RESEARCH CENTRE

Inria Centre at Université Grenoble Alpes

IN PARTNERSHIP WITH:

CNRS, Université de Grenoble Alpes

2023 ACTIVITY REPORT

Project-Team STEEP

Sustainability transition, environment, economy and local policy

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

DOMAIN

Digital Health, Biology and Earth

THEME

Earth, Environmental and Energy Sciences

Inria

Contents

Project-Team STEEP

Creation of the Project-Team: 2015 December 01

Keywords

Computer sciences and digital sciences

A5.2. – Data visualization

A6.1. – Methods in mathematical modeling

A6.1.4. – Multiscale modeling

A8.2.1. – Operations research

A9.6. – Decision support

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1 Team members, visitors, external collaborators

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- Peter Sturm [Team leader, INRIA, Senior Researcher, from Jul 2023, HDR]
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- Nils Ferrand [INRAE, Researcher, 50% secondment at Inria]
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- Emmanuel Prados [INRIA, Researcher, from Jul 2023, HDR]
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2 Overall objectives

2.1 Context

> "We are eroding the very foundations of our economies, livelihoods, food security, health and quality of life worldwide. [...] [However] it is not too late to make a difference, but only if we start now at every level from local to global, [and by this we mean] a fundamental, system-wide reorganization across technological, economic and social factors, including paradigms, goals and values."
>
> *Robert Watson, President of the IPBES, on May 6, 2019*

Environmental issues now pose a threat to human civilization worldwide. They range from falling water tables to eroding soils, expanding deserts, biodiversity loss, rising temperatures, *etc.* For example,

half the world's population lives in countries where water tables are falling as aquifers are being depleted; roughly a third of the world's cropland is losing topsoil at an excessive rate; glaciers are melting in all of the world's major mountains. The consequences on the present human societies are critical; they comprise for example increasing threats on global food security, increasing pressures resulting in important population movements (such as climate refugees) and explosive geopolitical tensions. See [63] for a global picture of the situation.

The risks associated with delayed reaction and adaptation times make the situation urgent. Delayed reactions significantly increase the magnitude of the overshoot of the planet's carrying capacity and the probability of uncontrolled and irreversible evolutions on a number of fronts, potentially leading to global environmental collapse [80, 70]. This systemic problem is amplified by two facts: the environment is degrading on all fronts at the same time and at the global planetary scale, a first in human history.

Sustainable development is often formulated in terms of a required balance between the environmental, economic and social dimensions, but in practice public policies addressing sustainability issues are dominantly oriented towards environment management in Western countries. This approach is problematic as environmental problems and sustainability issues result from socio-economic phenomena (for example the economic growth model which is strengthened by powerful and polluting technologies). In addition, most efforts towards tackling them bear on developing technological solutions. However, it is clear, for several years already, that this will not be sufficient [68, 69, 75]. We need to rethink our socio-economic and institutional models in order to leave room for a possible paradigm shift. In this perspective, we believe that crucial steps should be taken in research to help elaborating and implementing socio-economic alternatives.

Although environmental challenges are monitored worldwide, the search for appropriate lines of action must nevertheless take place at all institutional levels, in particular at local scales. We indeed believe that local levels are pivotal in this effort. In particular, we think that two local scales are going to be increasingly dominant in the near future: urban areas (more exactly the employment catchment areas of main cities) and "regions" (such as *régions* in France, *Länder* in Germany or *Province* in Italy). It seems essential to us that local policies and actions are made coherent and articulated across different scales, from local to global.

2.2 Objectives and outline of research axes

The research program of the STEEP team takes the above warnings seriously and aims to "help bring about a profound transformation of economies" at all scales, with a particular focus on sub-national scales over which actors have more control. This program is articulated around two axes.

The **GSR** (**Global Systemic Risks**) axis analyzes, on a global scale, the trend dynamics of risks and collapse, with a characteristic time step of the order of a decade, as well as the risks of systemic contagion, with a much shorter time step, due to the interconnection of key sectors of the economy (e.g. energy, finance, food supply chains).

Our objective here is to rely on or develop numerical models (such as system dynamics, hybrid models including agents, etc.) that allow us to understand the vulnerabilities of our society and the environmental and socio-economic determinants that will constrain its sustainability. The systemic dimension is a key point here. Given the levels of uncertainty and complexity linked to the factors involved here, the idea is not to make predictions, but to understand the mechanisms and processes at play by providing robust qualitative analyses (or even semi-quantitative ones; providing orders of magnitude or comparative elements, for example). This work has for us a double function: 1) to bring new crucial elements of scientific enlightenment to the public debate on these issues and to continue to alert and sensitize the public opinion and the different actors (which is for us an absolute necessity); 2) to enlighten the decision making regarding the alternatives that can be implemented (in terms of vulnerability and sustainability determinants).

