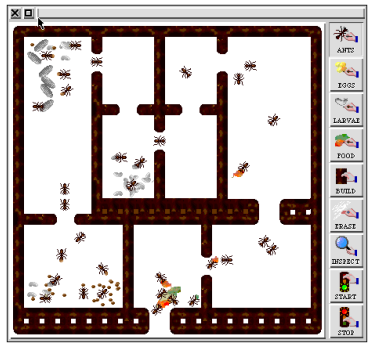
Simulating sustainability

Challenges and opportunities in open-source agent-based platforms for supporting transdisciplinary approaches

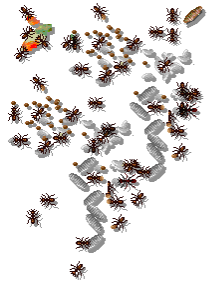
http://across-lab.org

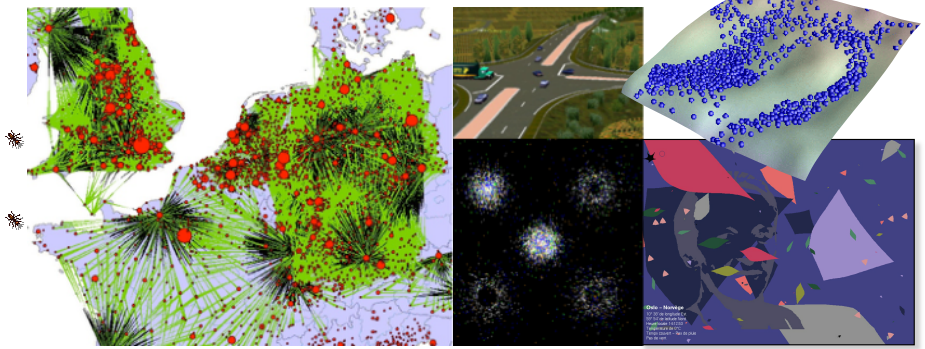
Alexis Drogoul, IRD — SIMULTECH 2024

Early career was devoted to Artificial Life, i.e. building a virtuous circle between agent-based simulation, collective robotics and AI

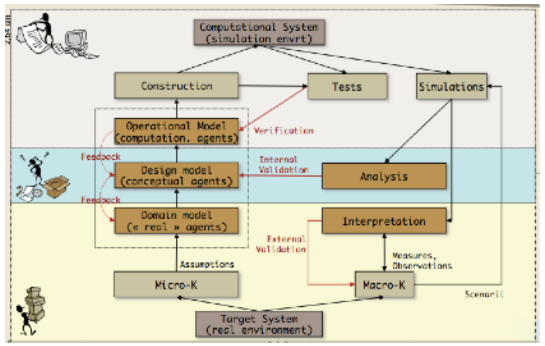


Manta (Agent-Based Modeling)





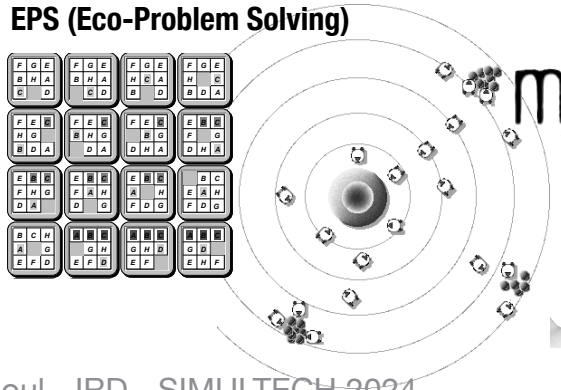
SimPop2, Archisim, Garden of Chances, Rivages…



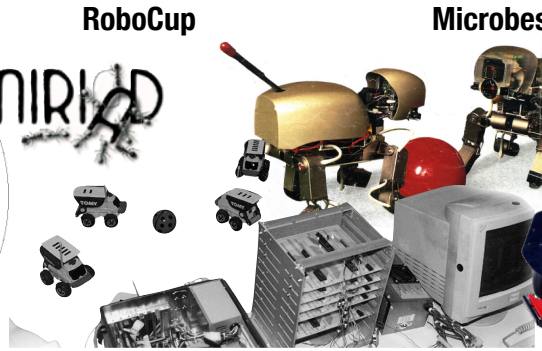
Agent-Based Meta-Modeling

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



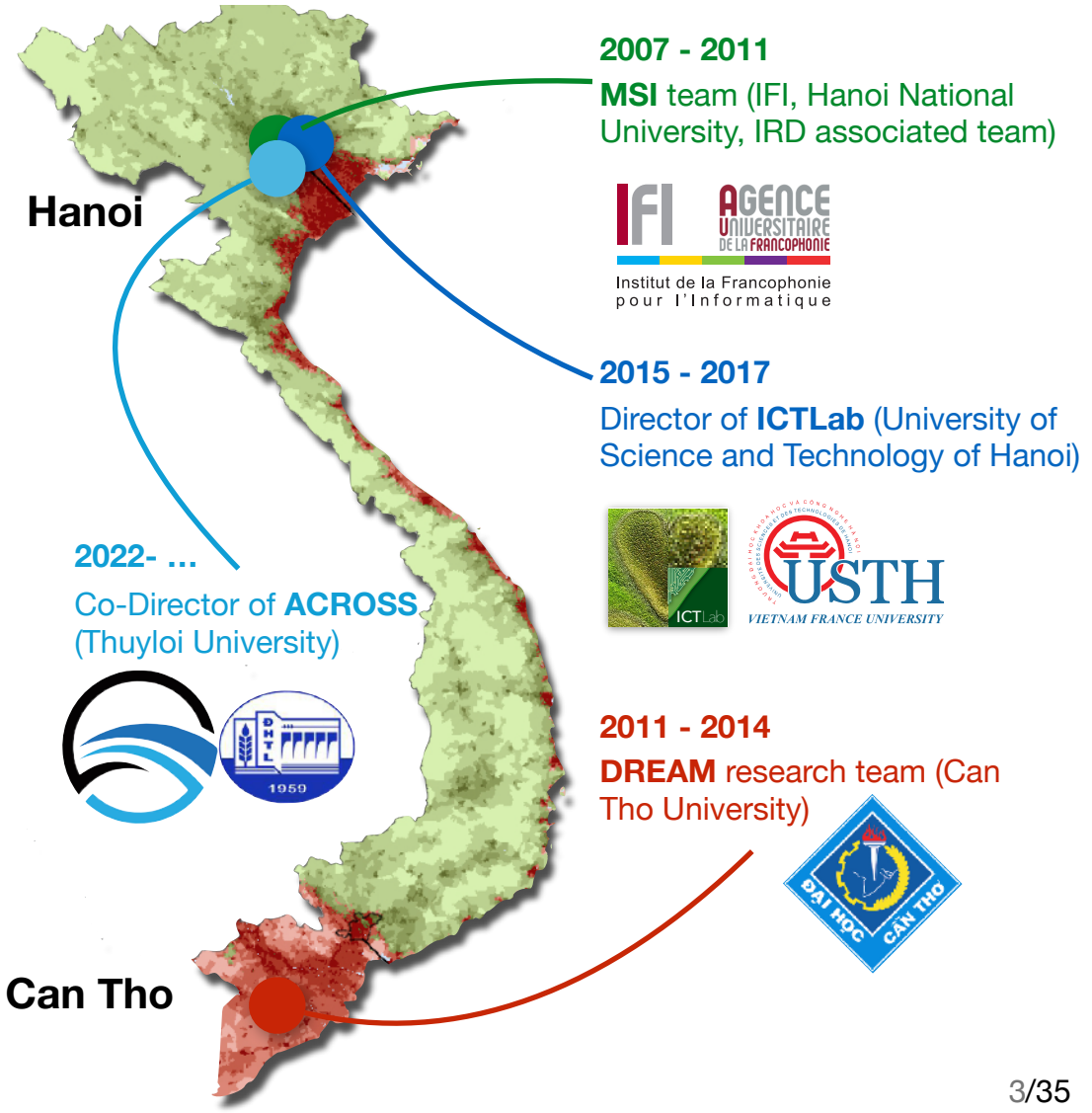
Microbes Social Robots

ComMod (Participatory Simulations)

I moved in 2005 to IRD, for which I have been working in Vietnam since 2007.

- As the head of 4 joint research teams (MSI, ICTLab, DREAM, ACROSS)
- As the designer of the GAMA modelling and simulation platform
- As the deputy director of the maths/computer science team UMMISCO hosted by Sorbonne Université

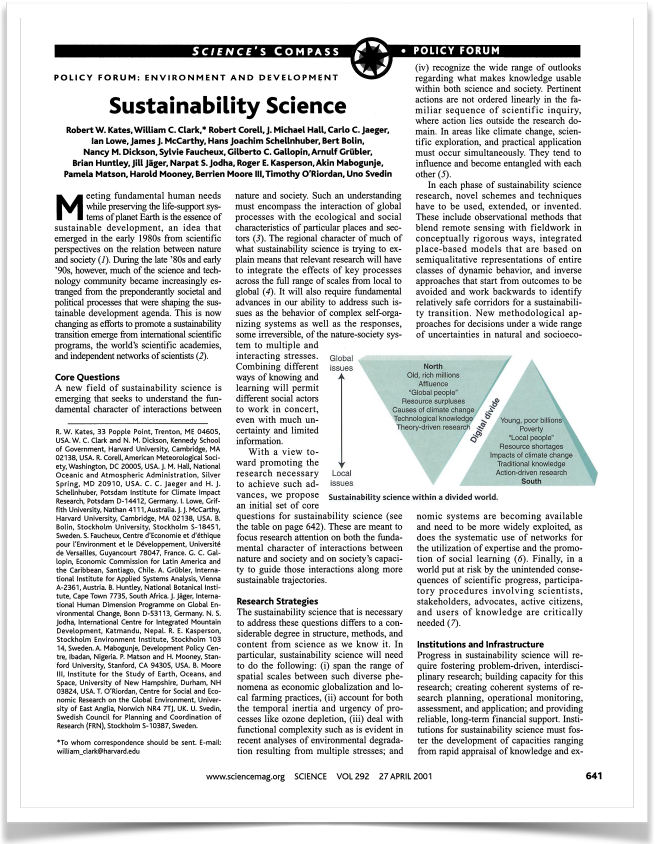
UMMISCO
Unite Mixte Internationale



IRD is a French public institute that undertakes research & capacity building activities in sustainability science

- 75 research units (jointly with other institutions)
- 77 International laboratories (in partner countries)
- 850 researchers (60% abroad) and a community of 7000 researchers
- Over 2000 publications/year, 60% in co-publication with partners

”Sustainability science” was 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.

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-10451, Sweden. S. Faucheux, Centre d'Economie et d'éthique 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.

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Sustainability science within a divided world.

