
w2 = ??
w3 = ??



Real data at initial time

Simulated data at the end of the simulation

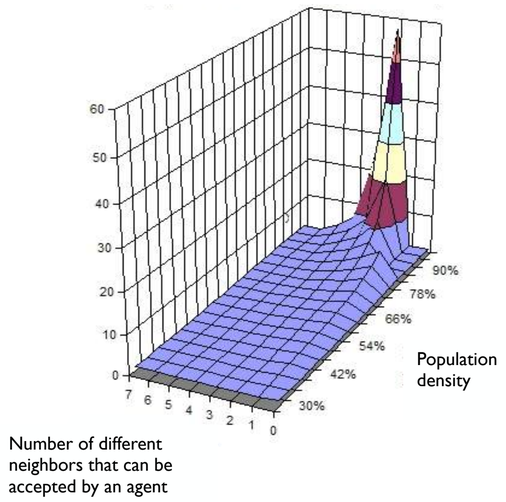
Issues linked to the calibration.

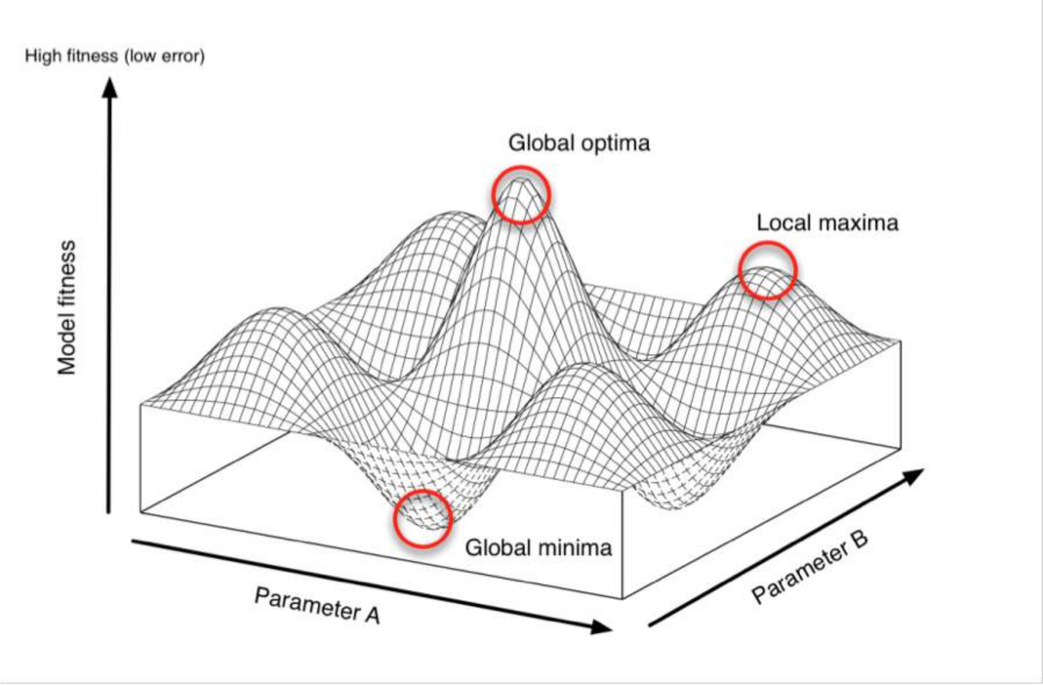
Find a good **indicator** (often named <u>fitness</u>) to represent the fact that a **simulation is «good»** (e.g. the difference between real and simulated data):

- in the case of urban growth model, this indicator should represent the distance between real and simulated maps.

To find the parameters is closed to an optimisation problem (minimise a value):

- lot of methods exist (exhaustive, Genetic algorithms, ...)





http://nickmalleson.co.uk/wp-content/uploads/2013/04/parameter_space.png

Steps in an experiment design.

- **General method :**
  - Define an **initial situation** and a **stop criterion** (of 1 simulation)
  - Select the **set of parameters** to explore and the **indicators**
  - Define a **strategy of exploration**
  - Execute, collect and save the data
  - Analyze the collected data

Can Tho Case study

- Objective: reproduce the urban growth of the agglomeration of Can Tho from 1999 to 2014

Empty space

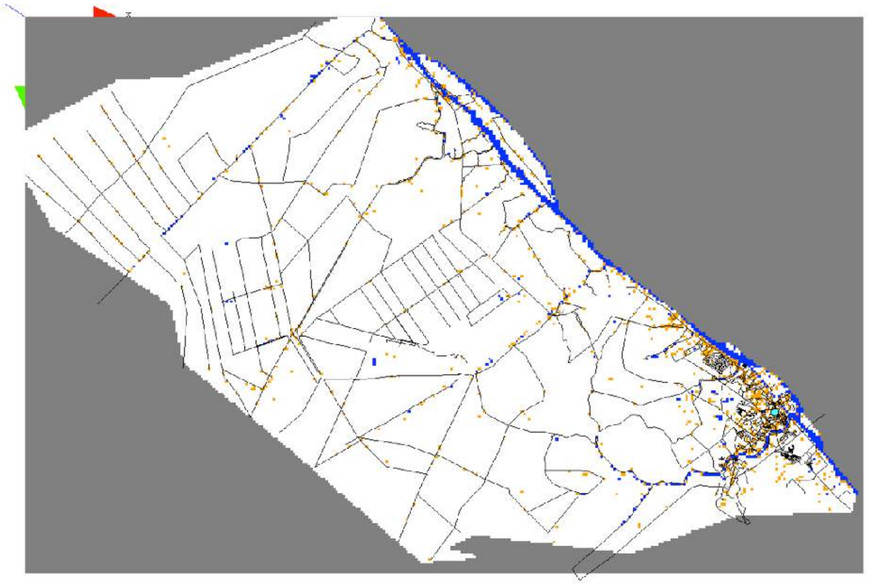
Water space

Built space

Road

City center

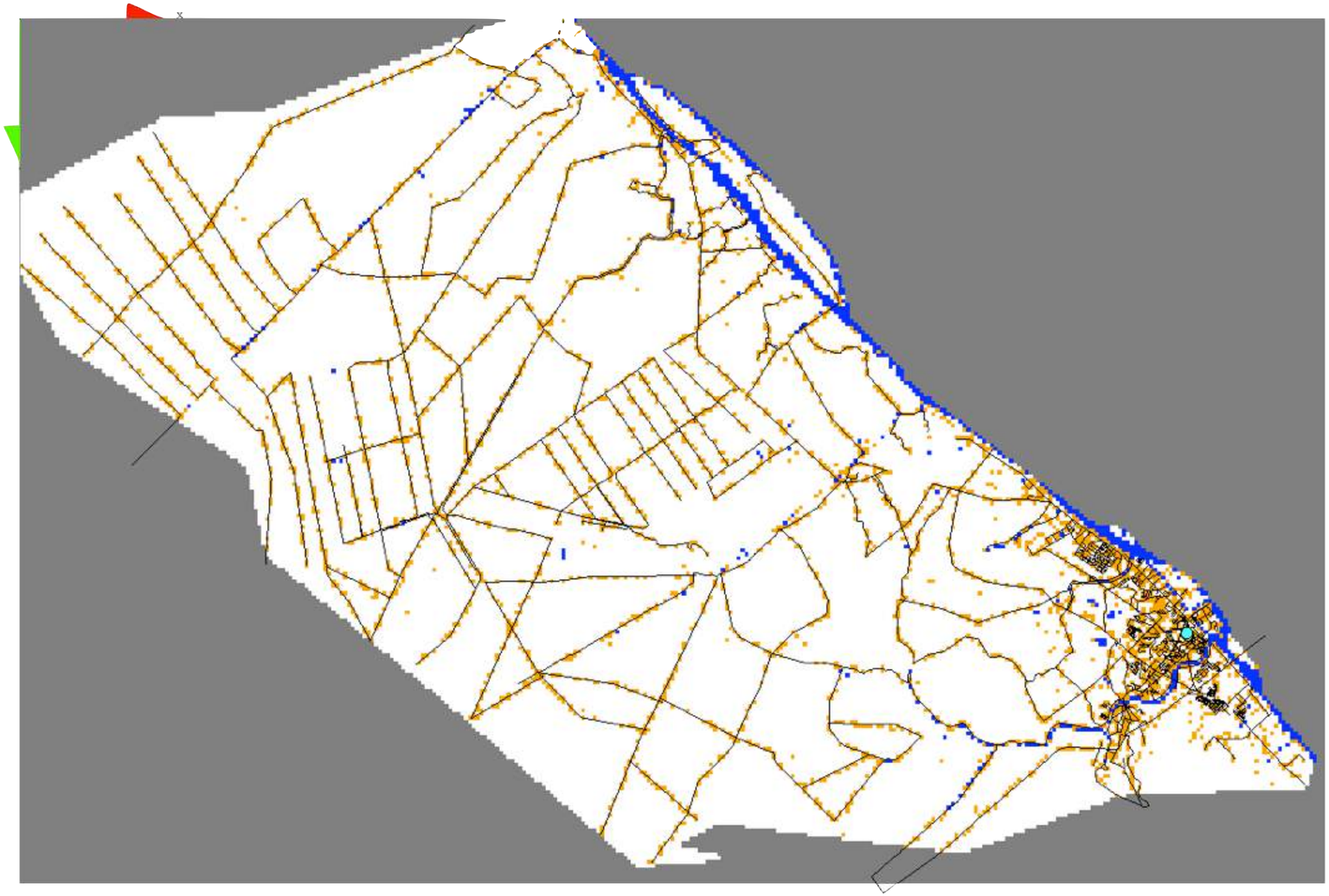
Can Tho 1999



For each free cell (empty space): evaluation of their constructability value based on 3 criteria:
- density (C1)
- distance to road (C2)
- distance to city center (C3)