The second research axis is called **STA** (**SocioTechnical Alternatives**). Its objective is to contribute to enrich the debates around possible alternatives: what would an economy within the planetary limits look like and what living standards would correspond to it? What trade-offs would have to be made between socio-economic and environmental criteria, between vulnerabilities, equity and territorial sustainability? The approach adopted does not consist in seeking to optimize the existing system but to imagine and evaluate radically different futures. In this perspective, the first step is to correctly describe *"where we are*

starting from and where we want to go", which might then guide reflections on the trajectory (*"how do we get there?"*).

Work in this axis relies on several types of approach: modeling the material basis of the economy (in particular through material and energy flow analysis), which requires numerical tools (such as numerical optimization and uncertainty propagation), modeling immaterial and institutional aspects of the territorial metabolism, participatory processes.

Overall, the objective of STEEP is to develop tools for decision aiding which are based on or enable a systemic vision of the issues – both globally and locally – and to implement sustainable policies at local scales, in particular to transform the productive system and consumption patterns.

- It is very important to integrate the whole **decision process** in the analysis of sustainability issues, for three reasons: 1) to ensure that the designed models address the most relevant issues in terms of **sustainability**; 2) to develop tools that have a real impact; and 3) to amplify the effective use of these tools by the different stakeholders in the territories (decision makers, decision-help agencies, citizens, organized civil society, ...).

- The focus on **local scales** reflects not only the relevance of these decision levels, but also the relative lack of relevant modeling exercises at such scales.

- Because the numerous and interrelated pressures exerted by human activities on the environment make the identification of sustainable pathways arduous in a context of complex and sometimes conflicting stakeholders and socio-ecological interactions, the **systemic and integrative dimension**, whether **multisectoral** or **multi-scale**, is essential from the scientific point of view, as well as for the decision process. We expect to provide highly integrated tools compatible with practical use taking into account the intrinsic constraints of decision processes. A strong level of integration is desirable to identify feedback phenomena which would be very hard to anticipate otherwise. This is why we also strive to develop **transdisciplinary approaches**.

Figure 1 is an attempt to map the structure of the research axes and the links between them and their components. The figure also includes our previous work on LUCC (Land Use and land Cover Change) modeling which is complementary.

3 Research program

3.1 Research axis 1: Global Systemic Risks

Strictly speaking, in the scientific literature, the term “risk” designates a hazard compounded by its probability of occurrence (e.g., the risk of a plane crashing). Systemic risks refer to system wide risks (e.g., risk of financial crises of large magnitude). Global systemic risks (cross-sectoral risks) arise because systemic risks are often interconnected, and characterized by many feedbacks at various spatial and temporal scales (e.g., climate change and its impacts on the environment and human life and activities). A number of global systemic risks are subject to an intrinsic form of indeterminacy that invalidates the very possibility of a probabilistic approach. Quite often, the term risk is then used in a more casual way, referring to a vulnerability associated to a hazard, and this second, more informal meaning is the one used in this document, in particular because some risks are indeterminate in the meaning just specified.

The literature devoted to systemic risks is extended and varied, with roots in exact and environmental sciences [77, 74] or in social sciences [64]. Two areas of systemic risks have been the object of a particular focus in the past decades: environmental risks (e.g., climate change), and financial risks, but many more types of interconnected risks can be identified. They are often grouped into five categories: economic, geopolitical, environmental, social and technological. In the economic sector, the main risks are related to market instabilities, particularly in the energy sector, and financial risks. Geopolitical risks are largely related to potential sources of conflict, whether or not linked to the threat of terrorism. On the environmental front, climate change, loss of biodiversity and their consequences appear to be dominant, but natural disasters can also play a role; issues related to changes in land use (deforestation, erosion and desertification, artificialization) are also very important. At the societal or socio-political level, issues of