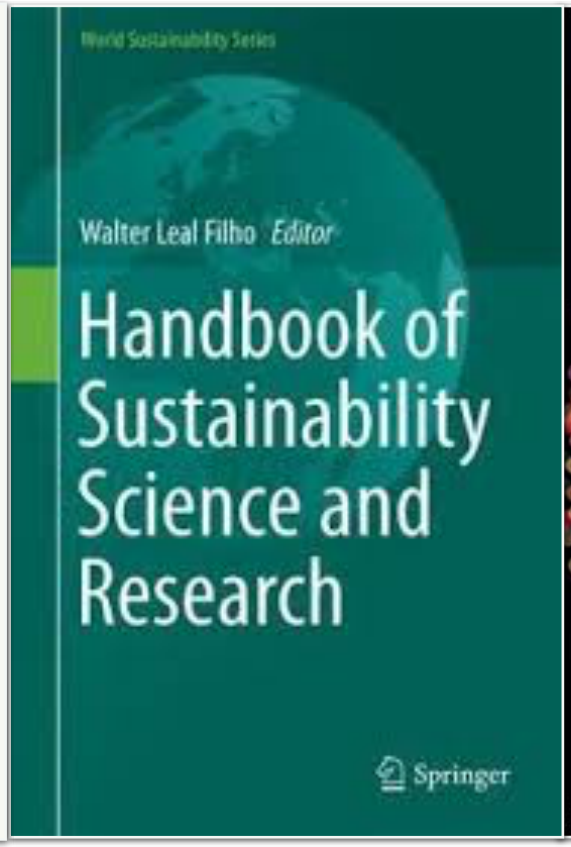
Research Strategies

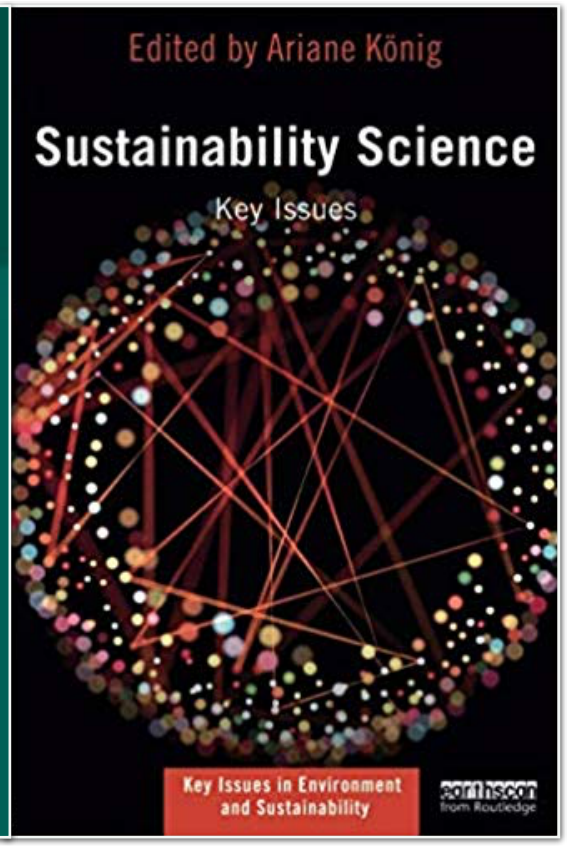
The sustainability science that is necessary to address these questions differs to a considerable degree in structure, methods, and content from science as we know it. In particular, sustainability science will need to do the following: (i) span the range of spatial scales between such diverse phenomena 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-





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

Sustainability science is an interdisciplinary research domain seeking to facilitate the design of interventions that foster shared prosperity and reduced poverty while protecting the environment

Sustainability science is **science about sustainability**, to understand how complex physical, biological and social systems function; and it is **science for sustainability**, to support sustainable policies and positive social transformations.
***UNESCO**, Sept. 2023*

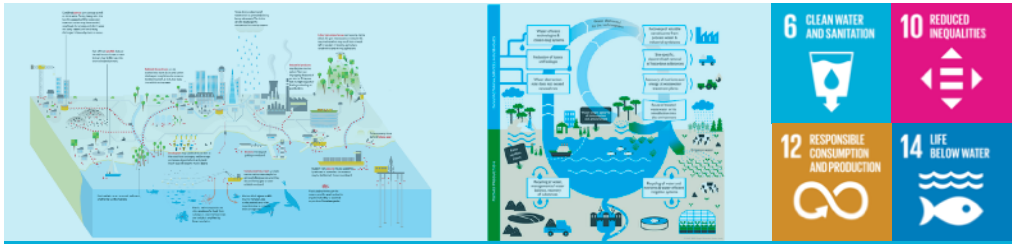
https://www.unesco.org/fr/management-social-transformations-most-programme/sustainability

https://sdgs.un.org/gsdr/gsdr2023

It is characterised by the use of **transdisciplinary methodologies**, [based] on the co-construction of knowledge and know-how, based on collaboration between scientists from different disciplines and non-academic players, in a participatory and committed approach.
***IRD**, June 2020*

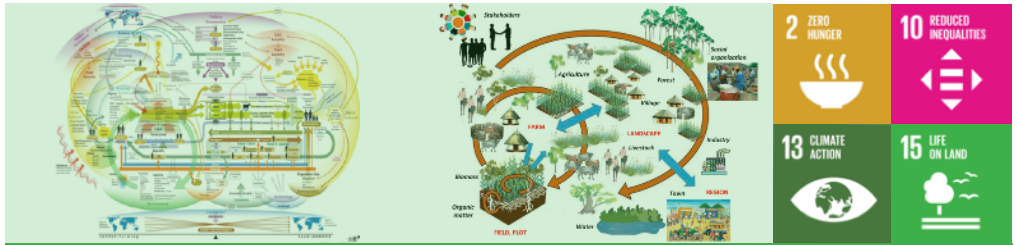
https://www.ird.fr/en/sciencedeladurabilité

The problems tackled by sustainability science are therefore characterised by the concomitant objectives of understanding and decision support, as well as by attention to stakeholder participation.



Improve the efficiency of water use, combat water pollution and ensure sustainable use of and equitable access to water resources.

Pham Van, C., & Nguyen-Ngoc, D. (2022). Multiple linear regression and long short-term memory for evaluating water levels in irrigation and drainage systems: an application in the Bac Hung Hai irrigation and drainage system. Water Supply, 22(12), 8587-8602.

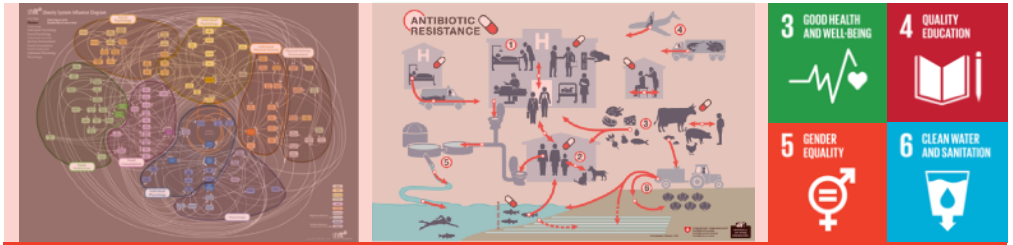


Design agricultural practices to help mitigate climate change and adapt to its impacts, preserve ecosystems and ensure equitable access to nutritious food.

Traore Cheick Amed Diloma Gabriel, Delay Etienne, Diop Djibril, Bah Alassane. 2024. Sahelian transhumance simulator (STS). Software Impacts, 19:100627, 4 p. https://doi.org/10.1016/j.simpa.2024.100627

Build sustainable cities and communities by reducing inequalities and waste production, promoting clean modes of transport and a more circular economy

A Laatabi et al., Assessing Public Transport Strategies in Marrakesh using ABMS, in The 15th International Conference on Ambient Systems, Networks and Technologies (ANT), Procedia Computer Science, 2024



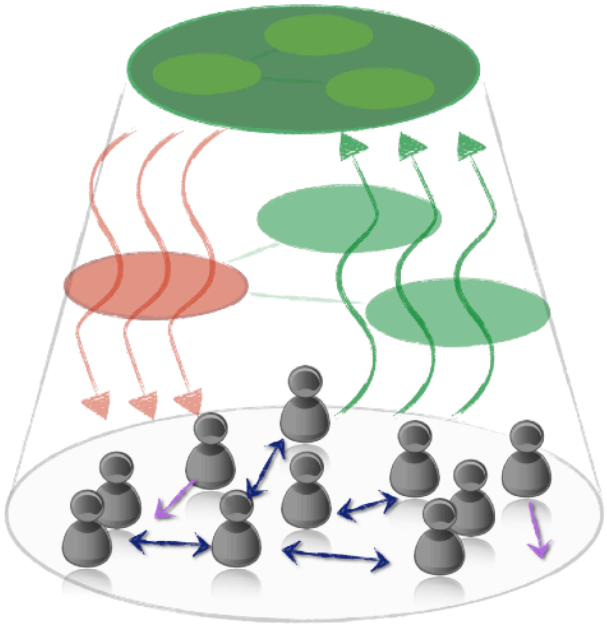
Anticipate pandemics by understanding the interactions between environmental, human and animal health, improving diagnostic tools and inventing new treatments

J. Azanzi, H. Tapamo, G. Camara, Combining Scrum and Model Driven Architecture for the development of an epidemiological surveillance software, Revue Africaine de Recherche en Informatique et Mathématiques Appliquées, 2023,

However, understanding, decision-making and participation come up against the complexity of the systems studied

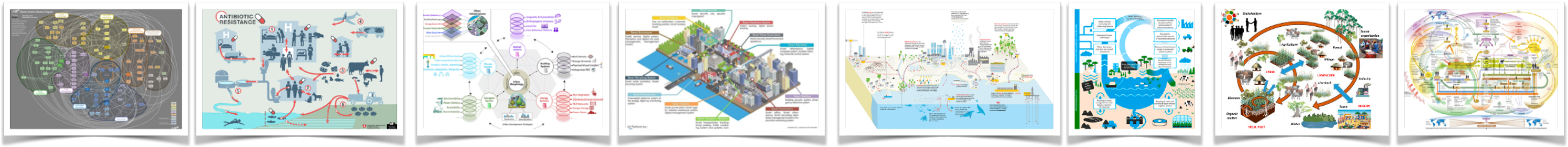
Multiple components, players, interests, points of view, scales of analysis depending on the issue.

Evolution dependent on the **self-organisation** of components and **non-linear interactions** between them.



Emergence of collective structures and behaviours that cannot be deduced from the individual properties of components

Dynamic adaptation and changes of state, with no predefined plan or scheme



Hedelin, B. Complexity is no excuse. Sustainability Science 14, 733–749 (2019). https://doi.org/10.1007/s11625-018-0635-5

We need to offer tools and methods that support interdisciplinarity, different scales and viewpoints in order to:

1

Improve understanding of the emerging dynamics of the systems studied,

Explore trajectories and scenarios of development of these systems,

2

Anticipate the impact of policies or interventions on their development,

Support public decision-making on sustainable development,

3

Provide platforms for interdisciplinary experimentation, collaboration and creativity,

Provide mediation and negotiation tools to the stakeholders concerned.

Which methods ? Which tools ? Let's start with a quiz !

Final resolution of COP28 in 2023 ?

We recognize that a world equilibrium can become a reality only if the lot of the so-called developing countries is substantially improved (…). We affirm that the global issue of development is (…) closely interlinked with other global issues (…), including in particular those of man's relationship with his environment.

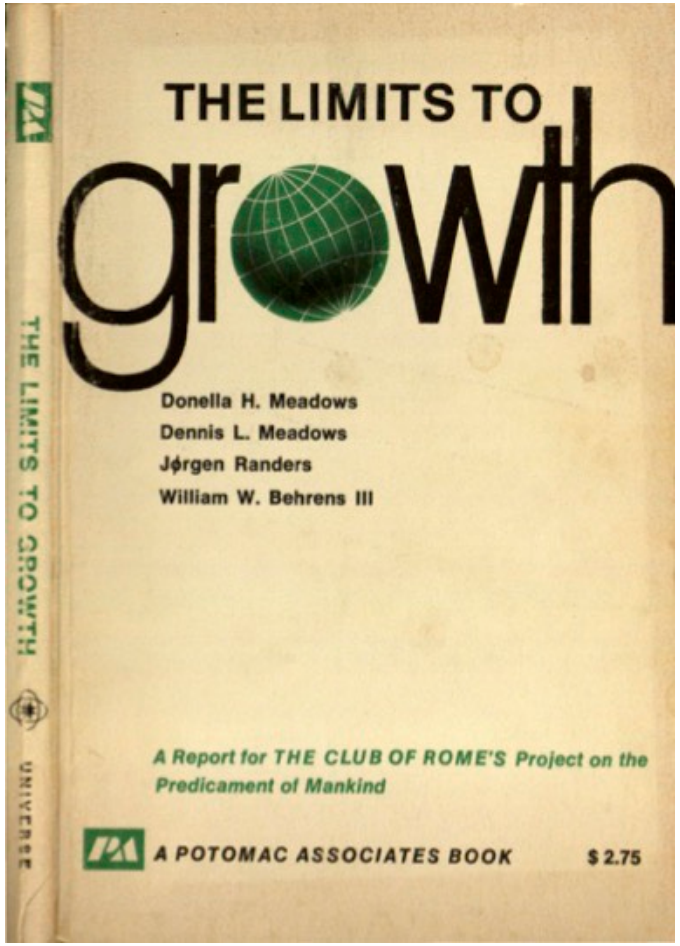
Presentation of SDGs by the UN in 2015 ?

We are unanimously convinced that rapid, radical redressment of the present unsatisfactory and dangerously deteriorating world situation is the primary task facing humanity. (…) This supreme effort is a challenge for our generation. It cannot be passed on to the next. The effort must be resolutely undertaken without delay, and significant redirection must be achieved during this decade.