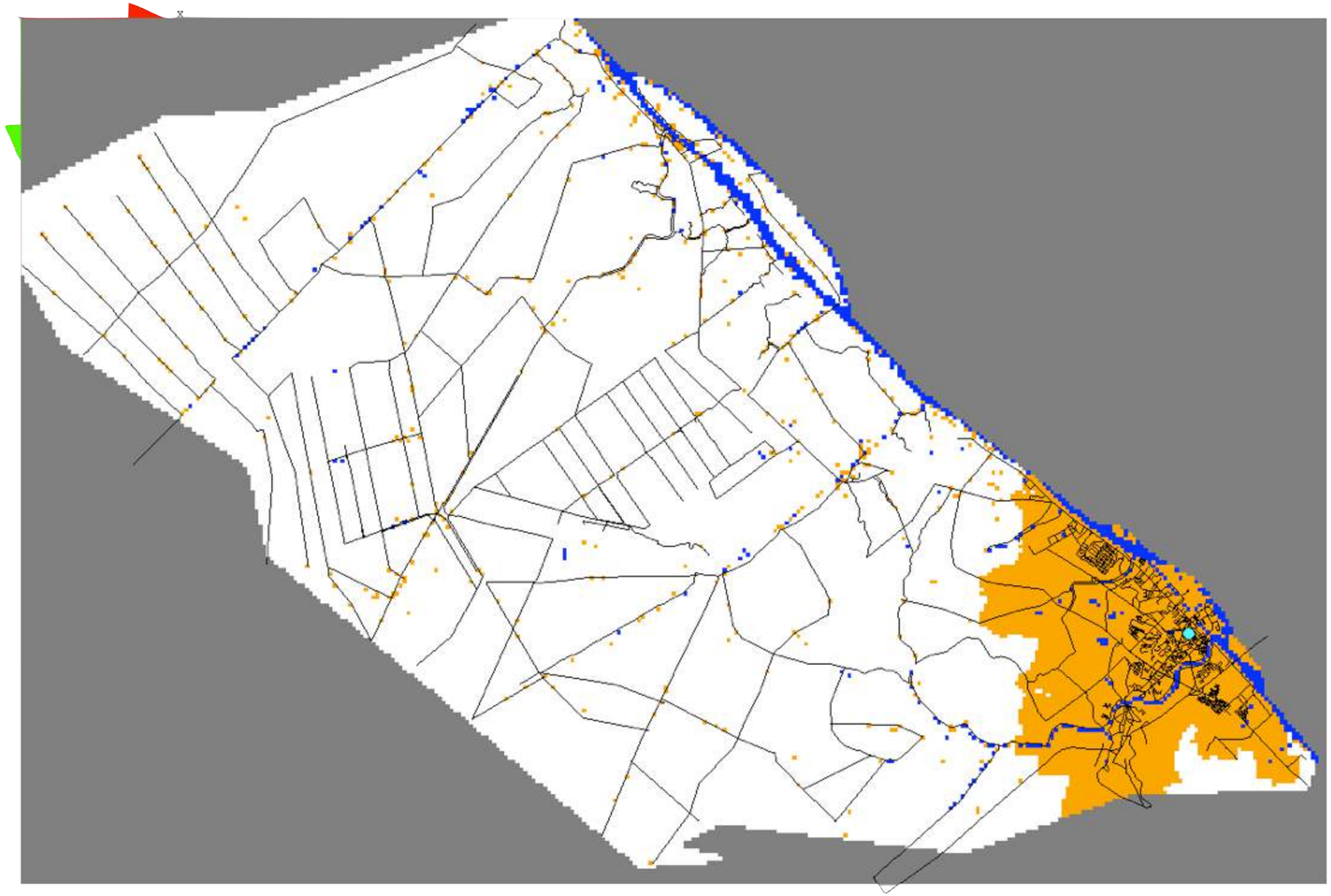
The decision is made using multi-criteria (**weighted mean**) decision-making process, with 3 weights (w1, w2, w3) associated to each criteria.

Can Tho Case study: first simulation with only the distance to road criterion



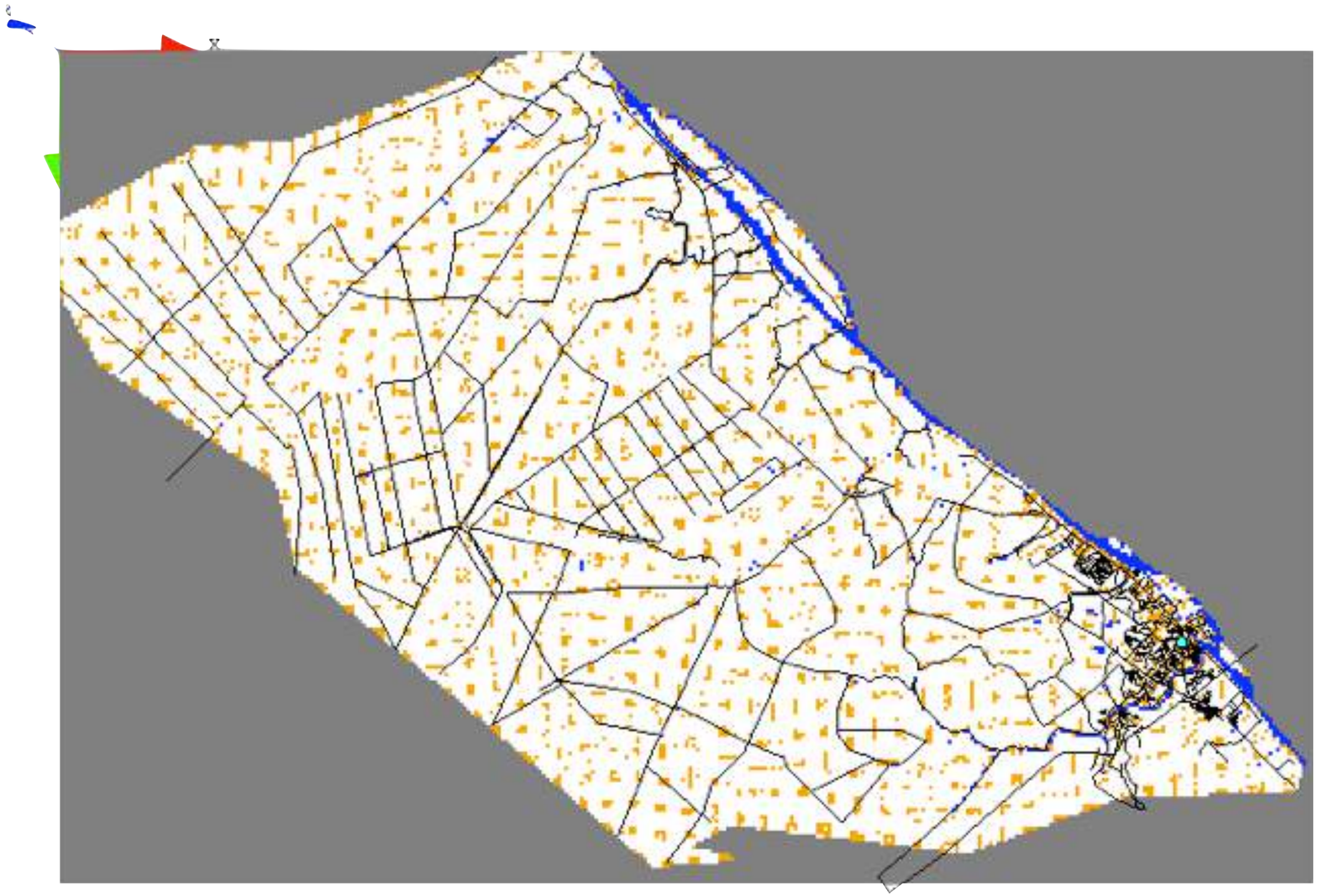
Construction along the roads

Can Tho Case study: first simulation with only the distance to city center criterion