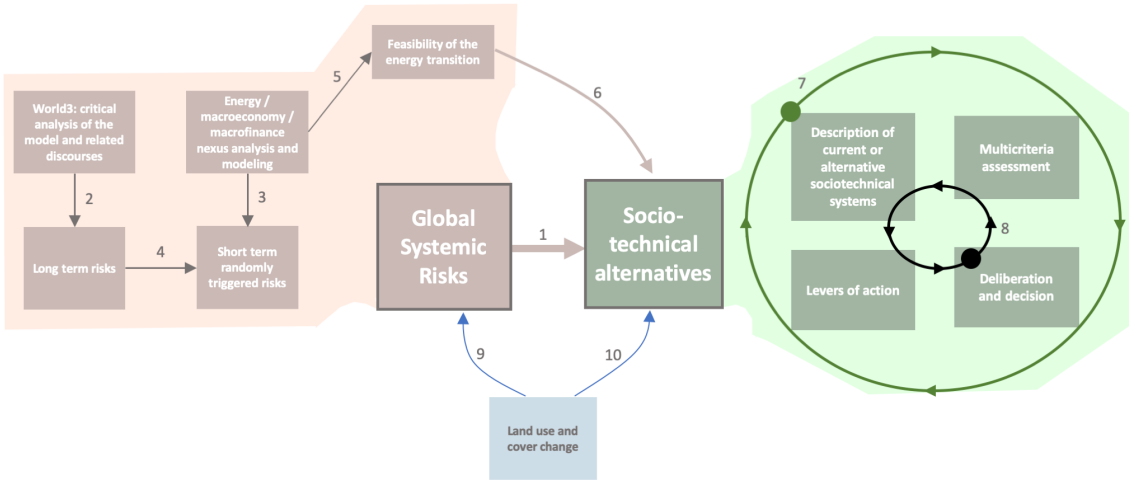

Figure 1: Sketch of the team structure: building blocks of the two research axes and logical connections. The orange and the green areas respectively depict the contents of the Global Systemic Risks axis (GSR) and of the Sociotechnical Alternatives axis (STA). Participatory processes can (and should) intervene in each part of STA (participatory modeling, participatory simulation, participatory decision-aiding).
The meaning of the arrows is as follows: (1) GSR's inform on the vulnerabilities of current or imagined sociotechnical systems and potentially change actors' representations, priorities and decisions; (2) Long term risks are currently analyzed through our work on the World3 model; (3) Short term risks are currently analyzed through our work on the energy/macroeconomy/macrofinance nexus; (4) Long term degradation trends increase the probability of occurrence of (short term) domino-effect crises; (5) The nexus model is an input to assess the feasibility of an energy transition; (6) The latter limits the option space for STA's; (7) The most common way to navigate between the 4 STA blocks is to start by describing, assessing and evaluating the current system and then to identify levers of action to modify it. Note that this cycle is performed for several alternatives depending on the chosen levers. STA's are seen as biophysically consistent narratives that feed (and derive from) people's imaginations. After deliberation, a decision is made on the desired alternative and actions are taken; (8) It is also possible to go the other way round, that is, to deliberate on the desired goals (here, desired indicator values) and then examine the option space corresponding to these goals, in terms of STA's and levers of action. Sociotechnical lock-ins can be an obstacle to the decision on, and implementation of, levers of action; (9) LUCC (Land Use and land Cover Change) is a planetary boundary which is triggering GSR's; (10) Finally, LUCC models contribute to the description of the system and the spatialization it provides enables the translation of environmental pressures into impacts on ecosystems.

inequality, food security, access to water, health risks (particularly pandemics) and migration are prominent. As for technological risks, they largely concern the fragility of modern computerized communication systems and network infrastructures (e.g. electricity distribution networks). These categories of risk and their interactions are represented in Figure 2.

From a process point of view, global systemic risks can be grouped into two categories:

- **Long term trends related risks:** These are produced by the decade or century long evolutions of our modern global societies. They arise from the growing tension between resource use, production of (often diffuse) pollutions of various kinds, and the capacity of our environment to absorb the related impacts. The induced environmental changes affect our socio-ecosystems, and are amplified by existing socio-political, economic and historical dynamics.

- **Short term, randomly triggered risks:** These risks occur on much shorter term (months to a few years). They are intermittent, random[1] and related to the high level of interdependence of

[1] As for the predictability of their time and order of occurrence.

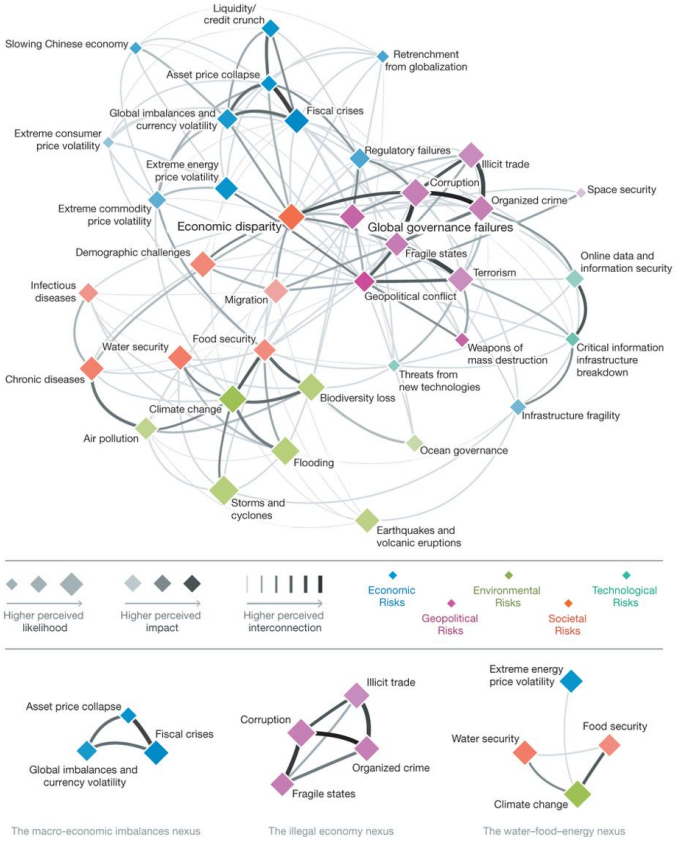

Figure 2: Global systemic risks and their interconnections according to the 2011 World Economic Forum report (reproduced in [74]). These risks are assessed by expert opinion and the importance attributed to them reflects in part cyclical concerns.