Last IPCC report in 2023 ?

”Limits to Growth” / ”Meadows’ report” in 1972

- Commissioned from MIT by the Club of Rome in 1970, published in 1972
- Realisation of the unsustainability of exponential growth in a finite environment by linking :
  - accelerating industrialisation ;
  - strong growth in the world's population ;
  - persistent global malnutrition ;
  - depletion of non-renewable natural resources;
  - environmental degradation.
- **First (public) references to concepts such as sustainable development, ecological footprint (or collapse)**

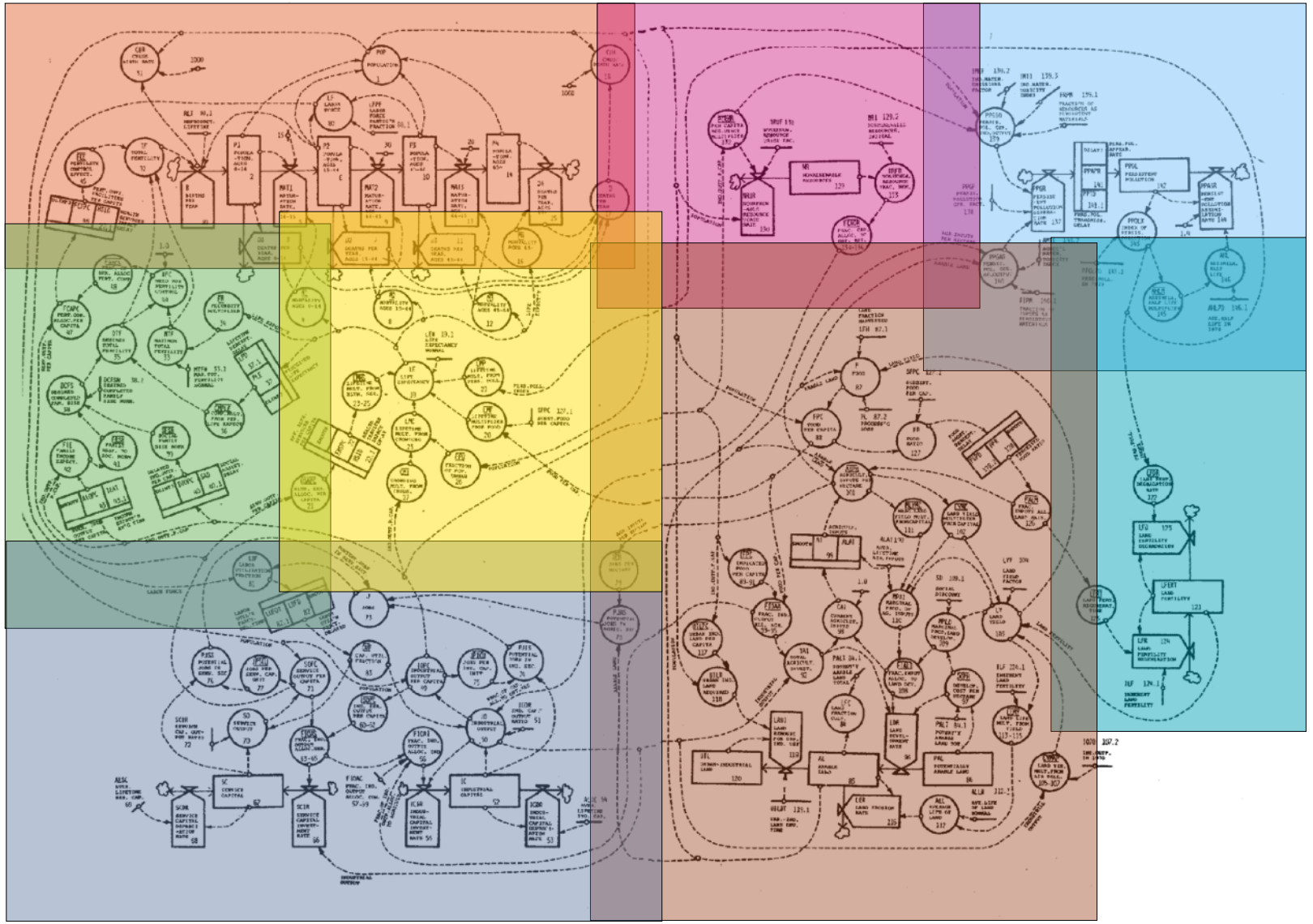


http://www.donellameadows.org

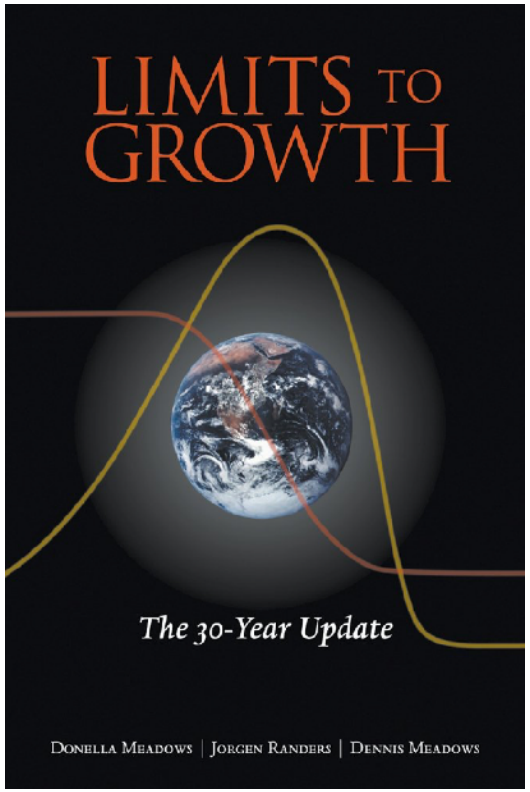
LTG is based on an interdisciplinary integrated model called World3

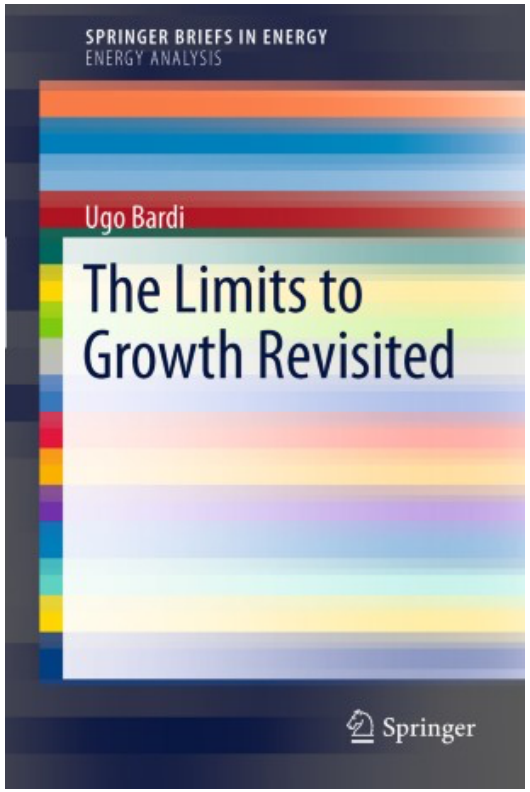
World3 is a set of interconnected thematic sub-models linked by non-linear feedback loops.

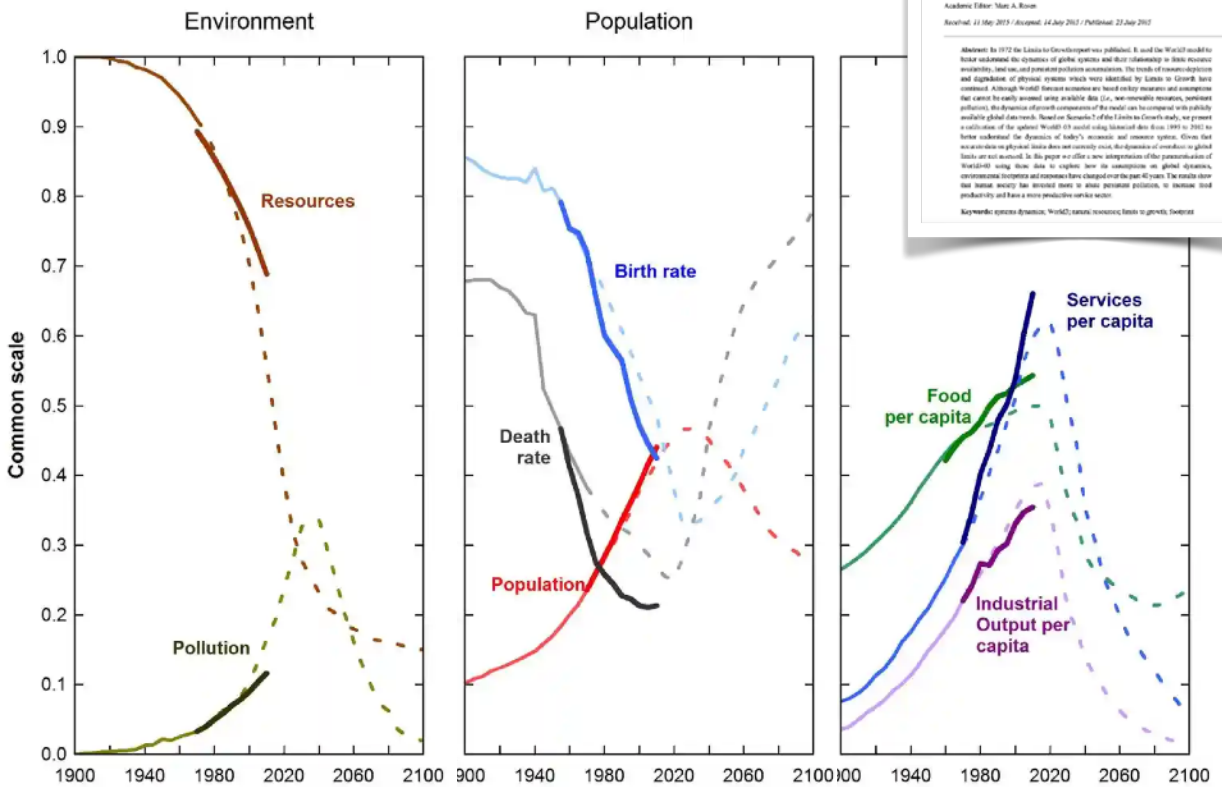
Open Modelica implementation available here:



LTG's merit: since 1972, the debate on "sustainability" is no longer based on intellectual posturing, but on the results of simulations of models available to everyone.