Expansion of the city center

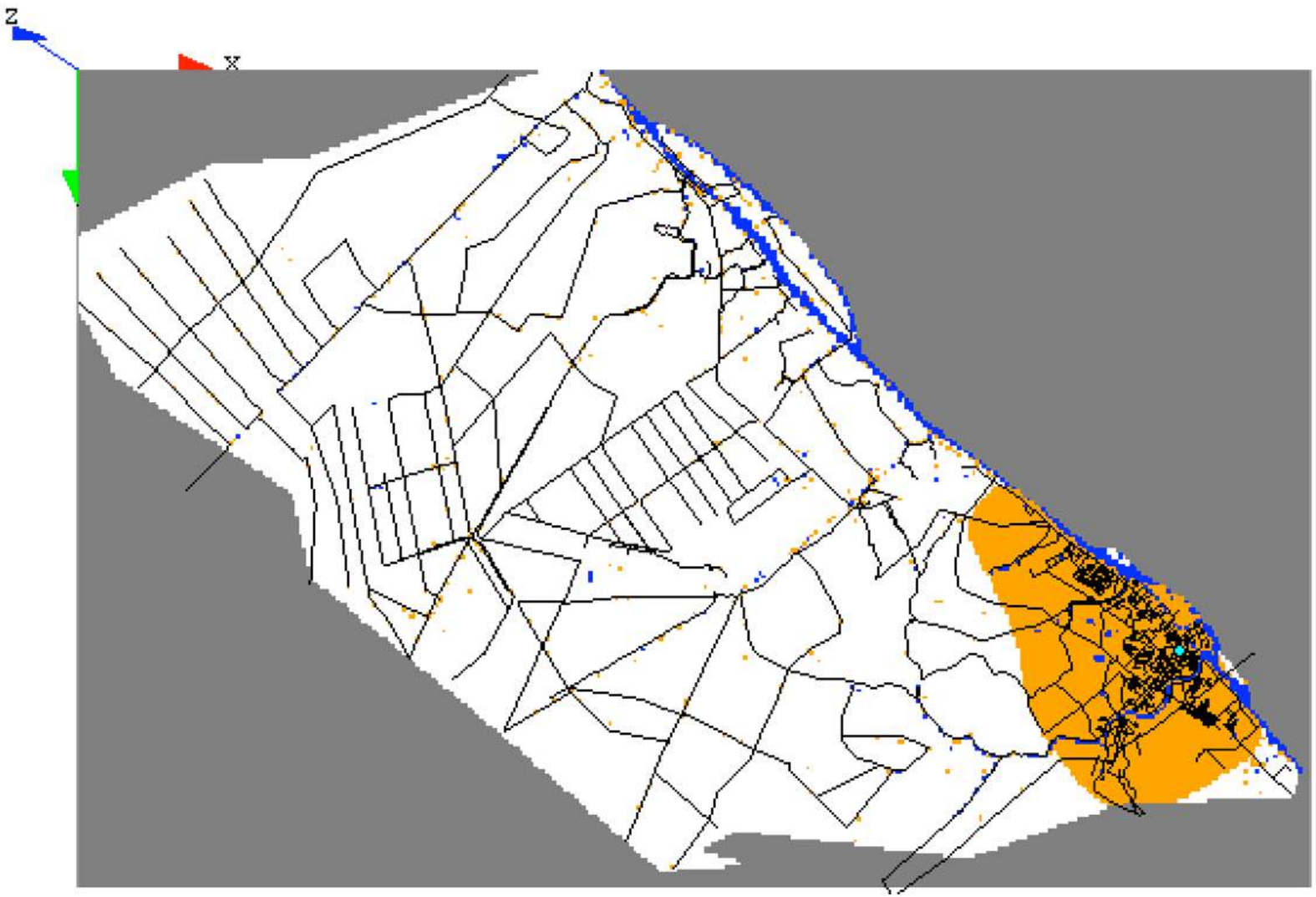
Can Tho Case study: first simulation with only the (low) density criterion



Lot of small «building blocks» covering uniformly the space

w1 : density = 1 - (number of built neighbor cells / number of neighbor cells)

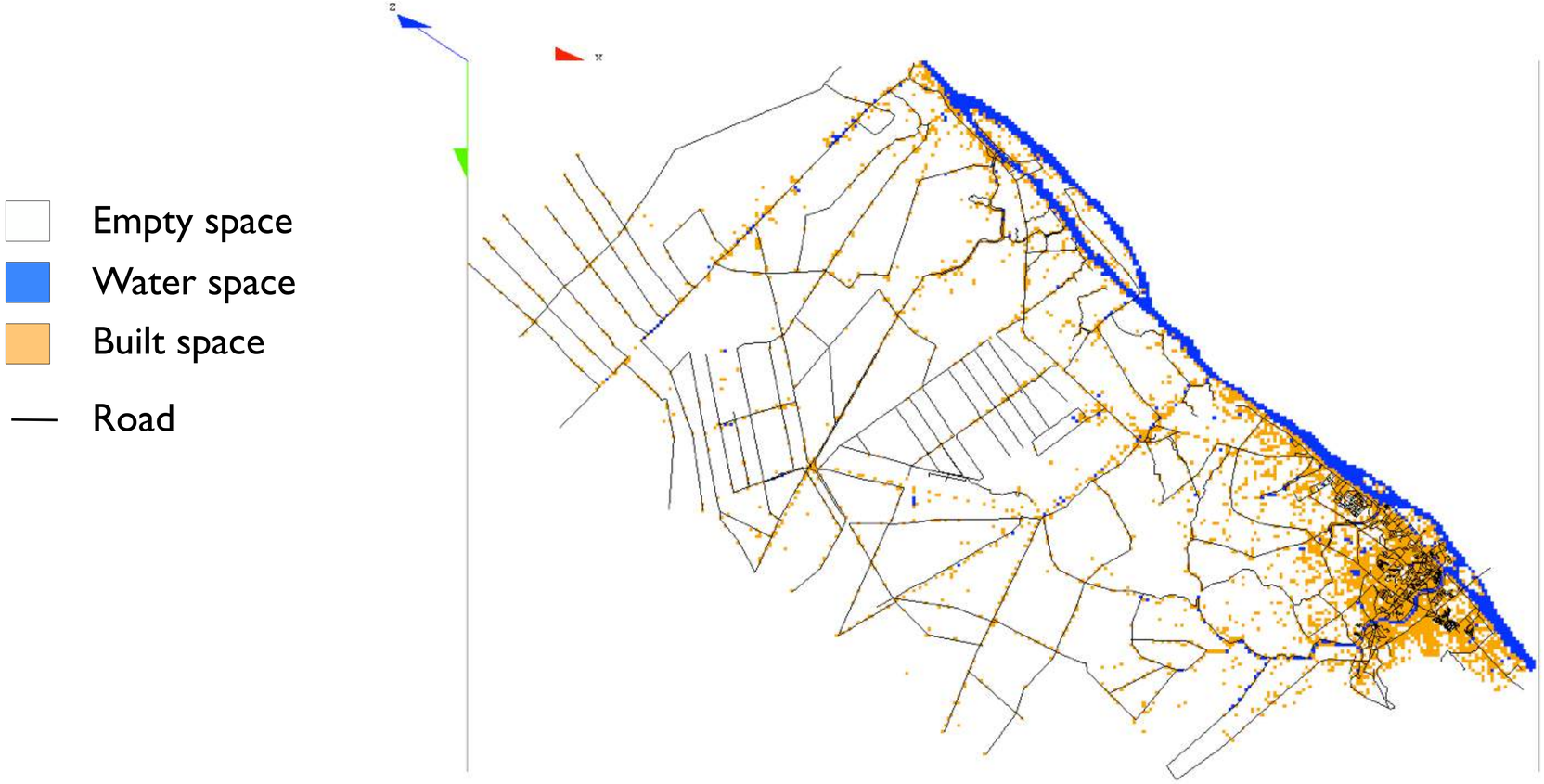
Can Tho Case study: first simulation with only the (high) density criterion



Expansion from high density areas

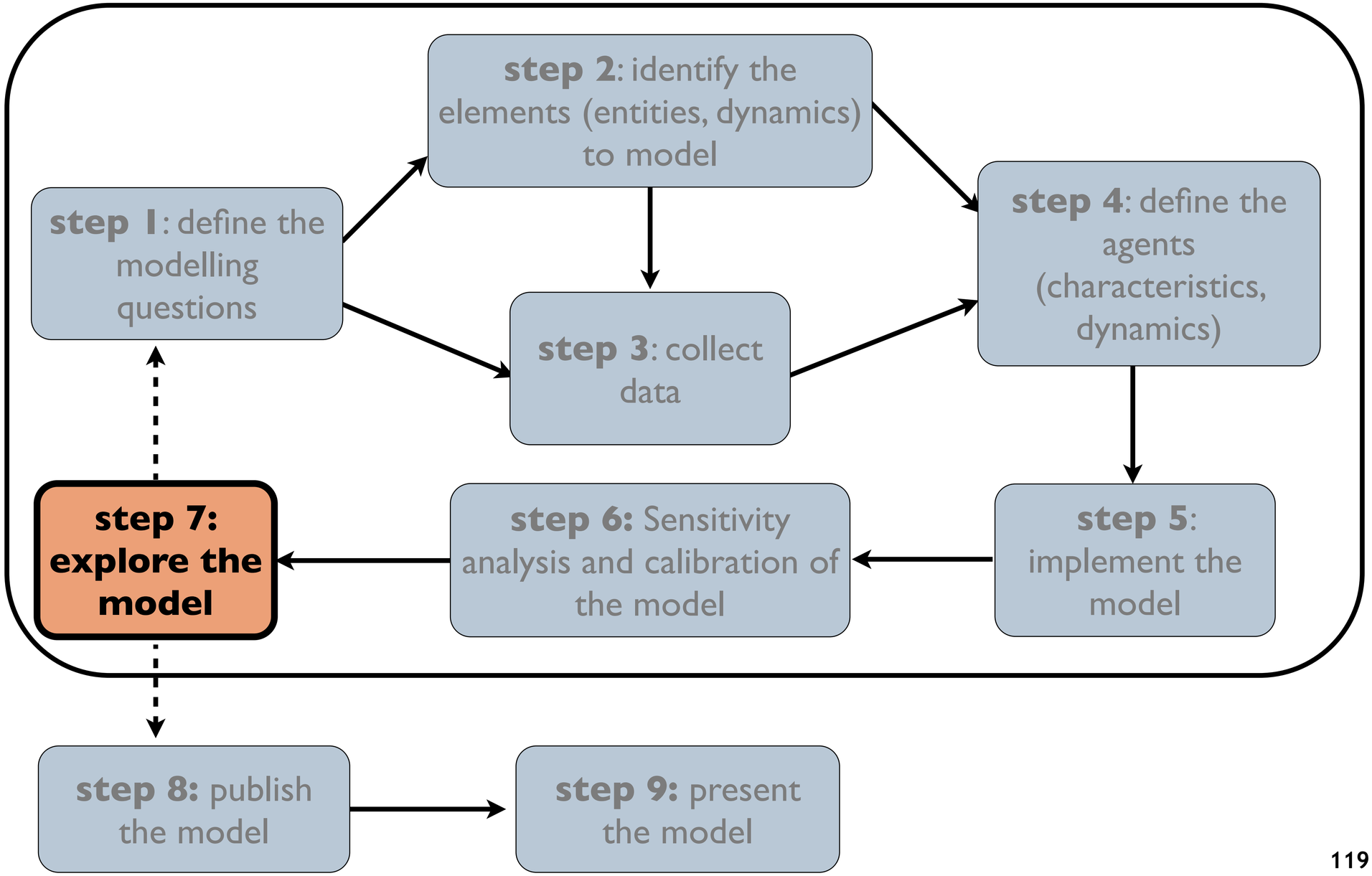
w1 : density = (number of built neighbor cells / number of neighbor cells)