many sectors of activity, to intrinsic instabilities produced by this interdependence, and to their propagation through all sectors of activity through a kind of domino effect. The occurrence of such risks is accelerating. In the last decade or so, one can mention the 2008 financial crisis, the COVID crisis and the russian-ukrainian conflict and its implication on global energy and food security. This acceleration is not coincidental, as these risks interact with and are amplified by long term trend ones.

The emblematic model of the first category is the World3 model developed by the Meadows group for its famous report on the limits to growth [78, 77]. The re-analyses of [81, 82] and [60] have renewed interest in this model while raising more specific questions about the robustness of the conclusions drawn from it. We approach these questions through an analysis on three complementary fronts:

1. An analysis of the choices of parameterization based on a sensitivity analysis that is much finer than the existing ones.

2. An analysis of modeling choices based on a sectoral and geographical disaggregation of the model.

3. Elements of epistemological analysis.

The main practical interest of this research lies in the possibility of discerning the risks of collapse in the short term (pre-2050) or further out in time (post-2050), both of which require different mitigation and adaptation strategies that must be properly anticipated.

In terms of systemic contagion risks, and although an exhaustive analysis of all the categories of potential risks is impossible in an exploratory phase, the energy/finance/supply chain nexus plays a particular role in our societies and presents a specific criticality. Sectoral or cross-sectoral analyses of

certain aspects of this nexus already exist in the literature (see for example [73, 76, 62]), but apparently no overall model has been produced on this subject, and in particular no dynamic model. Such a realization would constitute in itself a significant advance.

More precisely, our work concerns the following points:

1. Identify the most important feedback loops of the energy/supply chain/logistics/finance system.
2. Identify the most fragile links in this system.
3. Assess the likelihood of this type of risk and, if necessary, define mitigation strategies.

3.2 Research axis 2: Sociotechnical Alternatives

The main motivation of the STA axis is to help actors **produce narratives** of the future which are **consistent from a biophysical viewpoint** and which take into account indirect (systemic) impacts. In a more and more constrained world, this means being able to **identify and decide on trade-offs** relative to the different aspects of the problem. Another way of formulating the axis' goal is that we wish to design **planning tools** that would address social and ecological stakes, and reflect on their use by a variety of actors, in a **democratic context**.

Our work concerns three aspects: (1) description of current sociotechnical systems, (2) description and assessment of STAs, (3) participation.

1 – Description of sociotechnical systems. The cornerstone of the STA research axis are a method and associated software for multi-scale Supply Chain Material Flow Analysis (SC-MFA, see [67] for an overview and Figure 3 for a simple example). Material flows (production, transformation, exchanges, consumption, waste) are the basic building blocks of our supply chain studies. We designed methods and tools to model a supply chain (in terms of products, sectors and possible flows between them) and reconcile incomplete and/or inconsistent data. The flows allow:

- To apprehend up/downstream vulnerabilities of supply chains (e.g. dependence on imports),
- To question the use of natural resources and the possible problems of competition for use (e.g.: can the development of biofuels lead to competition between food and energy production?),
- And finally to estimate environmental footprints (e.g. carbon, energy, water, chemical pollution, land use, etc.).

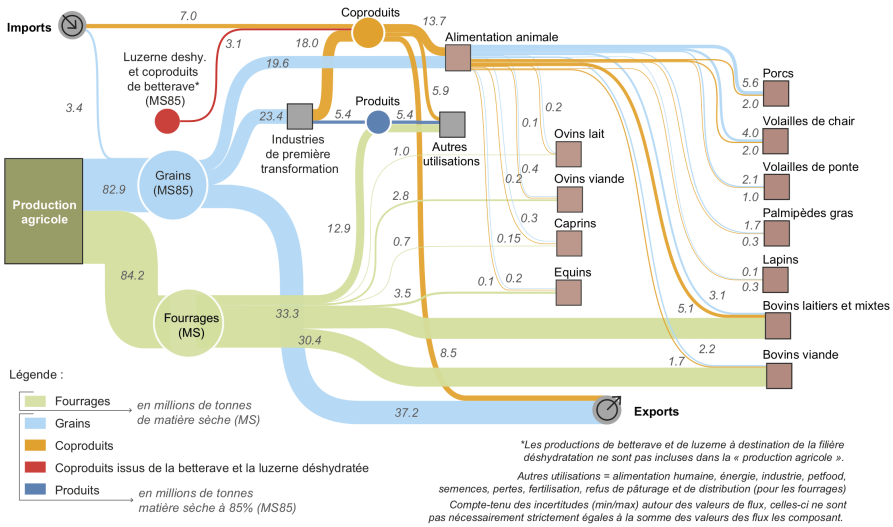

Figure 3: Example of a Sankey diagram resulting from a single-scale SC-MFA: Agriculture raw materials fed to livestock in France in 2015 (millions of tons) [65].