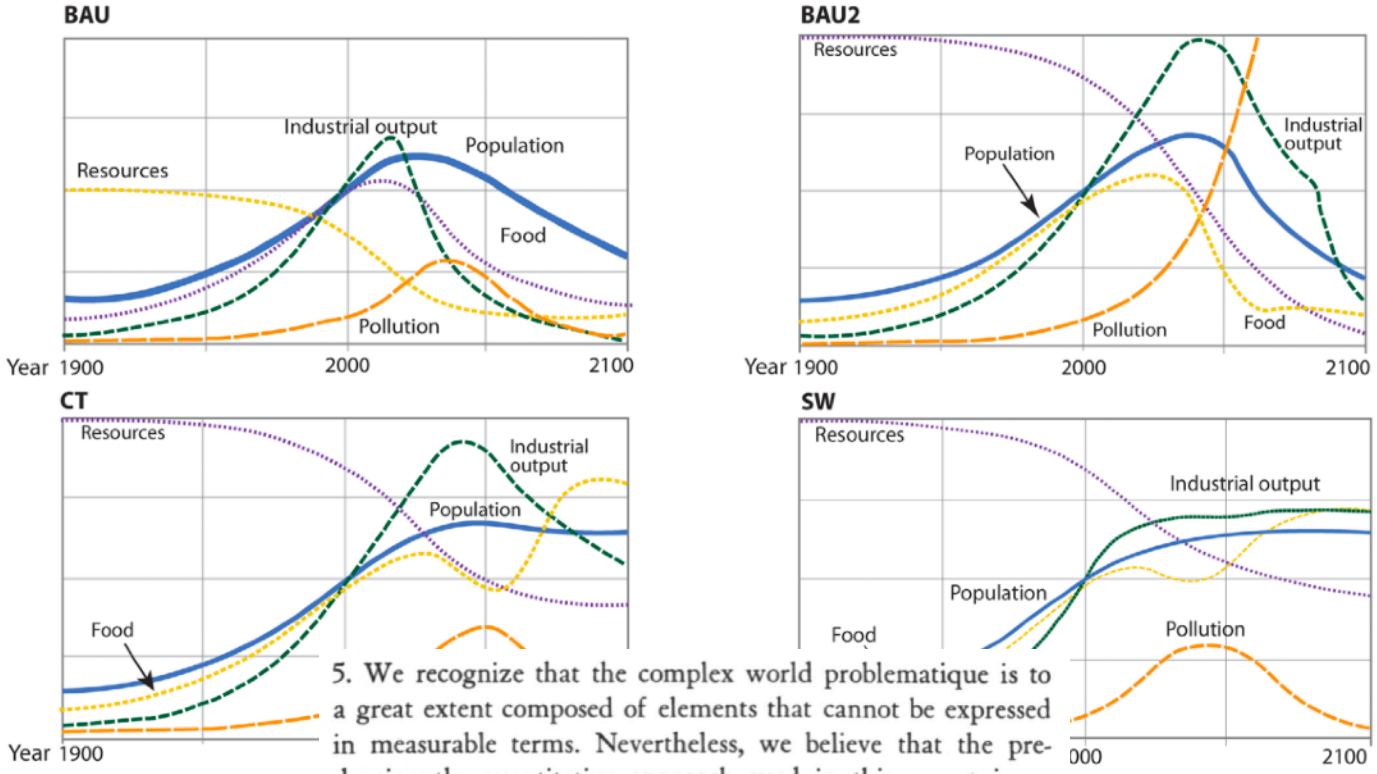






However, if World3 is helpful in identifying different scenarios it cannot support decision-making

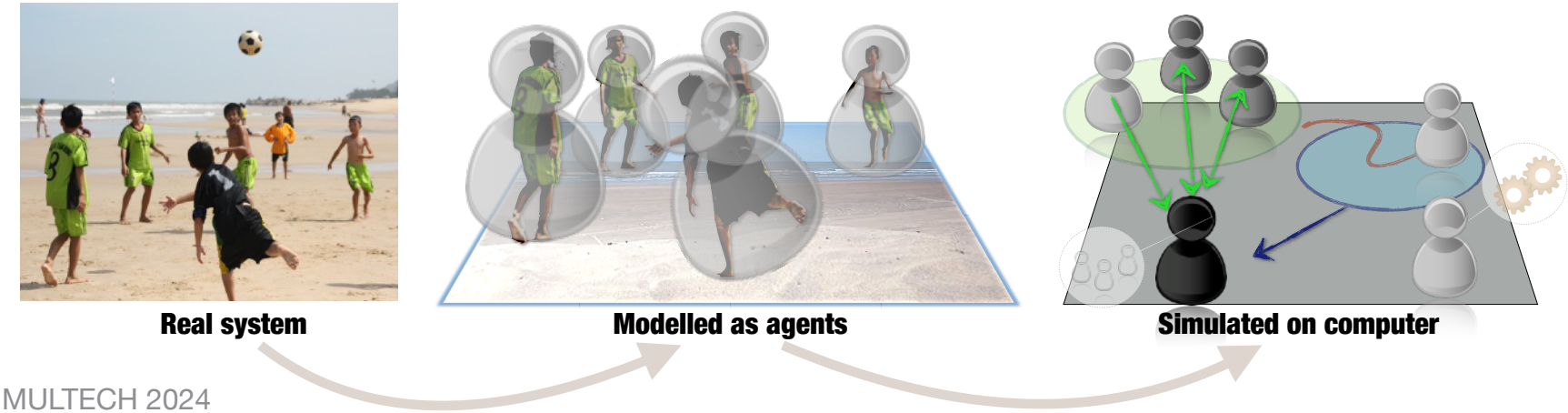
- The role of World3 is to raise awareness on global problems, not to represent and help formulate their (generally) local solutions
- If we want to have an impact, with models, on the design of sustainable solutions, **we need to embrace in models the various scales at which solutions can be formulated** and understand their effects



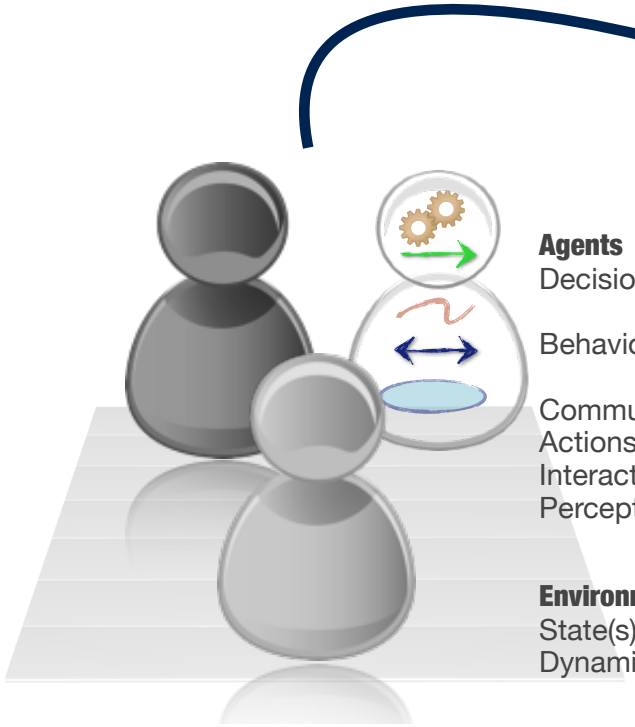
5. We recognize that the complex world problematique is to a great extent composed of elements that cannot be expressed in measurable terms. Nevertheless, we believe that the predominantly quantitative approach used in this report is an indispensable tool for understanding the operation of the problematique. And we hope that such knowledge can lead to a mastery of its elements.

One solution for addressing complex sustainability problems is to use Agent-Based Models (ABM) as a basis for integrated models

- **ABM is a versatile data-driven approach**: in addition to quantitative data one can incorporate qualitative data, e.g. rules, narratives, or social knowledge;
- **ABM is generative:** allows to explore ”what-if” scenarios and the emergence of properties in virtual worlds;
- **ABM is modular:** the ability to add or remove entities during simulations provides flexibility when building a model;
- **ABM is agnostic:** any formalism can be used to express the dynamics of agents, and different modelling approaches can coexist in the same model.
- **ABM accepts heterogeneity:** agents can represent any entity or aggregation of entities, at any time / space scales



ABM platforms like GAMA support building integrated models that combine multiple modelling paradigms, including physical models, and operate on real data



Agents
Decision-making

Behavior

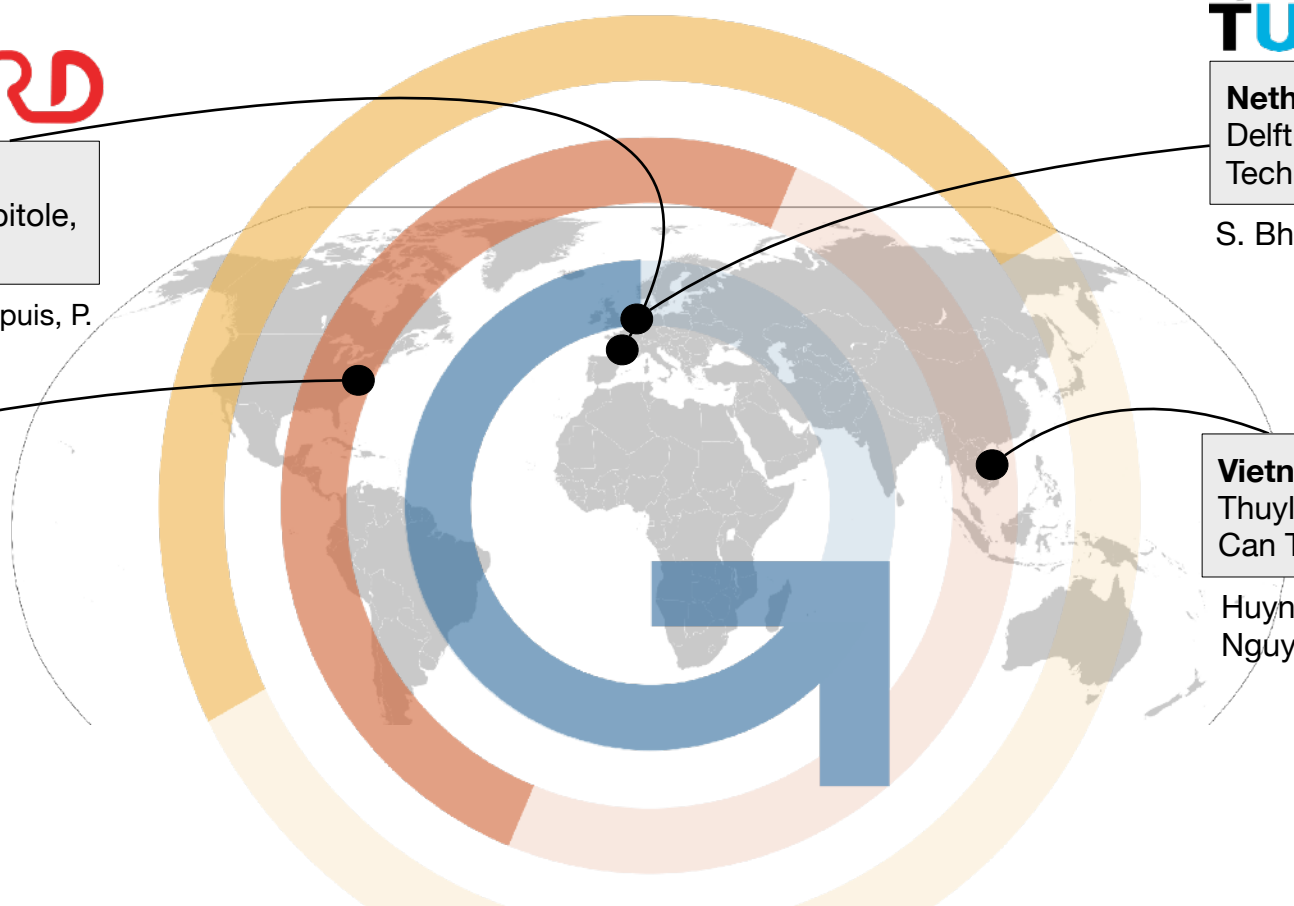
Communication
Actions
Interactions
Perception

Environment
State(s)
Dynamics

https://gama-platform.org

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.