Can Tho Case study: calibration of the model to reproduce the real urban growth



How to evaluate the error between the simulation and the observed data?
Use of the **Fuzzy Kappa Sim** indicator

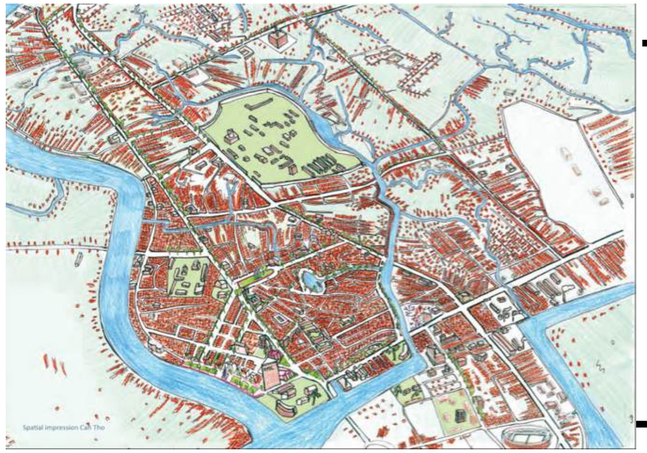
Modelling is a multi-step cycle.



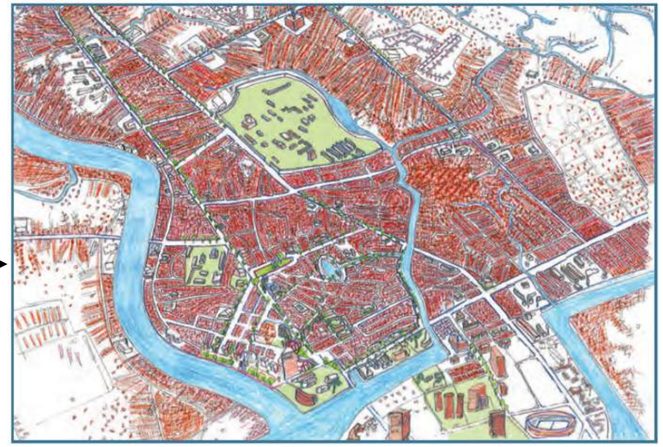
Once the model has been calibrated, we can explore the result of the simulation to various scenario.

We can define scenario that we want to explore:
- building of a new road, of new houses, services...

From an initial state



What-If no change is done in terms of urban planning ?



??????????

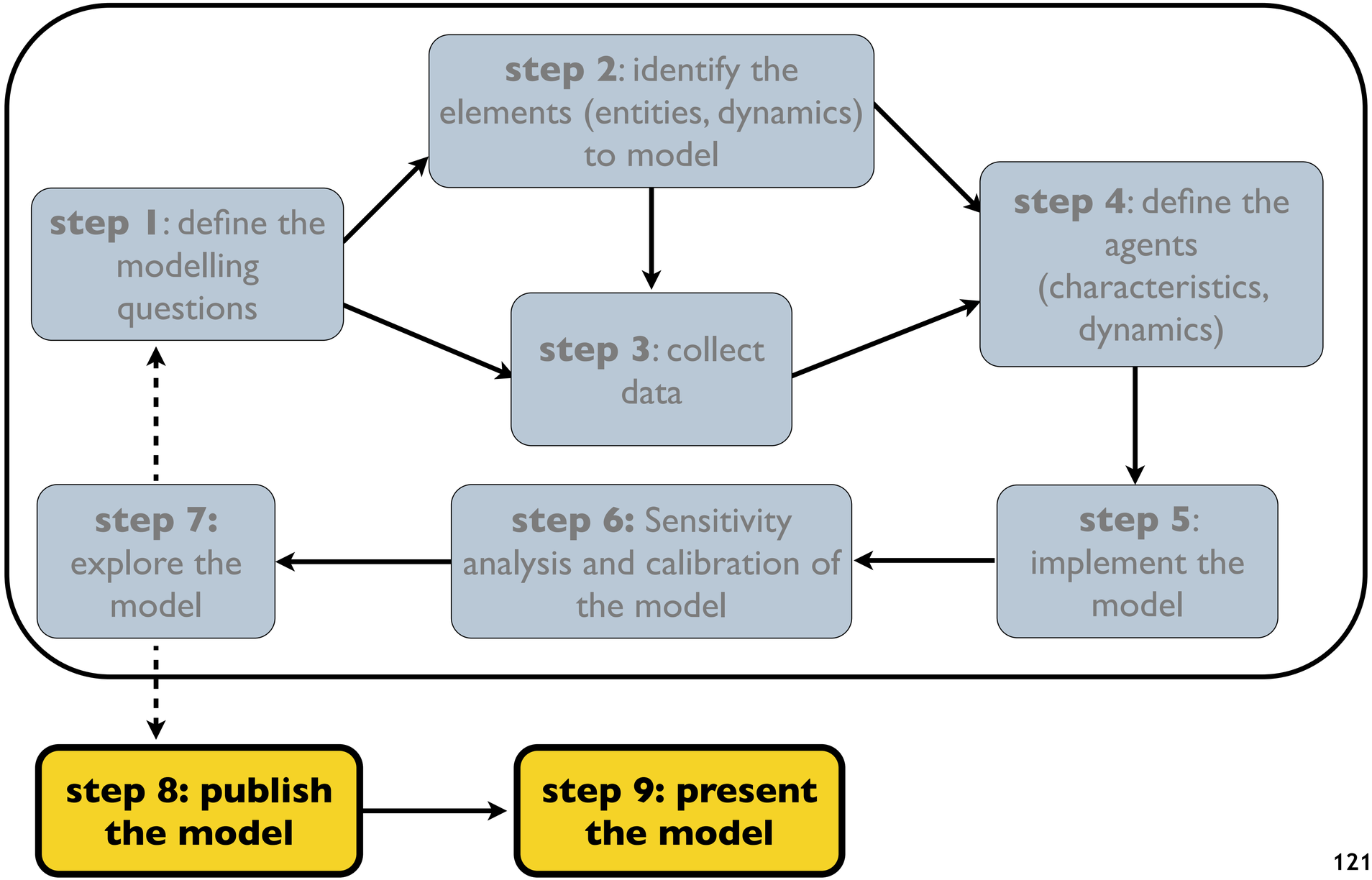
What-If water channels are improved ?

??????????

Modeling can be useful:
- to build Decision-Support Systems (DSS)
-> to help urban planning.

[Konings, 2012]

Modelling is a multi-step cycle.