2 – Description and assessment of sociotechnical alternatives. The most significant novelty compared to our pre-2018 work relative to territorial metabolism is to tackle the design and assessment of sociotechnical alternatives (STAs) for the future. The term alternative is used in place of scenario to emphasize that we currently describe possible points of arrival in the future and not pathways to move from today's situation to the desired outcome.

The objective of this research program is to help shed light on the debates around possible alternatives: what would a one-planet economy look like and what standards of living would it imply? What compromises will have to be made between socio-economic and environmental criteria, between resilience, equity and sustainability of territories?

Our work is structured around four main objectives:

- To propose a formalism to describe sociotechnical alternatives. In particular, we are working on extensions of physical supply/use tables, able to provide information on the interactions between materials and energy. We are also interested in coupling quantitative (technical dimension) and qualitative (social dimension) representations.
- To propose a methodology (and eventually a software) allowing groups of actors to imagine their own alternatives,
- To develop a methodology and associated tools to evaluate an alternative (cf. Figure 4):
  - What needs does it cover?
  - What are the local, remote or global pressures and impacts generated? How do they compare to local and global limits?
  - What would be the vulnerabilities of the system described?
  - What are the socio-economic performances of the system described (e.g., in terms of allocation of the workforce, allocation of added-value…)?
- To help comparing alternatives and structuring related debates.

3 – Participation. The work on STAs for the future motivated this last sub-axis which aims both at empowering local actors and to learn from them, in line with principles of post-normal science [72]. As explained above, one of our main objectives is to contribute towards having possible sociotechnical alternatives for a territory be co-constructed by all relevant stakeholders and be debated democratically. This covers all aspects, from the definition of what is at stake and of the criteria to use for assessing alternatives, to the actual co-construction and assessment of the latter. Furthermore, such participative processes may benefit from some form of training or awareness-raising on systemic issues. Our activities along these lines have started in 2021.

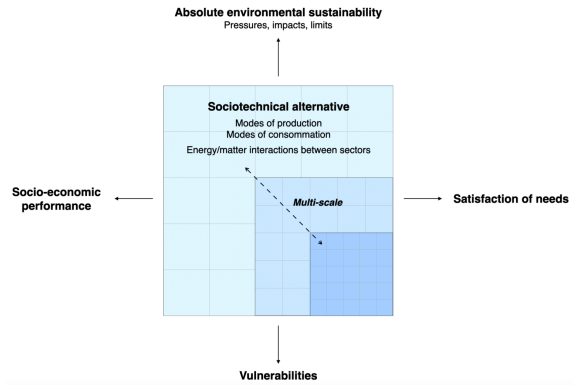

Figure 4: Schematic overview of research questions and concepts underlying sociotechnical alternatives. Center: targeted sociotechnical alternatives are typically of multi-scale nature. Borders: the four dimensions to be considered in evaluating sociotechnical alternatives (see text).

4 Application domains

One of the characteristics and objectives of our research project is to try to provide integrated and systemic visions and approaches to reduce and prepare for the consequences (shocks, depletion of resources, etc.) due to the overshooting of planetary limits and to identify the room for manoeuvre and means of action available to us to act against them. It is an "applicative" project as such.

Most of our scientific activities aim at aiding the design of, and decision on, public policies. Another important general goal of our activities is to raise awareness of environmental and associated social issues, and of their interrelated and systemic nature, through dissemination, education and training activities. Indeed, we are convinced that decision aid is intrinsically intertwined with such dissemination activities.

In the following, we detail both of these aspects.

4.1 Decision aid for public policies

We pursue this goal through the development of scientific knowledge, models and tools that aim to be directly relevant to policy questions. Further, we do so, whenever possible, in direct collaboration with public authorities or other relevant partners (such as representative bodies for agrifood supply chains). Besides contributing to scientific production as such, we are also present in expert groups or scientific councils of public bodies (municipalities, regional parks, etc.).

In the following, we list a few examples of policy-relevant issues we address or have addressed in our work. This list is not exhaustive.