GAMA is a free and open-source modelling and simulation platform created in Vietnam in 2007, developed since then by an international consortium



France
IRD (PI), CNRS, INRAE, University of Toulouse 1 Capitole, University of Paris Sud, University of Rouen

A. Drogoul, B. Gaudou, P. Taillandier, N. Marilleau, K. Chapuis, P. Caillou, A. Brugière, Nguyen Huu Tri, Y. Sklab, JD Zucker

USA
MIT Media Lab
Cambridge, MA

A. Grignard

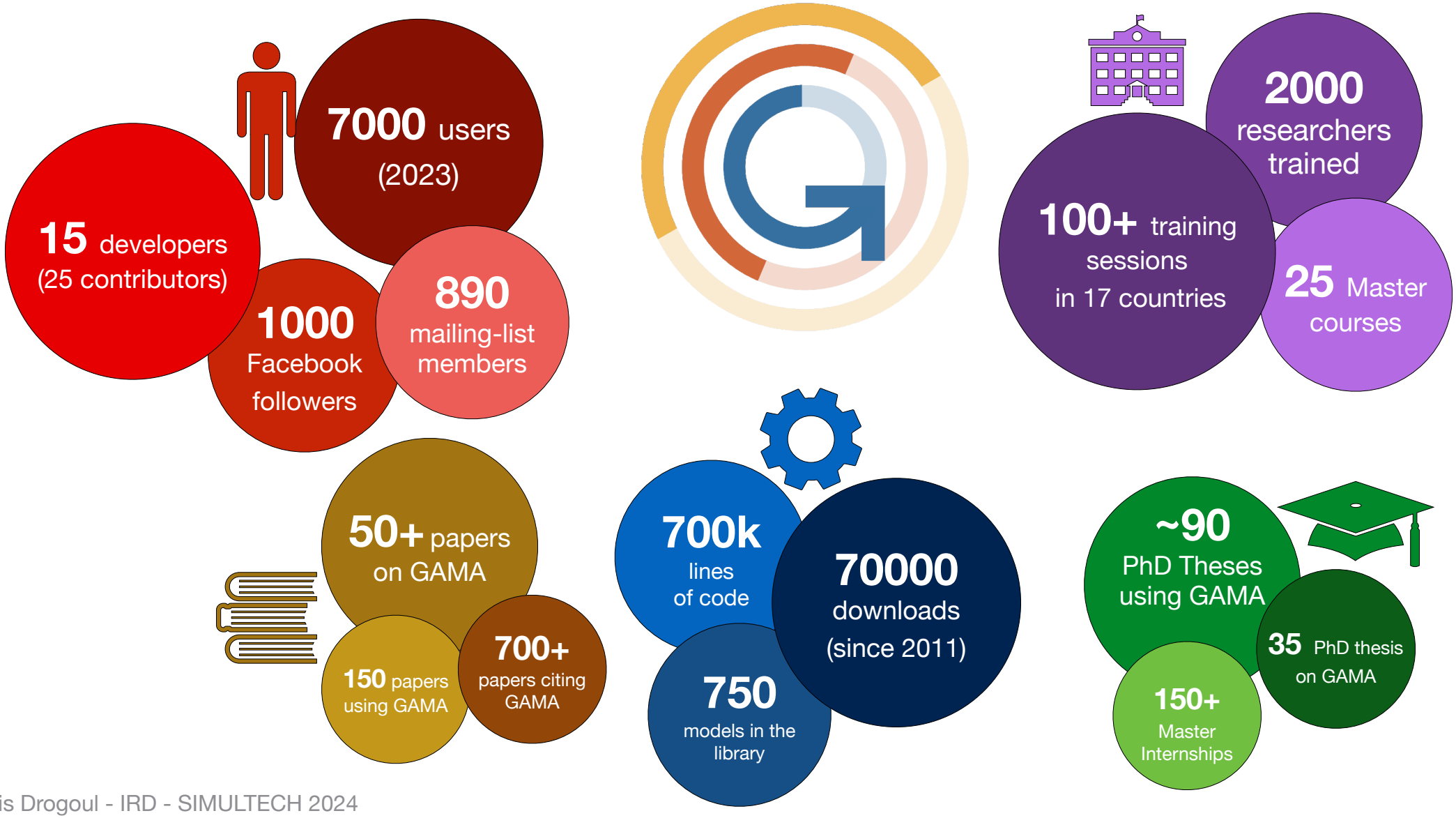
Netherlands
Delft University of Technology

S. Bhamidipati

Vietnam
Thuyloi University,
Can Tho University

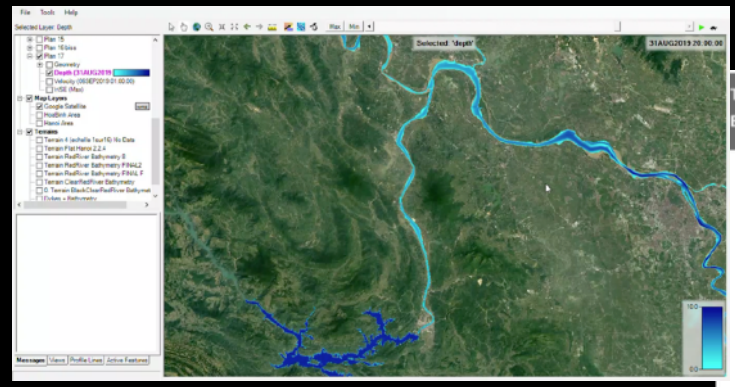
Huynh Quang Nghi,
Nguyen Ngoc Doanh

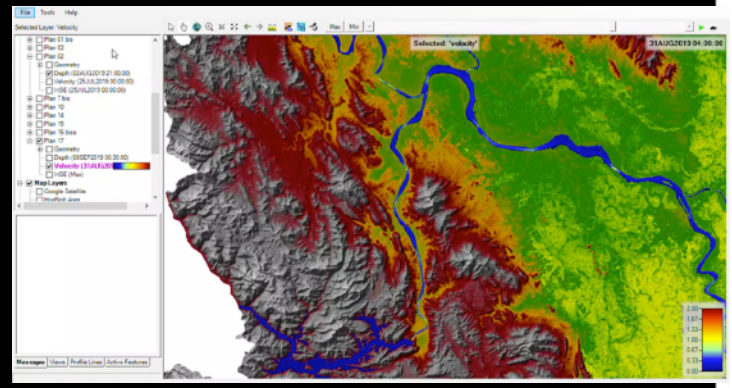
GAMA in a few figures

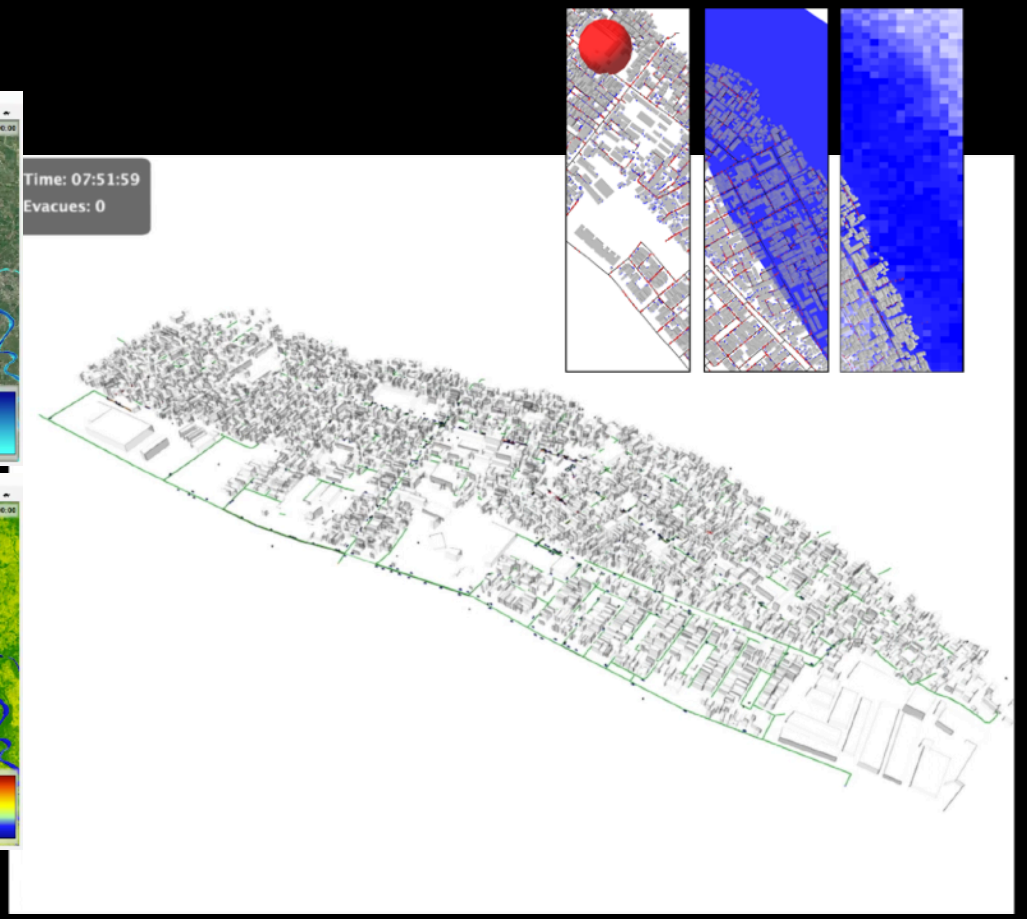


Example : ESCAPE, exploring the best evacuation strategies in different scenarios in Phuc Xa

- A project dedicated to exploring the best evacuation strategies in different scenarios of flooding
- Case study in Phuc Xa, a district in Hanoi that borders the Red River, with scenarios of a large dam break in Hoa Binh



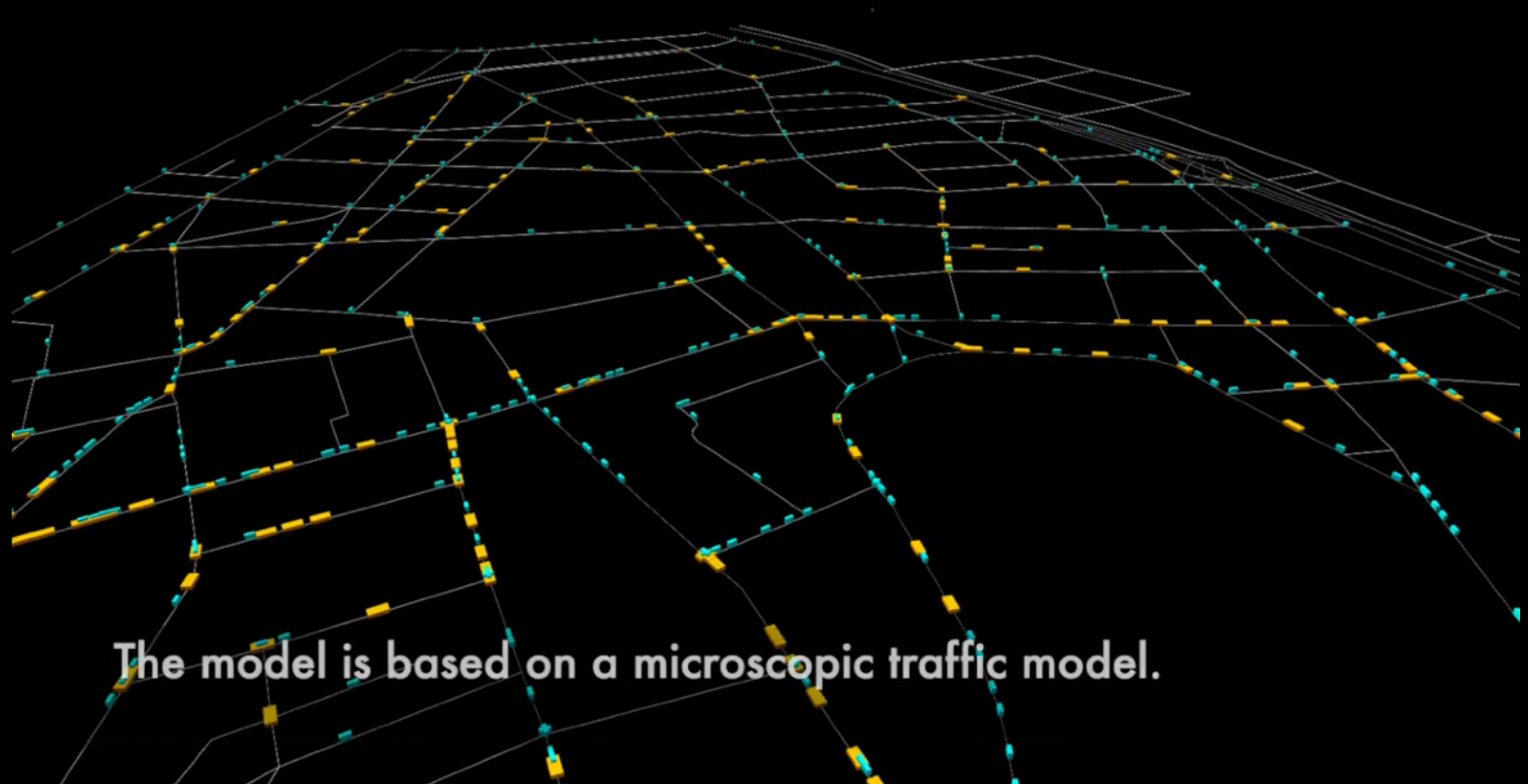




Chapuis, K., Minh-Duc, P., Brugière, A., Zucker, J. D., Drogoul, A., Tranouez, P., ... & Taillandier, P. (2022). Exploring multi-modal evacuation strategies for a landlocked population using large-scale agent-based simulations. *International Journal of Geographical Information Science*, *36*(9), 1741-1783.

Example: HoanKiem Air, linking air pollution with traffic and measuring the impact of pedestrian zones in Hanoi

- An integrated model in GAMA built with Hanoi Transport Department in 2019
- Used both to support policymakers' decisions and to raise awareness on the impact of pedestrian zones on traffic displacement and air pollution.