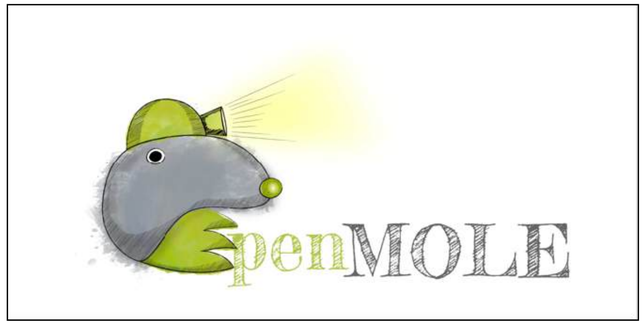


Description and publication of ABM: Status in 2000's

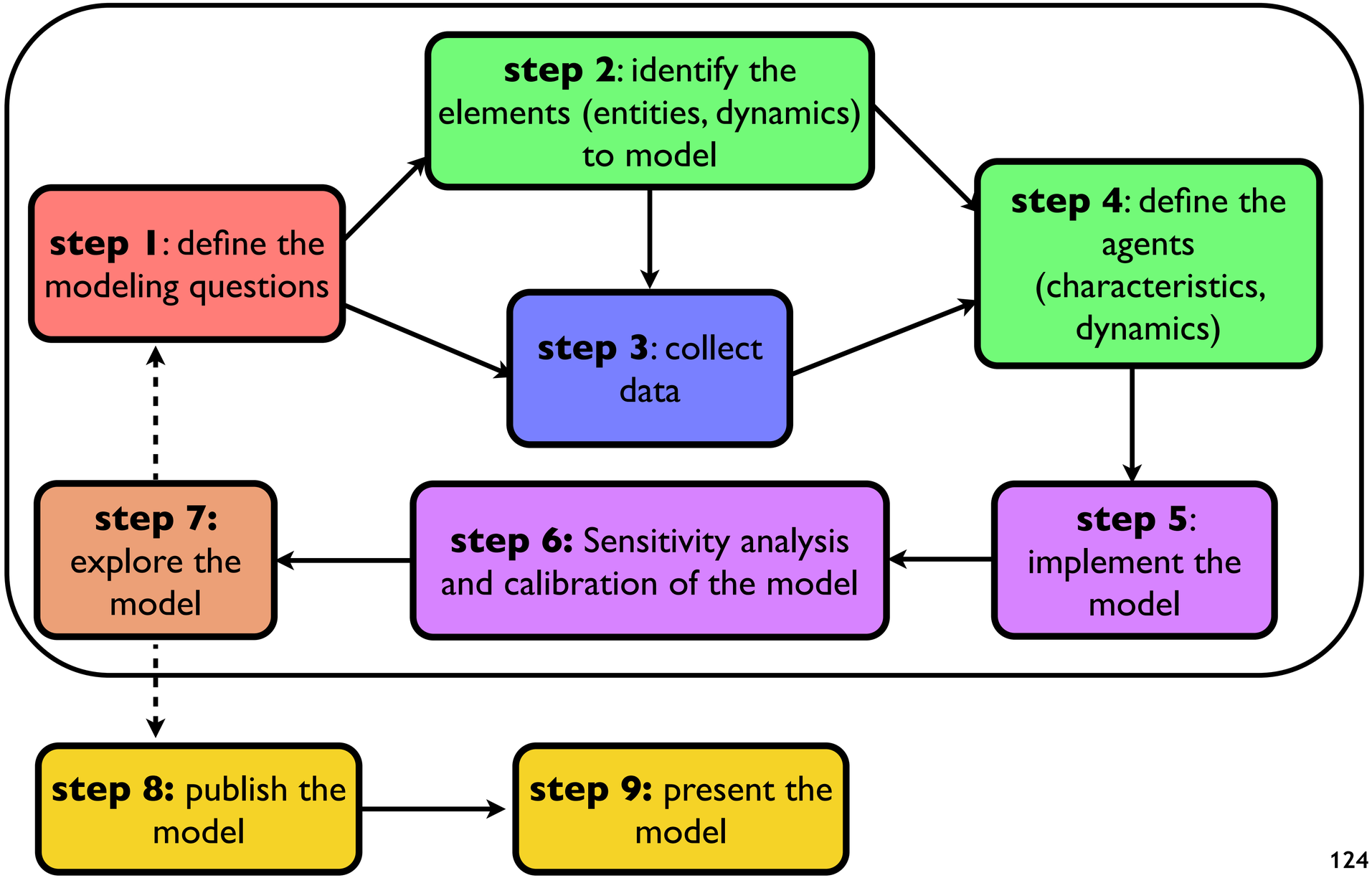
- ABMs description very variable
- UML descriptions not used/understood by everybody
- Specially in ecology: lots of ABMs not considered as "real science" because not reproducible

➡ Need of a description protocol for reproducibility and reliability

Tools box for modeling and simulation



Modelling is a multi-step cycle.



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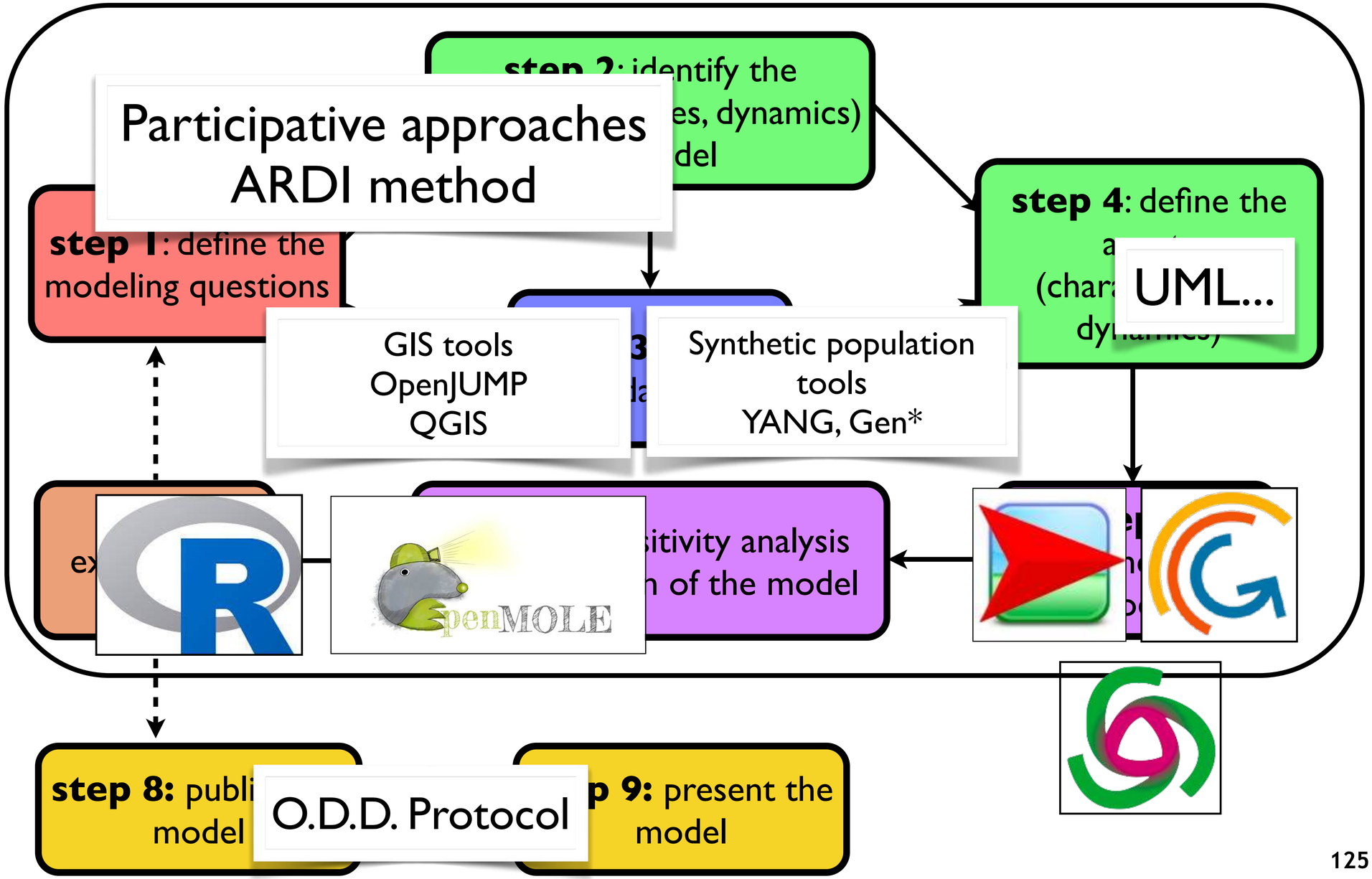

Example of a participative modeling workshop

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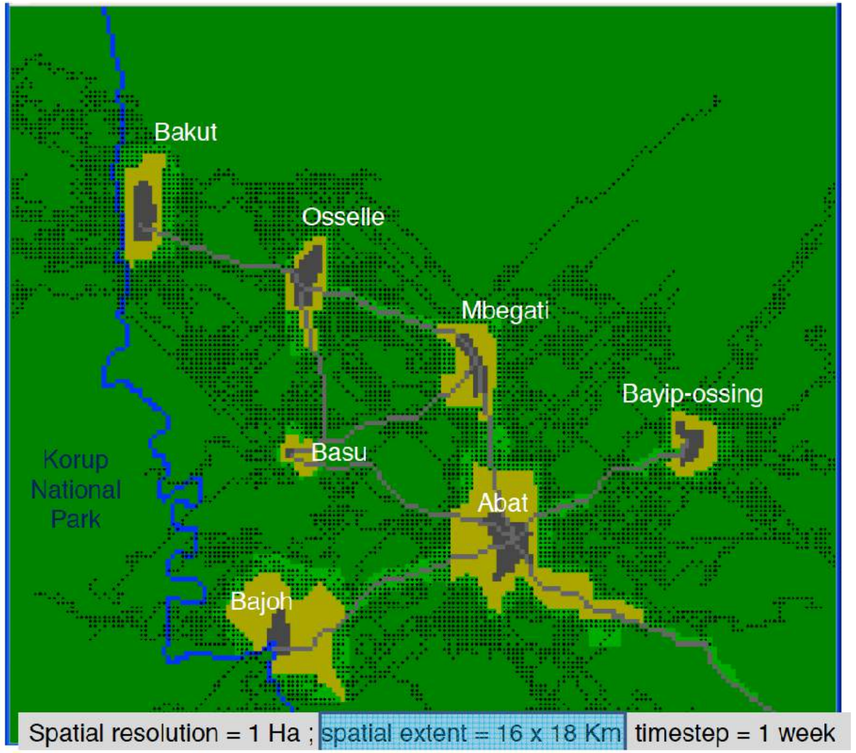
Example of a participative modeling workshop



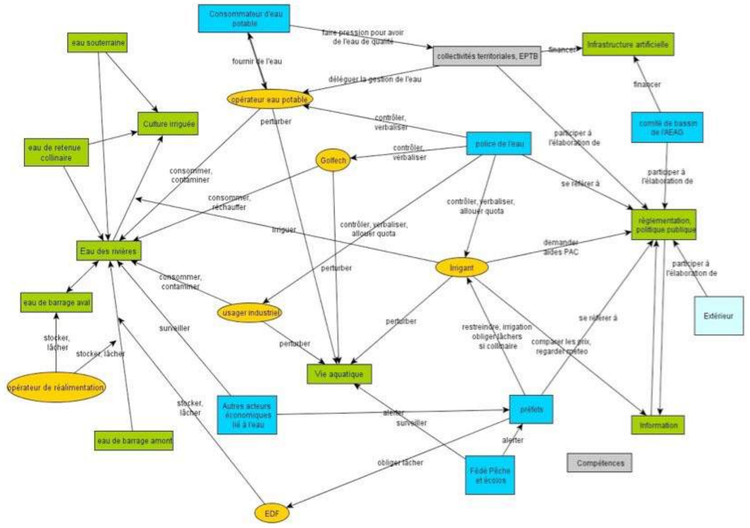
The ARDI method

A methodology for co-design of a conceptual model of socio-environmental interactions in a socio-ecological system.