- Material and energy flow analysis (of supply chains or "entire" economies), or MFA. With applications for instance in:
  - Ecological accounting for sectorial pressure assessment.
  - Analysis of public policies dedicated to building waste.
  - Decision aid for territorial strategies in the agrifood, energy and other sectors. In collaboration with, or through our startup Terriflux.
- Land cover and land use modeling, urban economy and urban/periurban planning:
  - Modeling of land cover changes.
  - Integrated modeling of land use and transportation.
- Systemic risk modeling and analysis, both on global and local scales:
  - Studying global systemic risks, for instance by analyzing the iconic World3 model [79, 77].
  - Systemic risks on the health sector.
  - Systemic risks on a local territory (Grenoble metropolitan area).
- Nexus modeling:
  - Modeling and analysis of the energy/macroeconomics/finance nexus.
  - Assessing the feasibility of an energy transition.
  - Analysis of cascade risks (domino effects). The present and future focus is on the consequences of a blackout on the health sector and on risks associated to potential supply chain disruptions.
- Particaptory approaches, with applications to territorial foresight studies or to several of the above issues (such as for decision aid for territorial strategies in the agrifood, energy and other sectors).

4.2 Raising awareness of environmental and associated social issues: Dissemination, training, teaching, popular education

We believe it to be important that scientists, based on scientific knowledge, engage themselves in raising awareness of the general public. As a matter of fact, we think that the systemic nature of environmental and social issues is not yet sufficiently developed in public discourse.

We try to contribute to awareness raising through tools available to scientists, and according to principles outlined for example in the MakeSEnS initiative we co-coordinated [61], the *Avis* "Entre liberté et responsabilité : l'engagement public des chercheurs et chercheuses" published in 2023 by COMETS (CNRS Ethical Committee) [66], or a similar report produced for the University of Lausanne in 2022 [71].

Team members are involved in the French government's initiative Formation à la transition écologique, aimed at familiarizing all French public service executives with the challenges of an ecological transition (see section 10.1.5). Since several years we teach interdisciplinary courses on the mentioned systemic issues; see also the Anthropocene FACTS initiative we have created and carried for several years (section 10.2.1). Our conference-debate series and YouTube-channel "Understanding and Acting" (see section 10.3.1) has been launched in 2016 and has featured a wide range of scientific presentations on environmental and social issues. We also intervene in many general audience actions and in popular education, through presentations, round tables, interviews, and the animation of our Global Systemic Risks fresco.

Overall, we consider this as a contribution to Inria's mission of knowledge transfer to society.

5 Social and environmental responsibility

5.1 Footprint of research activities

While the team does not apply any strict formal rules concerning the following issues, it is probably safe to say that a certain level of awareness on environmental issues that is natural given our line of work, guides many of our "daily" decisions. Examples of how environmental impacts are considered are provided in the following.

Contrary to what some might suspect, we do use computers, networks and other digital equipment for our research..., meaning that the direct footprint of our research activities is higher than if we were working with pen and paper only. Generally speaking, we aim at keeping our footprint as low as possible given the requirements of our work. For instance, computing equipment is used as long as possible (the current average age of our desktop computers for instance, is more than 8 years and these lines are written on a notebook of 10 years of age). Criteria for choosing publication venues include where conferences are held (to lower the footprint of work travel). The number of trips by plane in the last years is probably way below Inria average. Many team members use the bicycle for home-to-work trips, sometimes for work trips as such. The ratio of vegetarian over meat-based dishes taken for lunch at the local cantine, is rather high compared to the national average. The majority of our collaborations, be they with academic or with other partners, are local (in Grenoble or within the Région). This is natural given that our work requires partnerships with territorial authorities for instance, but is also a matter of choice. Besides trying to limit the direct footprint of our work, some team members are also involved in initiatives whose general aim is to reduce the environmental impact of research, such as Campus d'après Grenoble and MakeSEns.

Having said all this, we think that on average, the environmental and social impact scientists have is dominated by the topics and applications they choose to work on, more so than by the direct impact of their day-to-day work-related activities.

5.2 Impact of research results

All of the team's research activities are directly dedicated to environmental and social issues. On the one hand, this concerns both of our research axes – Global Systemic Risks and Sociotechnical Alternatives – and on the other, the type of collaborations we build to underpin these axes – partnerships with different territorial and environmental bodies and also more and more with civil society.

Besides research activites *per se*, we also pursue various dissemination activities related to social and environmental issues, towards general audiences, and give transdisciplinary university courses.