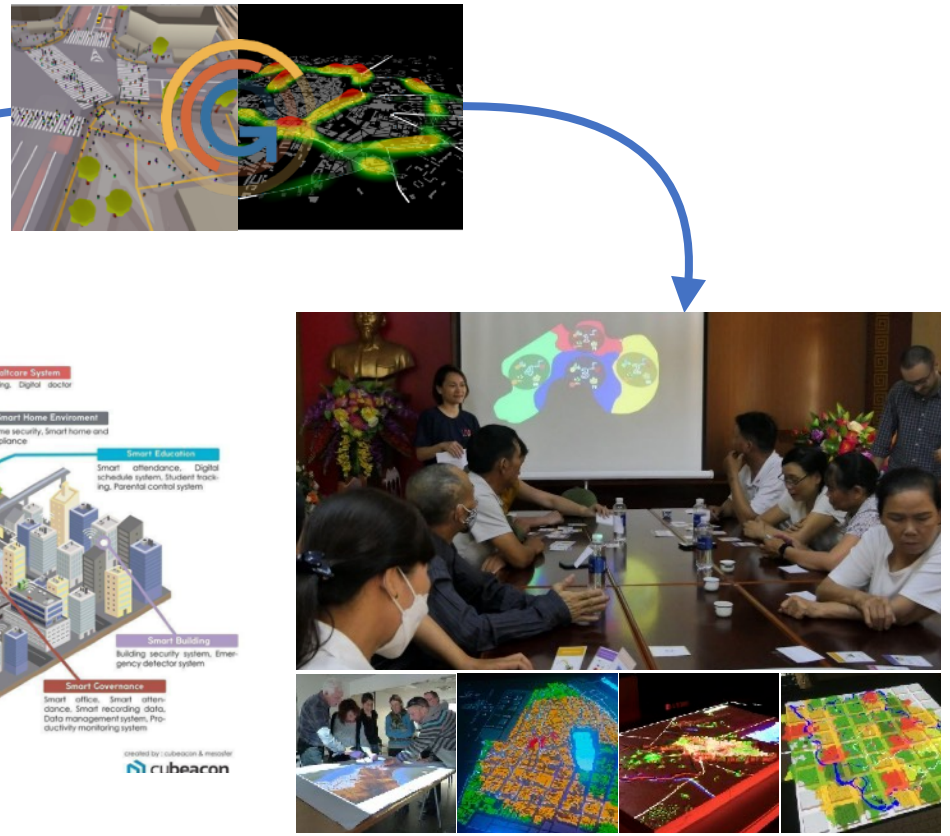
Duc, P. M., Chapuis, K., Drogoul, A., Gaudou, B., Grignard, A., Marilleau, N., & Tri, N. H. (2020, October). HoanKiemAir: simulating impacts of urban management practices on traffic and air pollution using a tangible agent-based model. In 2020 RIVFConference Proc. pp. 1-7. IEEE.

Challenge #1: combining models and participatory methods to improve stakeholder involvement in decision-making (the 3rd pillar of sustainability science)

- Models are mainly produced by scientists for scientists, and their outcomes take the form of scientific articles or reports for deciders (e.g. IPCC), but they should also aid in making better, more informed decisions about sustainability challenges.
- However, sustainable solutions can only be accepted if they are somehow co-constructed or at least shared in advance with the beneficiaries
- Inventing participatory scenarios supported by models for individual exploration or group deliberation is then essential to involve stakeholders.

ABM offers an advantage by providing natural support for participatory approaches

- In GAMA, the same models can be used for scientific research and to support real-time interactions with users.
- Users can play roles in the simulations, interact with the agents, manipulate them and directly see the potential impact of their choices.
- Can improve mediation and decision-making processes

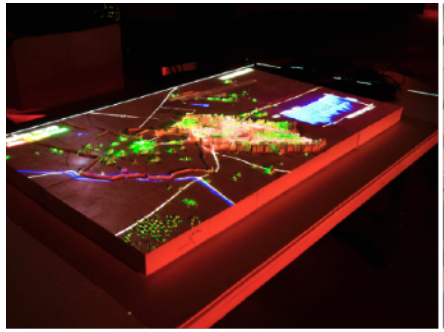


Taillandier, P., Grignard, A., Marilleau, N., Philippon, D., Huynh, Q. N., Gaudou, B., & Drogoul, A. (2019). Participatory modeling and simulation with the gama platform. Journal of Artificial Societies and Social Simulation, 22(2), 1-19.

Thanks to its extensibility and openness, GAMA supports the exploration of new "human-model interfaces" to encourage participation

- Exploring beyond charts/graphs, traditional 2D/3D displays and UI (mouse, sliders, interactive components) to engage people and allow multiple users to use models as a mediation tool.
- Technologies such as tactile and tangible interfaces open up new possibilities for the interactive visualisation of complex models and stakeholder participation.

CityScope project IRD/MIT MediaLab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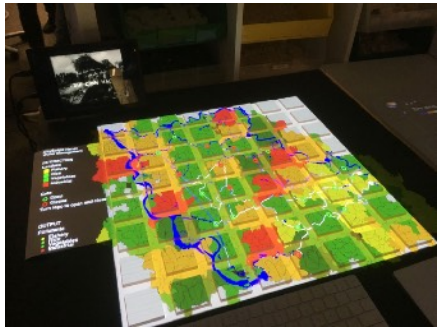

Bac Hung Hai


Lyon


LittoSim

As part of the SIMPLE project, any GAMA model will soon be easily translatable into one or several VR universes

- Allows to offer a complete immersion in the models in order to support learning, awareness-raising and mediation.
- SIMPLE is supported by the EU and implemented in schools in Cambodia, Laos, Thailand and Vietnam, to raise awareness among children, via VR activities coupled with scientific models, on the sustainability of solutions for preventing and mitigating environmental problems.

Global Gateway

Co-funded by the European Union

https://project-simple.eu

Challenge #2: supporting understanding of and confidence in models though openness

As their influence on policy-making becomes widespread, the design of **very detailed and realistic models** raises different challenges, among which :

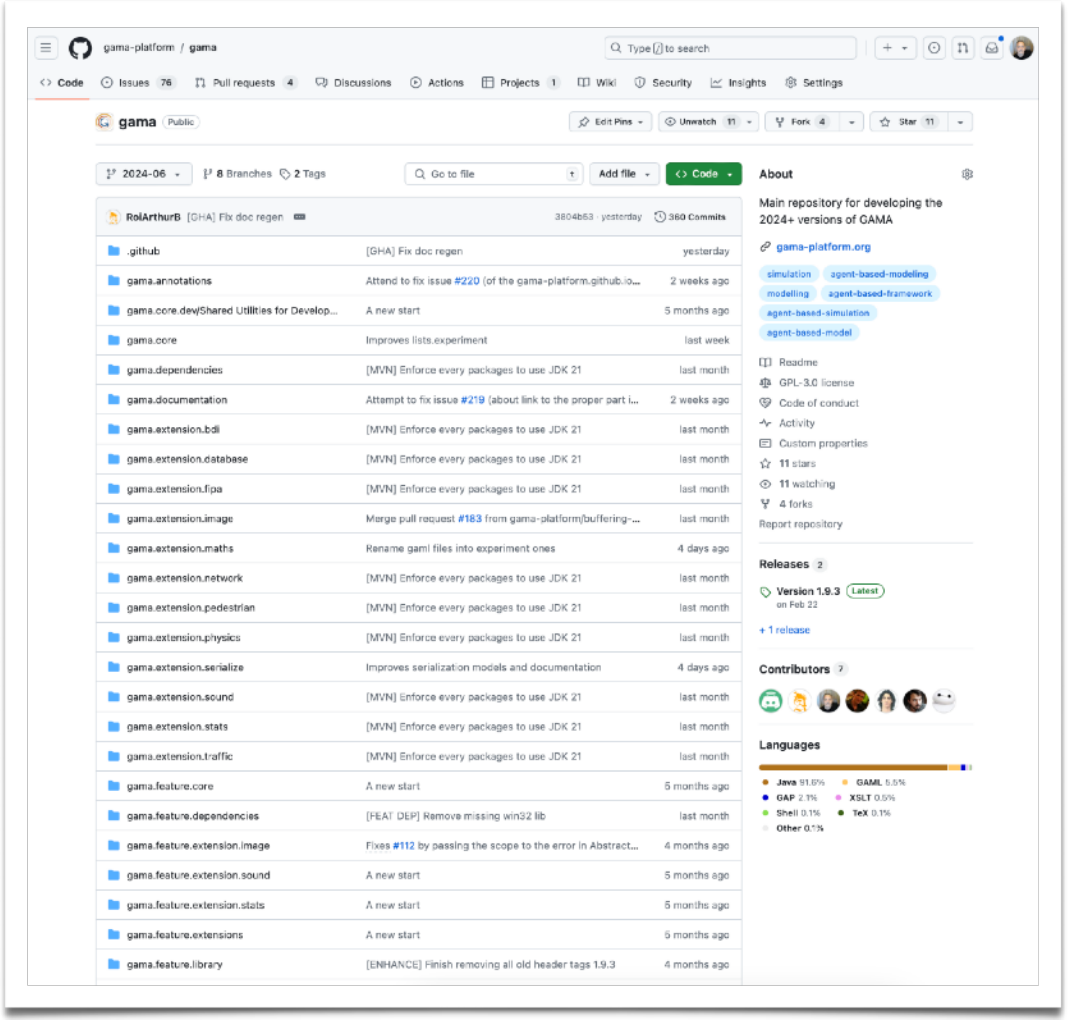
- the necessity to be as **transparent** and manipulable as possible in order to support multidisciplinary contributions;
- the necessity to remain **understandable** by stakeholders invited to participate in the design and assessment of strategies and policies;
- the necessity to be **trustable** by users: let people understand that there is no magic behind a model, and be able to unveil untold hypotheses

The openness of platforms, data, models and visualisation tools can improve reproducibility and thus stakeholder confidence in the outcomes of simulations

- Particularly **critical in sustainability science** because policy decisions may be at stake and because we deal with systems where validation on past data is neither always possible or even wanted (*the past is not always the best predictor of the future in complex systems*)
- Openness allows researchers to have **access to the ”black box” of simulators**: random number generators, scheduling algorithms, primitives, etc., which can have a strong influence on the outcomes of simulations.
- Openness should increase the reliability of our findings, the confidence of users, and allow the scientific community to build upon each other's work by making it possible to **reuse models**.
- ABM platforms however need mechanisms for sharing models, data, and experimental setups

GAMA has been free since 2006 and open-source since 2008

- First because of the **well-known advantages of open-source** (robustness, maintenance, evolution…) in software development
  - Community-driven development ensures flexibility and responsiveness to user needs.
  - Open-source fosters collaboration, transparency, and knowledge sharing between the developers.
- Also because an institute like IRD, present in 37 countries, could support distributed cooperative work