From identification of a problem…

… to a question

Actors
Resources
Dynamics
Interactions



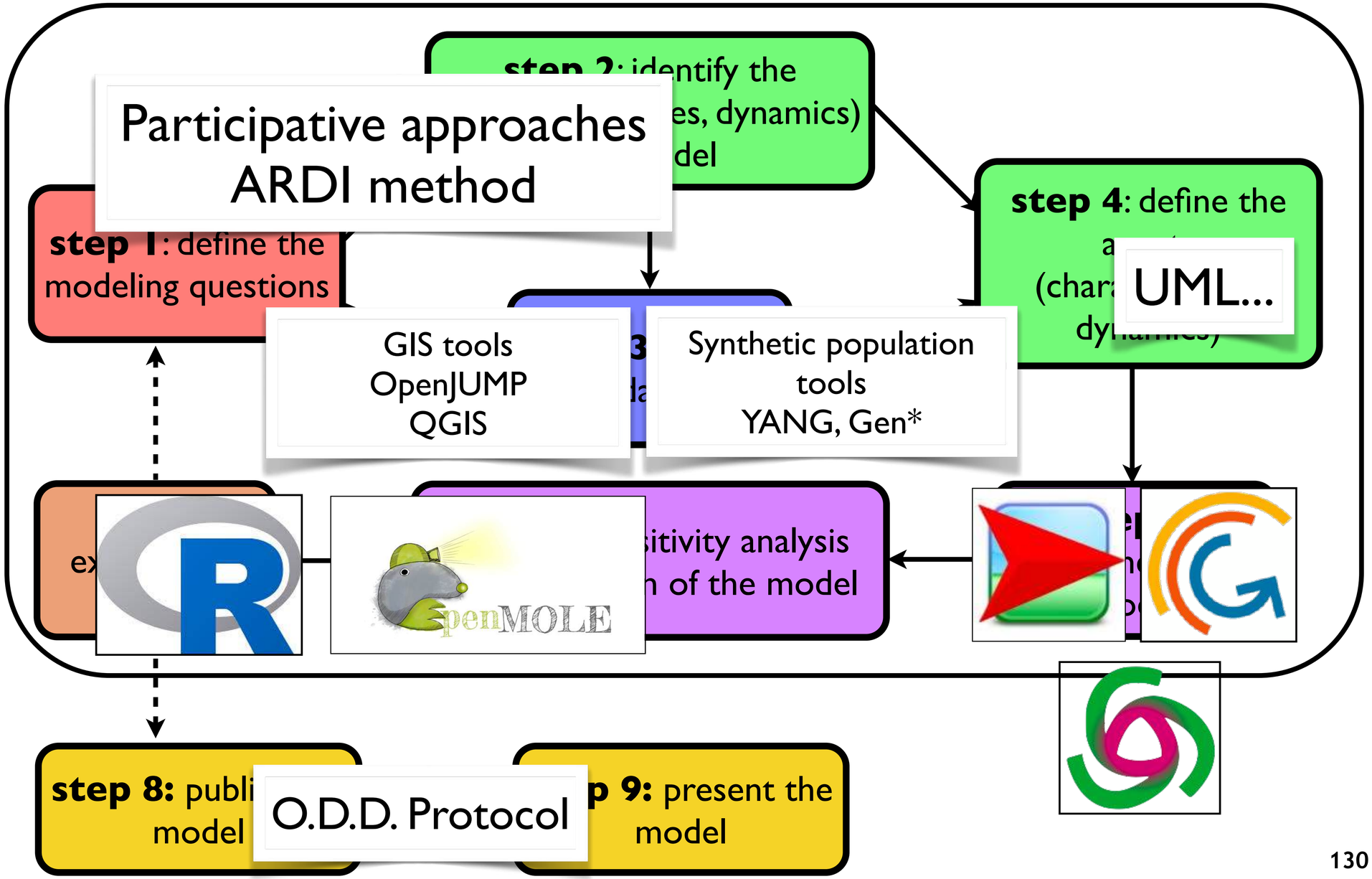
Co-construction of a shared representation in 4 steps

A = Actors
R = Ressources
D = Dynamics/ processes
I = Interactions

Each step corresponds to a particular kind of question.
[Example on a case study of studying Adour-Garonne water basin]

1. Who are the main actors who interact with the river and its flow?
2. What are the resources in relation to the debit?
3. What are the main processes occurring in the Adour-Garonne basin and affecting the flow of water?
4. How each actor uses the resource

Modelling is a multi-step cycle.

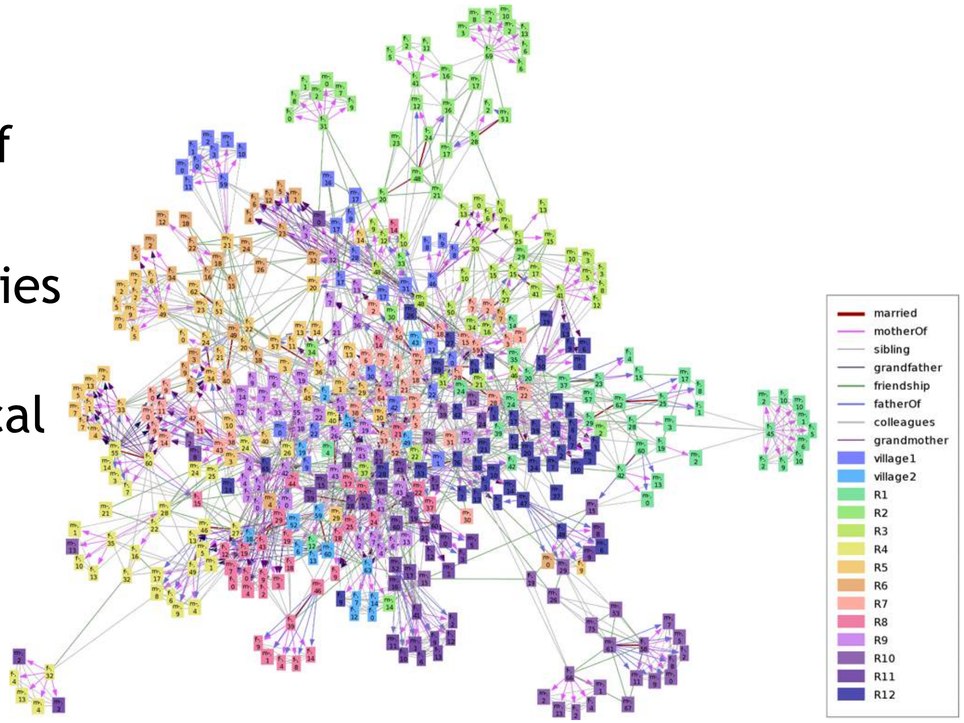


Yang : Yet Another Network Generator

YANG (Yet Another Network Generator) is a tool dedicated to generate plausible synthetic networks from local rules.

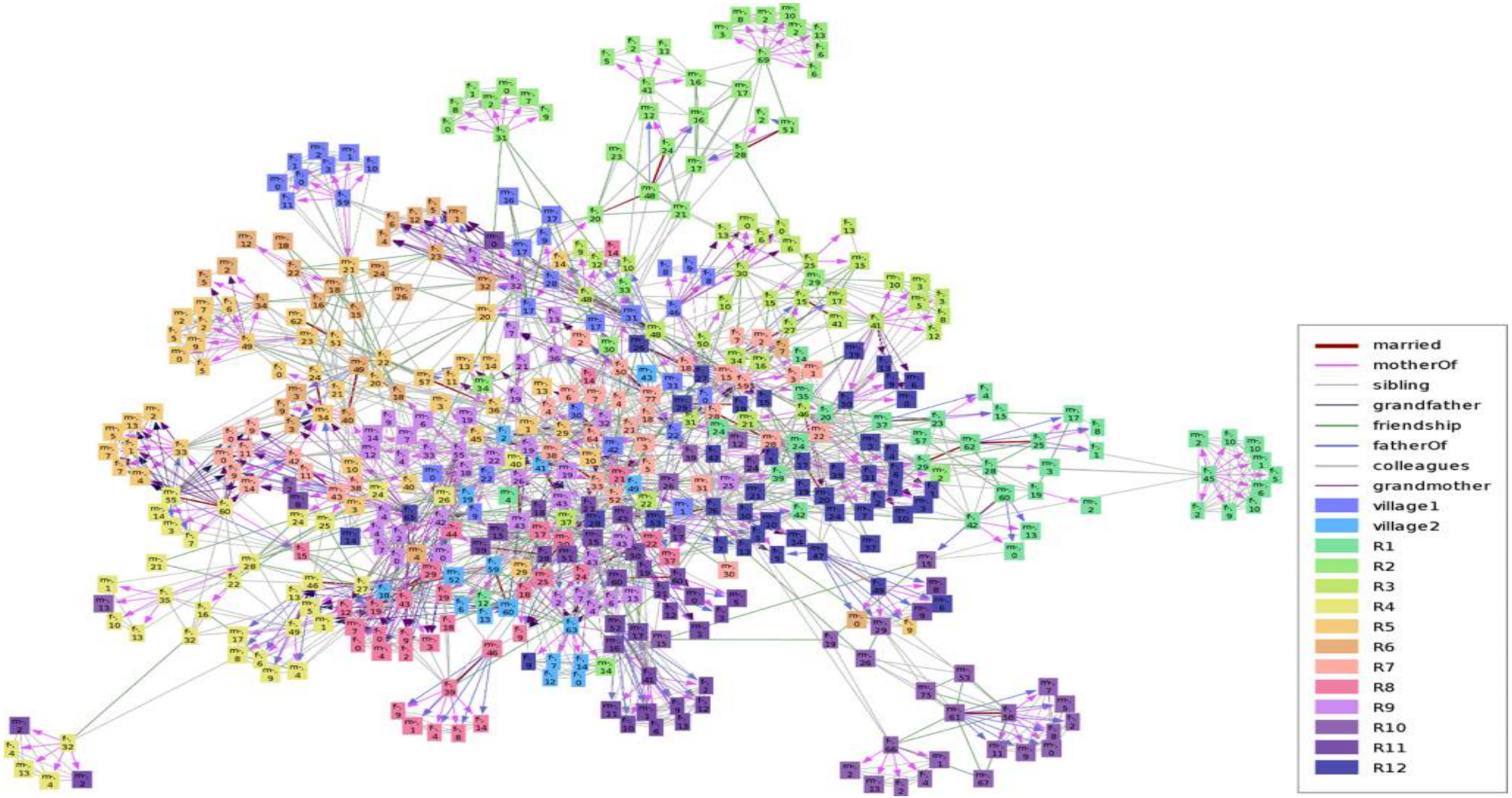
It has been applied to the generation of