6 Highlights of the year

6.1 Publication of the book "World3 et le rapport Meadows, les limites à la croissance – Questions raisonnées pour aujourd'hui"

The year 2022 marked the 50th anniversary of the report "The Limits to Growth"[79] to the Club of Rome. This report on the limits to physical growth in a finite world is an iconic work in sustainability science. In order to celebrate and popularize it, the STEEP team coordinated the edition of a FAQ on this report, the underlying World3 model, and limits to growth in a broad sense. Scientists and members of the civil society were interviewed to collect a wide range of questions: on the model as such, underlying assumptions, the public and scientific reception of the report, its destiny after the initial publication, its impacts, and so forth. These were then clustered and compiled into a list of 24 questions, submitted to knowledgeable researchers who provided chapters answering them. Some chapters were (co-) authored by team members (cf. [34, 35, 36, 37, 38, 39]). The finally produced book of about 260 pages [33], published in november 2023, aims at popularizing the issues raised by one of the first acts of global systemic modeling, widely known in the 1970s but mostly forgotten since. The main intended audience is scientists in social and human sciences, but the book is also accessible to the general public. Initial versions of the book chapters are accessible here. Several events accompanied the launching of the book (see section 10.3.5).

Figure 5: Cover of the book "World3 et le rapport Meadows, les limites à la croissance – Questions raisonnées pour aujourd'hui" [33].

6.2 Foresight exercise on environmental sciences

2023 was a year of evaluation for our project-team. This evaluation, coordinated by Inria's Evaluation Committee, is an important step in the team's life cycle. In particular, it enabled us to elaborate collectively on the future of all teams involved in the environmental sciences theme. We have produced a summary of this foresight, which raises more questions than it answers, but which reflects the topic's complexity and the debate that has opened up within the institute itself.

7 New software, platforms, open data

7.1 New software

7.1.1 Sankeytool

Name: Web app for drawing Sankey diagrams

Scientific Description: A Sankey diagram is a visualization of sectors that are arranged in layers: in each layer, sectors are represented by nodes which are organized and aligned vertically. Flows are only possible between distinct layers, therefore they are mainly horizontally oriented. Each flow is represented by a graphic link (e.g. a Bézier curve) having a width corresponding to the flow volume. The main objective is to visualize an economic sector or another structure in the most efficient way, in other words the representation of the elements must facilitate human understanding of the structure. Literature offers several criteria which can be used and optimized to achieve this objective. This software generates Sankey diagrams automatically. The creation includes several steps, each of them focuses on the resolution of a specific optimization problem. The formulation of these is inspired by the article "Optimal Sankey Diagrams via Integer Programming" written by Zarate et al. in 2018. The software includes an implementation of this and several new methods. They are based on solving linear programming optimization problems.

Functional Description: The software is an online web app that allows manual and automatic sankey diagram plotting. Among the functions these diagrams can be exported in svg or pdf format.

A Sankey diagram is a type of visualization of flows (of data, physical entities, money, etc.) between sectors (for example, economic sectors). The main entries of the software are a table comprising a description of these sectors and the flows, as well as the flows' volume. The software contains functions that aim at computing an optimal disposition of the flow diagram (position of sectors and flows on the produced chart), according to different possible criteria. For instance, a disposition that minimizes the number of crossings between flows or that contains as horizontal as possible flows.

URL: http://terriflux.fr

Contact: Julien Alapetite

Participants: Jean-Yves Courtonne, Julien Alapetite

7.1.2 STA-Explorer

Name: Socio-Technical Alternatives Explorer

Keywords: Decision aid, Ecological transition scenarios

Functional Description: The software is a decision support tool that allows to:

* Describe an economic model, in different territories with different types of actors, in terms of bio-physical exchanges (to take into account the interactions between sectors, for example the fact that renewable energies consume materials which in turn require energy to be extracted and transformed) * Describe a Socio-Technical Alternative (STA), i.e., an arrival point in the future that is coherent from a biophysical point of view (as opposed to the description of a past situation) * From this description, the software allows the alternative to be evaluated by "reconciling" by optimization the parameters controlling the value of the flows rather than the flows themselves.

URL: https://gitlab.inria.fr/steep/sta-explore

Contact: Jean-Yves Courtonne

7.1.3 TransKey

Keywords: Serious game, Flow visualization, Collaborative science

Functional Description: TransKey is a framework for modeling and serious games for transition support, based on a generic model to support new transition game designs, adapted from previous MFA (material flow analysis) games and goals. The framework is under development. A first playable game has been completed and tested with users. General target features for TransKey are: representing multiple resource stocks and flows, their dynamics, stakeholders' constraints and control, exogeneous drivers, multi-scale representations, player friendliness, data fitting when required, connecting material and digital version. A general description is given in https://hal.science/hal-04231486.

URL: https://gitlab.inria.fr/steep/transkey

Contact: Mathilde Boissier

7.1.4 Data reconciliation tools

Keywords: Data reconciliation, Operational research, Constraint Programming

Functional Description: To facilitate a meaningful comparison, multiple algorithms have been developed. A checker is proposed to ensure that the provided results are well-formed and respect the problem's constraints. A visualization program is also proposed, along with an algorithm that provides the optimum, to compare the difference with it. A random instance generator has been developed to carry out larger-scale tests. Finally, numerous algorithms have already been described and a benchmark of real instances is offered to establish a preliminary comparison framework.