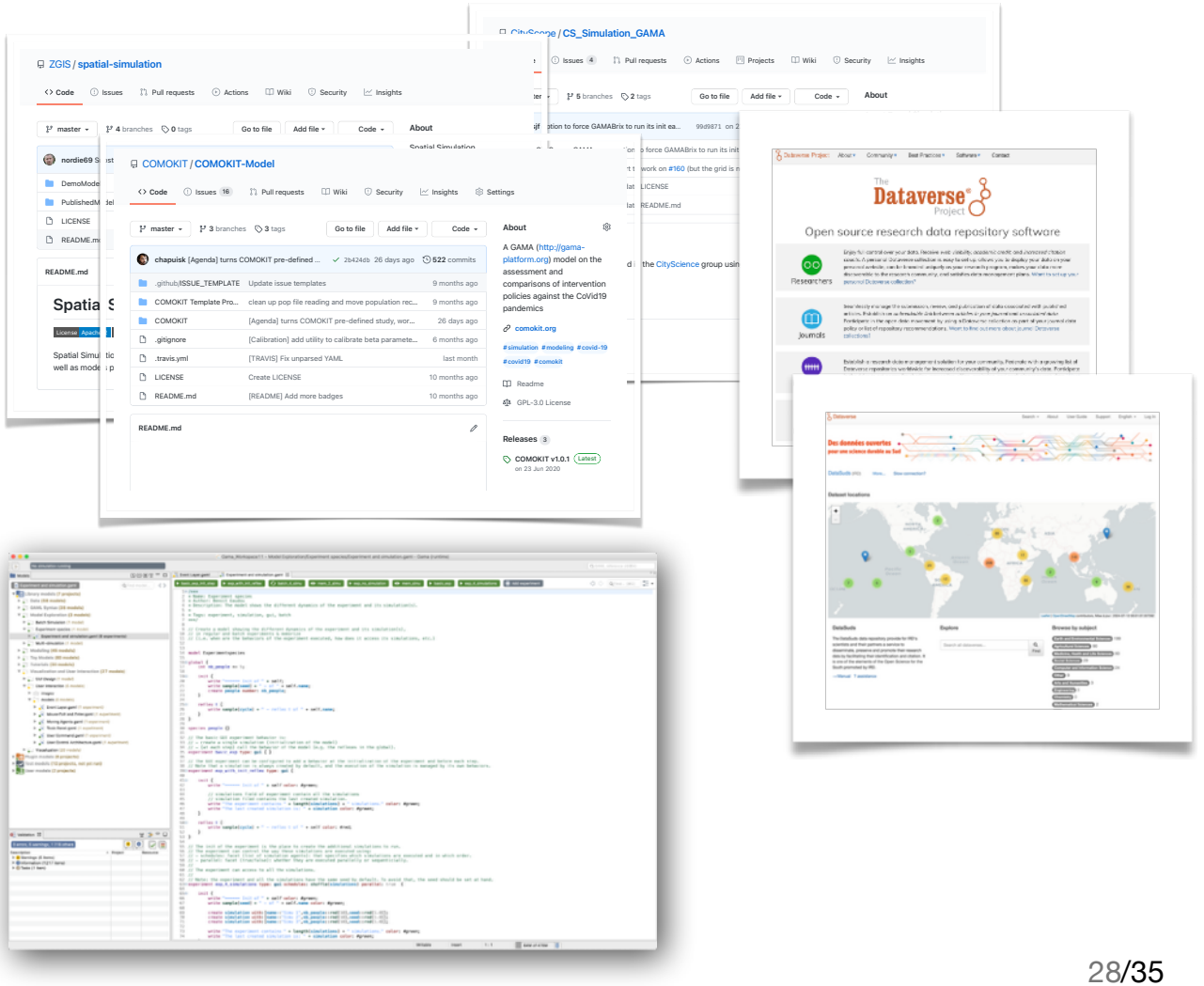


https://github.com/gama-platform/gama

From the outset, authors of models written using GAMA have been strongly encouraged to make their models open-source

- Modellers are encouraged to use open data when available and also publish the outcomes of simulations as open data (using a Dataverse installation like the one at IRD)

- A radical (and still discussed) choice in GAMA is also to **always make the source code available** for viewing and editing by ”users”/ modellers, even in ”demo” mode.

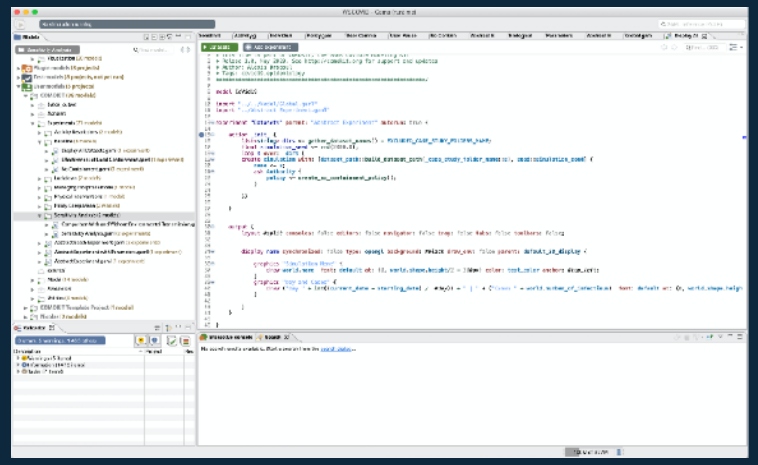


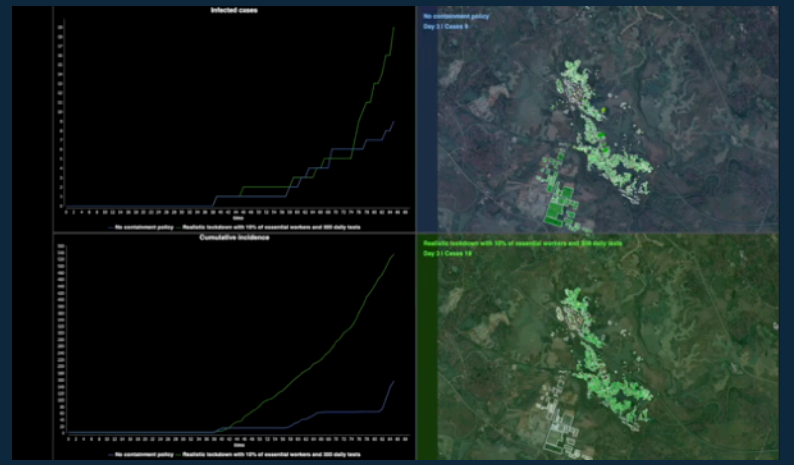
Example: COMOKIT, developed to support the Vietnamese authorities in their fight against COVID-19

- Designed in March 2020 as part of the efforts of the Rapid Response Team of the National Steering Committee under the Prime Minister Authority
- A generic model to assess and compare mitigation policies and interventions at the level of communes (i.e. ~10.000 inhabitants), taking into account spatial and social heterogeneities.

Gaudou B, Huynh NQ, Philippon D, Brugière A, Chapuis K, Taillandier P, Larmande P and 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. Front. Public Health 8:563247. doi: 10.3389/fpubh.2020.563247

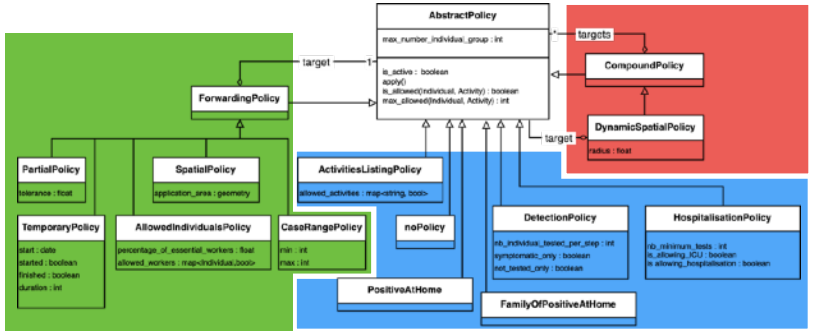
Taillandier P, Chapuis K, Gaudou B, Brugière A, Drogoul A (2024) COMOKIT v2: A multi-scale approach to modeling and simulating epidemic control policies. PLoS ONE 19(3): e0299626. https://doi.org/10.1371/journal.pone.0299626

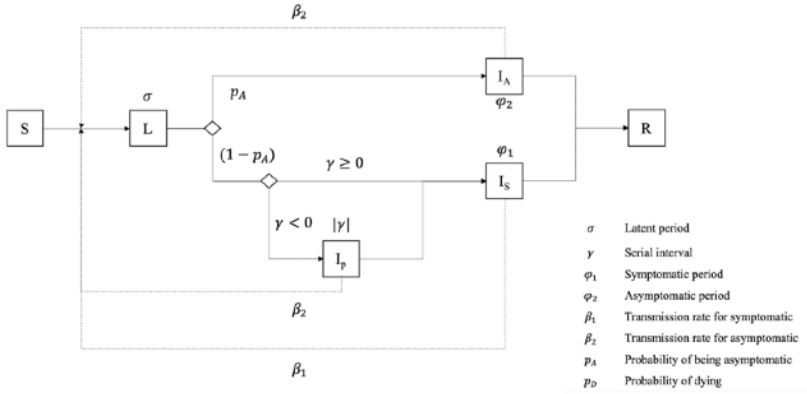


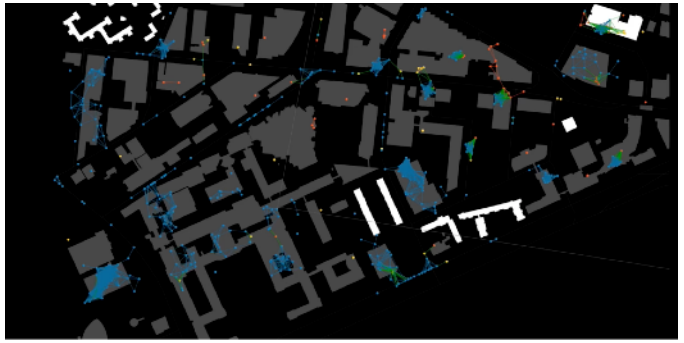


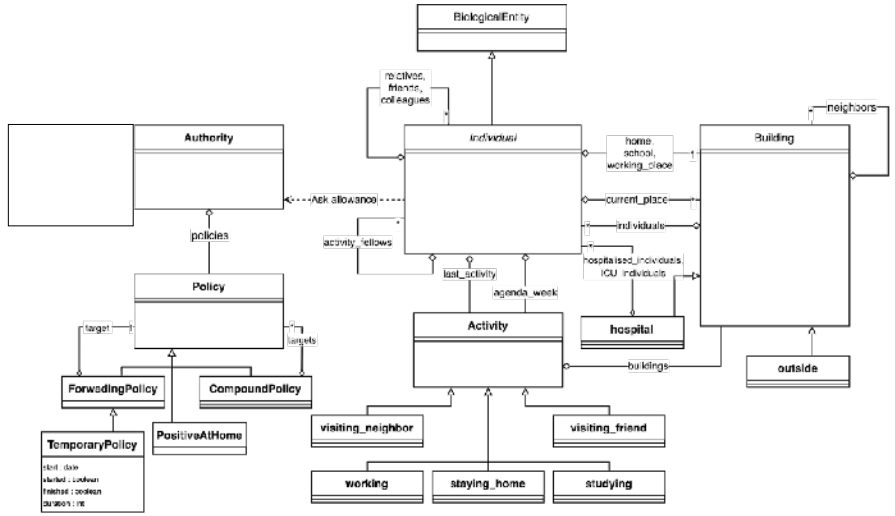
COMOKIT is an integrated model that couples 4 sub-models that cover epidemiological, spatial, social and policy aspects

- **Open-sourced from the beginning** to allow scientists and modellers to (1) apply it to other case studies (cities, countries, populations, epidemics); (2) extend it to take into account variations (vaccination, mutations, diseases interaction…)
- Latest version (2.0, Feb. 2024) **allows to take into account multiple scales and infectious diseases**