- social networks in Kenya,
- social networks of economic solidarities on the island of Mayotte,
- a neural network from neuro-biological studies.



Yang : http://sourceforge.net/projects/yang-j/

Yang : example of generated network on the case study of Kenya.

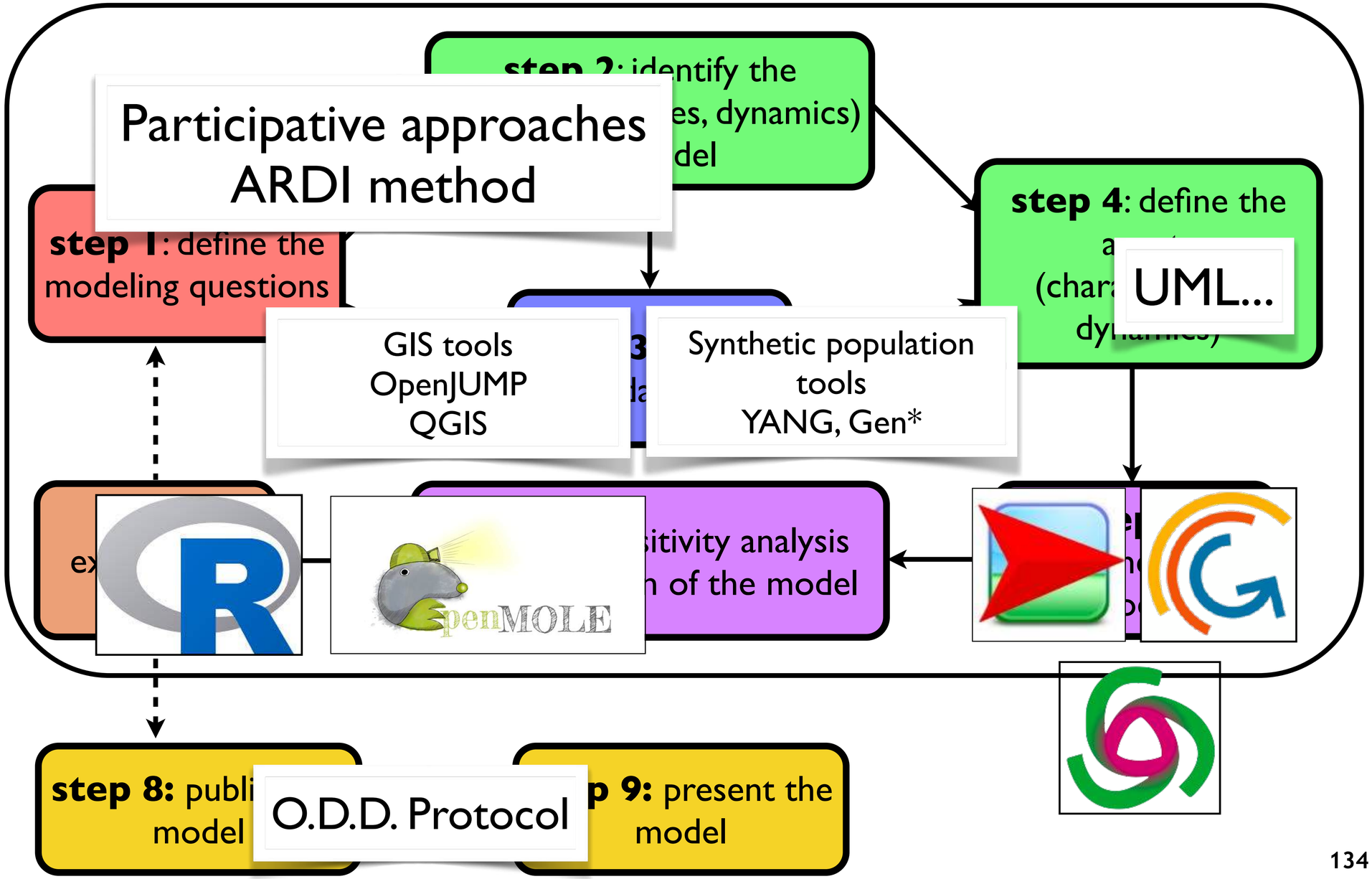


Synthetic population generation: the GEN* project

- Generation of **synthetic population** from aggregated data to feed agent-based simulations.
  - individual characteristics
  - localisation
  - social structure

GEN* Project
(PI: A. Drogoul, 2014-18)

Modelling is a multi-step cycle.

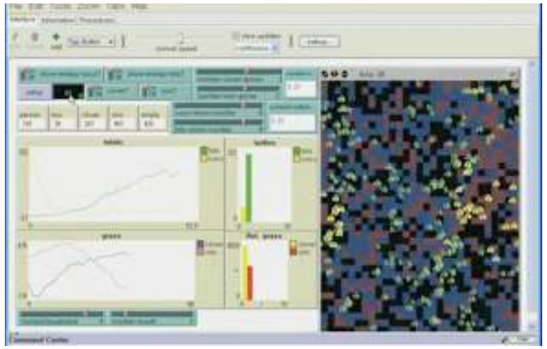


Models can be implemented and simulated using any generic programming language, but also with some dedicated (open-source) platforms.

NetLogo

http://ccl.northwestern.edu/netlogo/

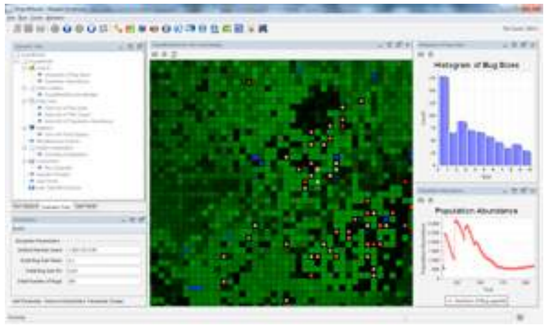
Pedagogical tool with a specific modeling language. Numerous examples in various domains. **Ideal for beginners and prototypes, but somehow limited for large models.**



Repast Simphony

http://repast.sourceforge.net/

Toolbox for agent-based modeling in Java, numerous libraries of connected technologies (statistical analysis, GIS, 3D models, etc.). **Very powerful but requires very good programming skills.**