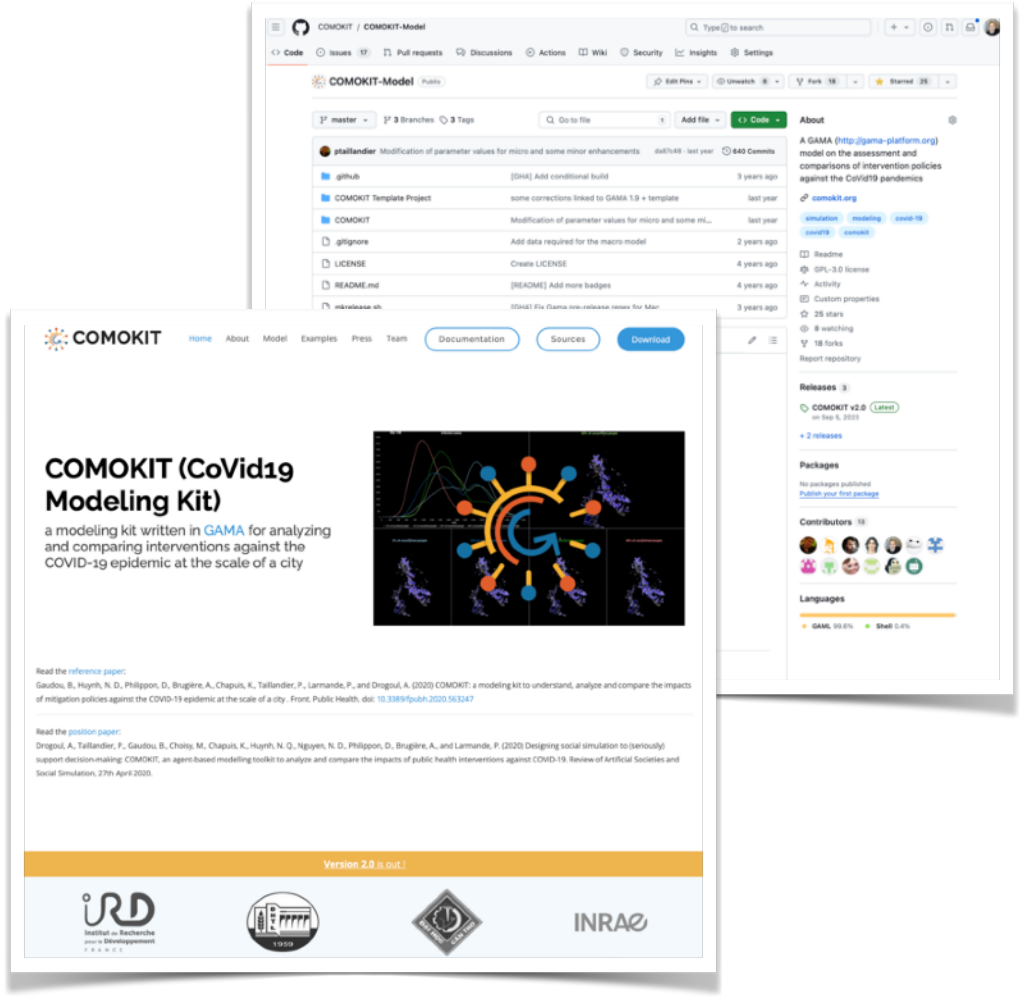






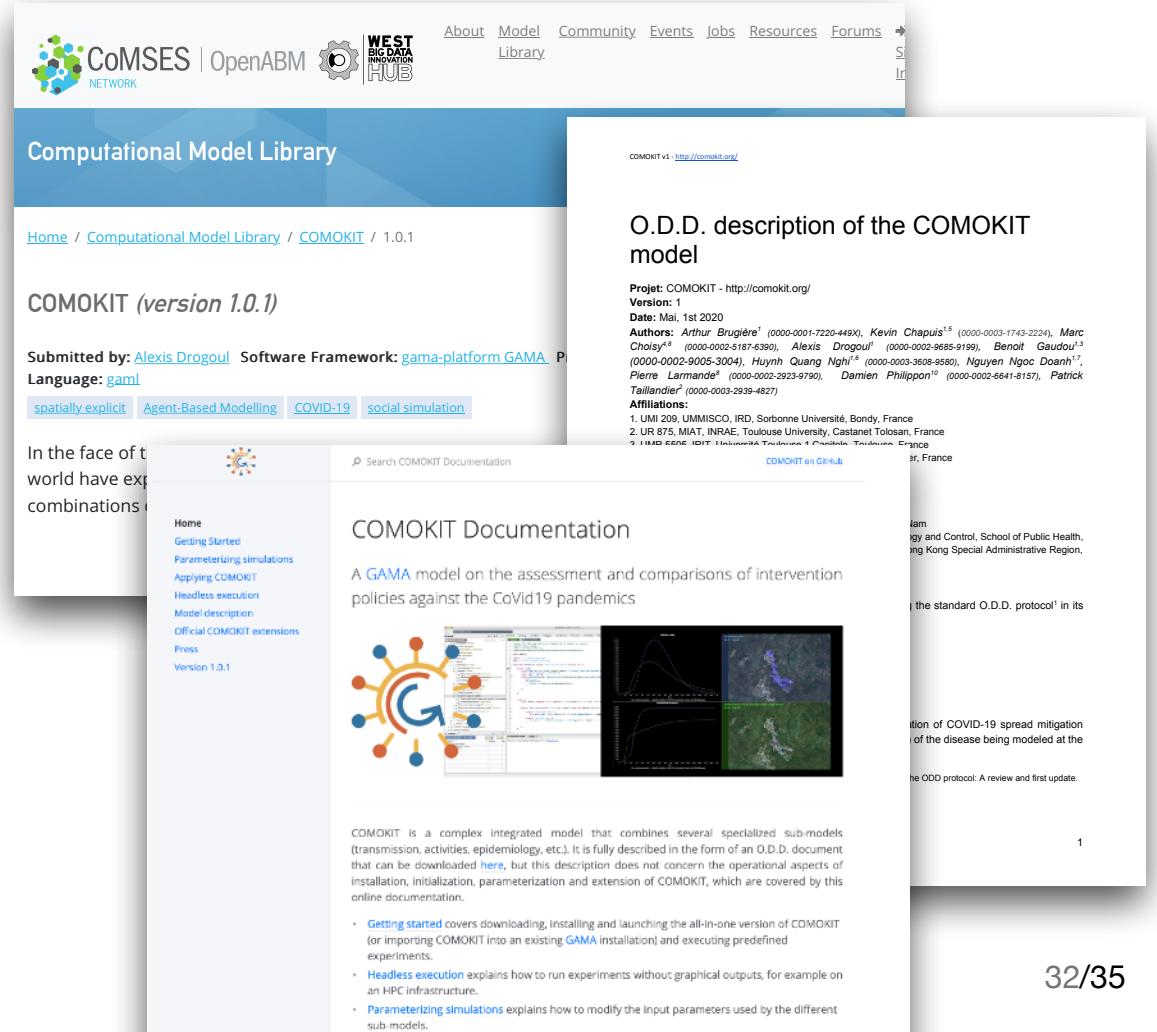
COMOKIT 2.0 is available at http://comokit.org

- Can be downloaded ”as is” with the relevant GAMA runtime, preconfigured with two case studies in Vietnam and several toy examples
- Open to contributions and extensions, among which:
  - Upscaling (population size, case study extent, …)
  - Addition of realistic urban fluxes (transportation, …)
  - Addition of more detailed activities
  - Extension to other infectious diseases
  - Coupling with existing models (urban planning, …)



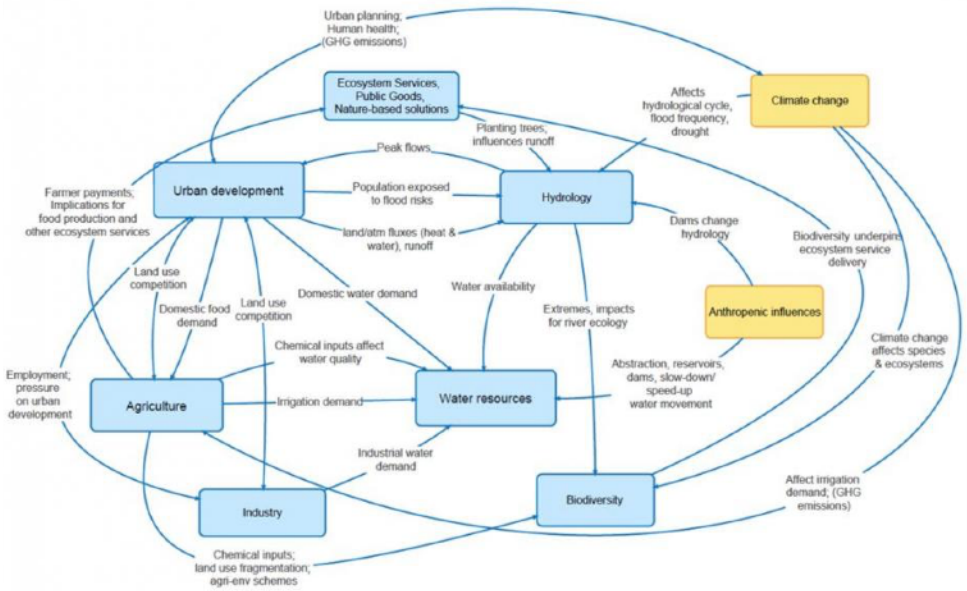
However, the effort required to open COMOKIT is significant and requires a lot of resources, beyond the 'simple' fact of making the code downloadable

- **Make deposits to the peer-reviewed model library CoMSES** (https://www.comses.net/) for keeping trace/history of the running versions (v 2.0 still not yet approved)
- **Write and maintain the ODD documentation** (see http://jasss.soc.surrey.ac.uk/23/2/7.html) of the models to provide a readable description of their logic and the questions they answer to improve their reusability
- **Build and maintain a dedicated website** for documenting how to use and how to extend it
- **Maintain GitHub repositories** for sharing the core source, extensions and datasets.



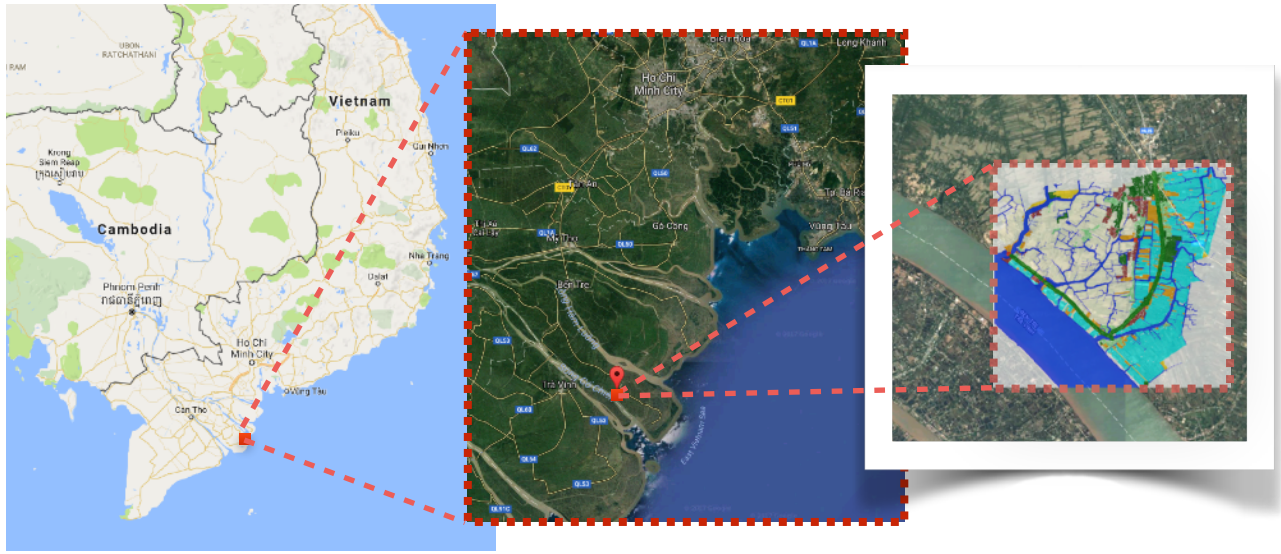
Challenge #3: offering a semantic support for reusing and coupling models

- Sustainability problems do not exist in isolation. For instance, if we want to understand the impact of climate change on water resources, we need to couple weather models, agriculture models, urban development models, hydrological models, etc.
- Operational syntactic issues (data format, languages, protocols, …) can be solved by standardisation (e.g. HLA), but sharing, open-sourcing and documenting (with loose formalisms such as ODD or more formal ones like DEVS) a model does not solve the ontological problem of **”what this model is really about”**
- Importance of structured knowledge bases and ontologies, with explicit scale support, in making knowledge explicit and re-usable between models, exchanging data with compatible spatio-temporal, biophysical and economic dimensions
- An open **ontology-based library of models** is probably what we should be aiming at, prolonging the efforts done in the ”digital twin” domain



Challenge #4: addressing scalability issues in a transparent and efficient way

- **The more ambitious the research questions, the larger the models and datasets.**
- When handling large-scale simulations with millions of agents, computational power and data management become a concern.
- Platforms need to scale gracefully and offer a **transparent** support for distributed simulation, parallel processing, GPU computing and/or cloud computing.
- Another approach is to dynamically build approximate / surrogate models using AI or ML, especially useful in real-time situations (e.g. participatory simulations).
- **Should not be done at the expense of reproducibility !**



Conclusion

- Interdisciplinarity is at the heart of sustainability science, and integrated computer models are proving highly effective in supporting it.
- They are however facing four challenges: participation, confidence, reusability and scalability.
- Open-source agent-based platforms such as GAMA address the first two ones, but the last two remain largely open-ended
- **Join the effort and the community !**

https://gama-platform.org/gama-days-2024/