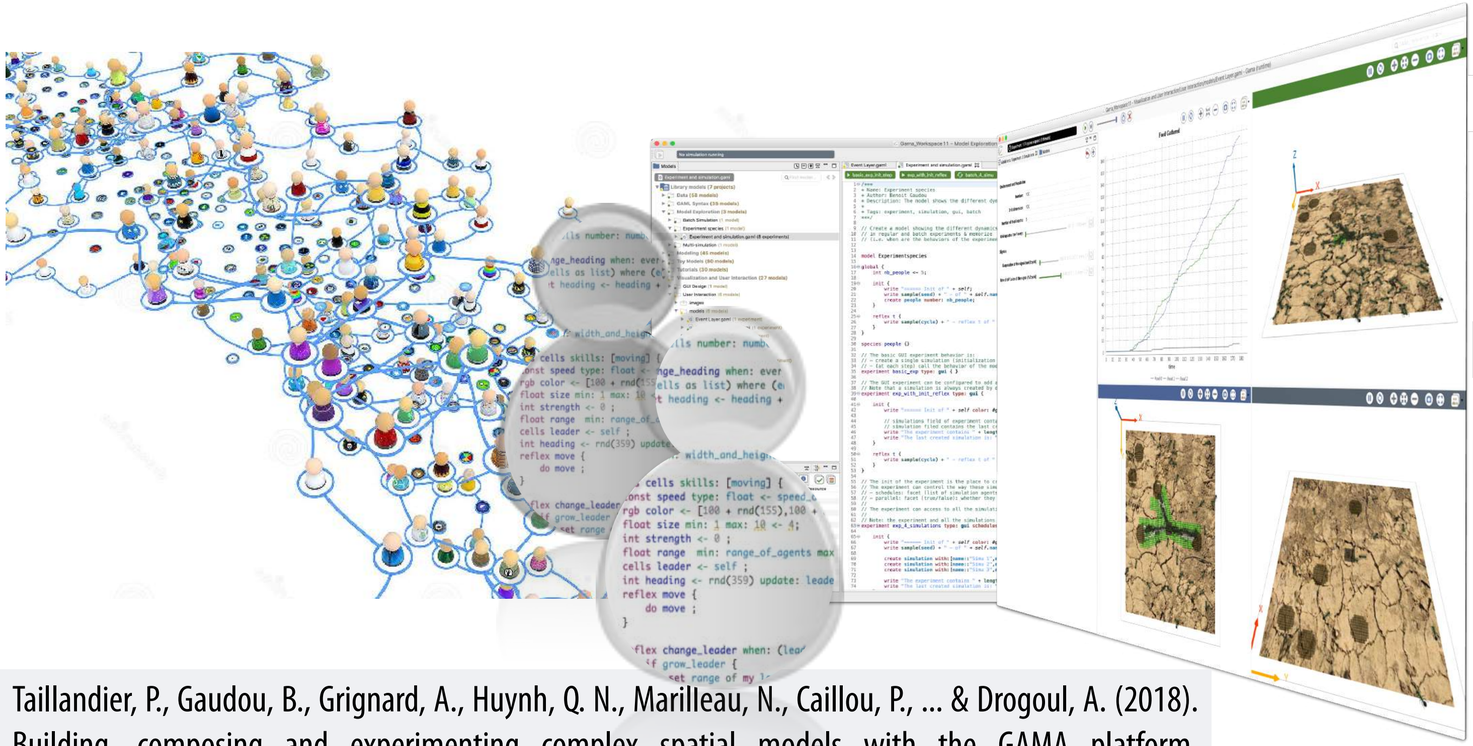


GAMA

http://gama-platform.org

A compromise between the two platforms above. Using a dedicated modeling language, this platform pays a great deal of attention to the modeling of the environment and the use of GIS data, while staying open to new technologies through plug-ins.

GAMA HAS THE ADVANTAGE OF BEING ABLE TO INPUT COMPLEX DATASETS (GIS DATA, QUALITATIVE AND QUANTITATIVE SURVEYS, DEMOGRAPHICAL AND STATISTICAL DATA...)



Taillandier, P., Gaudou, B., Grignard, A., Huynh, Q. N., Marilleau, N., Caillou, P., ... & Drogoul, A. (2018). Building, composing and experimenting complex spatial models with the GAMA platform. GeoInformatica, 1-24.

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Huynh Quang Nghi,
Nguyen Ngoc Doanh

http://gama-platform.org

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- Netlogo : http://ccl.northwestern.edu/netlogo/
- Cormas: http://cormas.cirad.fr/

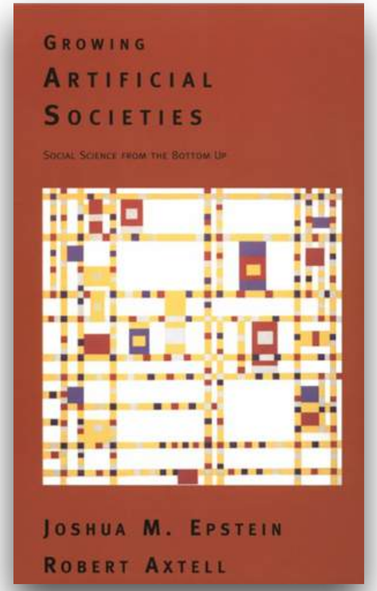
- ARDI method: http://cormas.cirad.fr/pdf/guideARDI.pdf

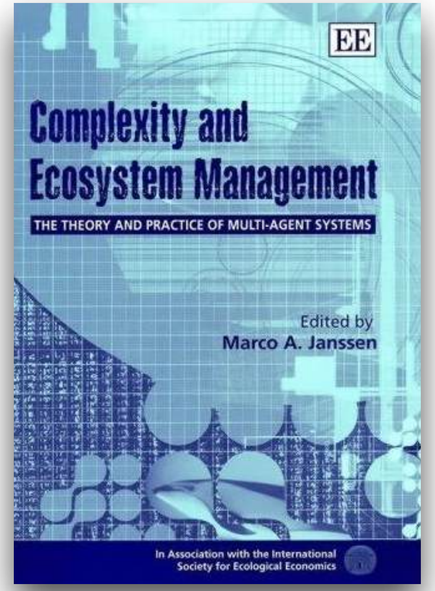
- Yang : http://sourceforge.net/projects/yang-j/

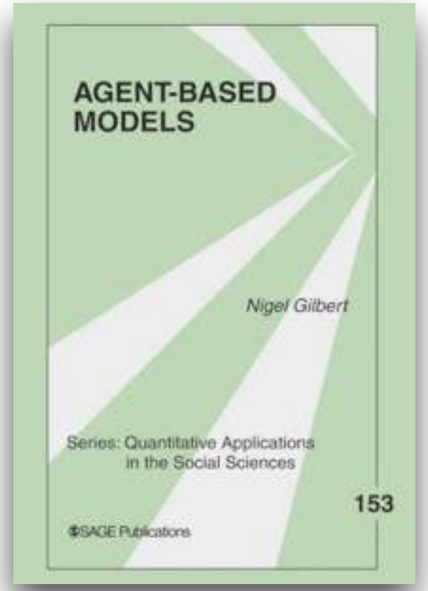
- SIG: OpenJUMP : http://www.openjump.org/
- SIG : QGIS : http://www.qgis.org/

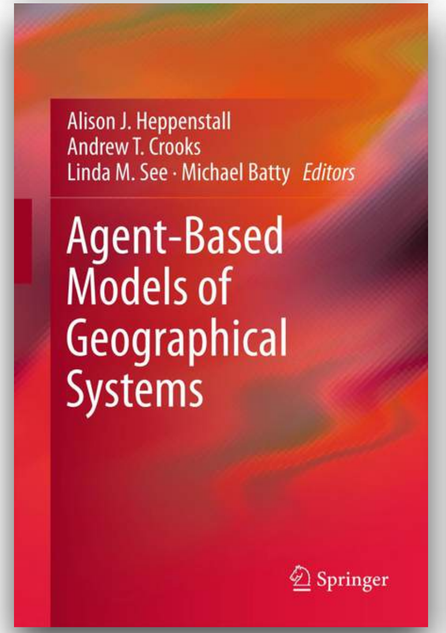
- Gephi : http://gephi.org/
- OpenMole : http://www.openmole.org/

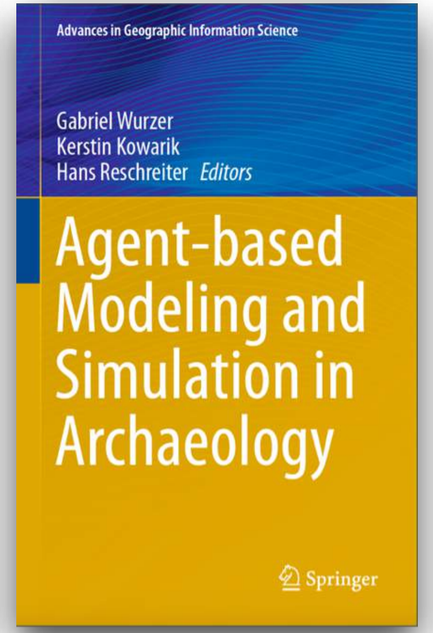
References: some books

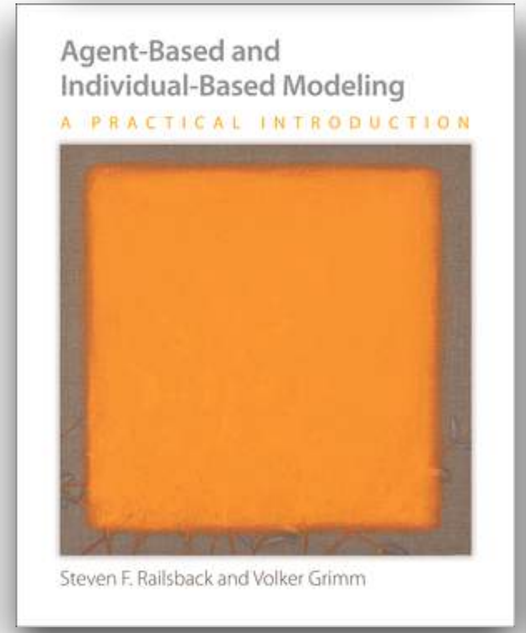


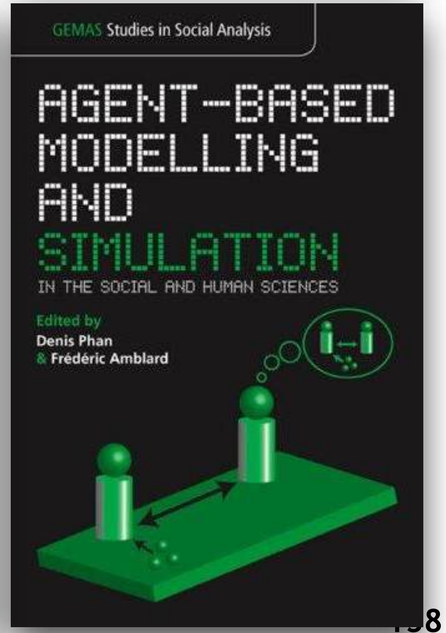












Slide by Alexis Drogoul