Publications: hal-03595273v1, hal-04305015v1

Contact: Alexandre Borthomieu

Participants: Alexandre Borthomieu, Peter Sturm, Jean-Yves Courtonne, Vincent Jost

Partners: INP Grenoble, CNRS, UGA

8 New results

8.1 Systemic risks: global and local

Participants: Antonin Berthe, Enzo Baquet, Valérie d'Acremont, Louis Delannoy, Serge Fenet, Pierre-Yves Longaretti, Mathieu Mangeot, Hugo Martin, Emmanuel Prados, Peter Sturm.

The Global Systemic Risks research axis of the team focuses at present on the analysis of the energy/macroeconomics/finance nexus on the one hand (conducted by Pierre-Yves Longaretti and Hugo Martin) and on the feasability of the energy transition on the other (conducted by Pierre-Yves Longaretti and Antonin Berthe). The choice of this topic is driven by the central role of energy in developed countries societies and economies. The specific approach adopted here focuses on critical topics that are not much investigated in the existing literature on the energy transition. Both activities are conducted through the elaboration of dedicated models, see next. We now investigate systemic risks also on local scales, as described in the last two parts of this section.

8.1.1 CRISIS model

The CRISIS model (Cascading Reactions in Society's Interconnected Systems) is designed to address the major issue of the nexus just mentioned, i.e., the role of energy tensions and financial speculation on structural macroeconomic crises. In particular, this model aims at pinpointing the dynamical conditions leading to long term economic decline and its consequences. This model has been calibrated this year and a central scenario is currently explored.

8.1.2 Feasibility of energy transition

The feasability of the energy transition research effort focuses on two aspects: speed and depth of penetration of the electric vehicle transition and speed of deployment of renewable sources of energy, through the elaboration of dedicated models. The main research question addressed in this way is the ability to cope with present and upcoming tensions on oil flows in the economy, due to increasing energy costs of oil exploitation (a topic explored in depth in the course of the PhD thesis of Louis Delannoy [42], see also our related works [18, 16]).

8.1.3 Systemic crisis propagation: study of the health sector

In January 2022, Enzo Baquet started a PhD thesis focusing on the analysis of the dynamics of the propagation of intra- and inter-sectoral disruptions in the context of short-term crises. This work will ultimately lead on the creation of a modeling methodology, but it first focuses on the development of a particular model guided by the central case study: the impact of an electrical blackout on the civil health infrastructure. In this context, Enzo is currently doing a 6-month research stay at the Unisanté center of the University of Lausanne, our partner. In a participatory approach, he currently works on formalizing with the actors involved a description of their perception of the anticpated impacts (their different possible states, as well as the probabilities of transition between different types of degraded states). Afterwards, Enzo will focus on a criticality analysis of the intra- and inter-sector connections identified in the first step, and that constitute the main vectors of crisis propagation. This type of analysis is based on a typology of relevant modes of criticality (for example, vulnerability/redundancy of inter-sectoral connections, intensity of said connections, etc.), and not only constitutes an obligatory and common point of passage whatever the modeling method, but is also a scientific production in itself, in which systemic analysis plays a crucial role for the academic community as well as for involved stake-holders.

8.1.4 Local Risk Report for the Grenoble Metropolitan Area

The local authorities of Grenoble and adjacent territories[2] have launched a long-term initiative entitled *l'Atelier des Futurs*. Its goal is to reconsider public action with regard to the complexity of current and coming issues (social, economic, environmental) and often contradictory injunctions between the urgencies of the short term and the uncertainties of the long term. To be able to better understand the changes linked to the climate and social degradations, and the associated public action methods, to share knowledge and experiences: these are the expectations expressed by elected officials faced with the complexity of territorial issues. STEEP was the first academic partner to join the initiative and sign (through Inria) its charter. We are particularly interested in aspects related to territorial prospective, participation, and risk analysis which are at the heart of the initiative. The first concrete action launched within *l'Atelier des Futurs* is concerned with the creation of a "Local Risk Report" for the area (about 500,000 inhabitants), nicknamed RARRe (Rapport annuel sur les risques et la résilience dans la région Grenobloise). STEEP has been involved since the beginning, to provide scientific and general expertise. The idea of this action is to identify vulnerabilities and especially, systemic links between them, as well as attenuation or preparation measures, on an annual basis, inspired by the Davos Economic Forum's annual Global Risk report. 2022 was dedicated to the specification of the perimeter of the first Local Risk Report and of the processes to be used to establish and later disseminate this first report. Our Systemic Risk Fresco (see Section 10.3.3) was used, among other approaches, to fuel discussions.

[2] Grenoble Alpes Métropole, Département de l'Isère, EP SCoT de la Grande Région de Grenoble, Ville de Grenoble, Massif du Vercors, Pays Voironnais, Le Grésivaudan, Parcs de Chartreuse et du Vercors, Agence d'urbanisme.

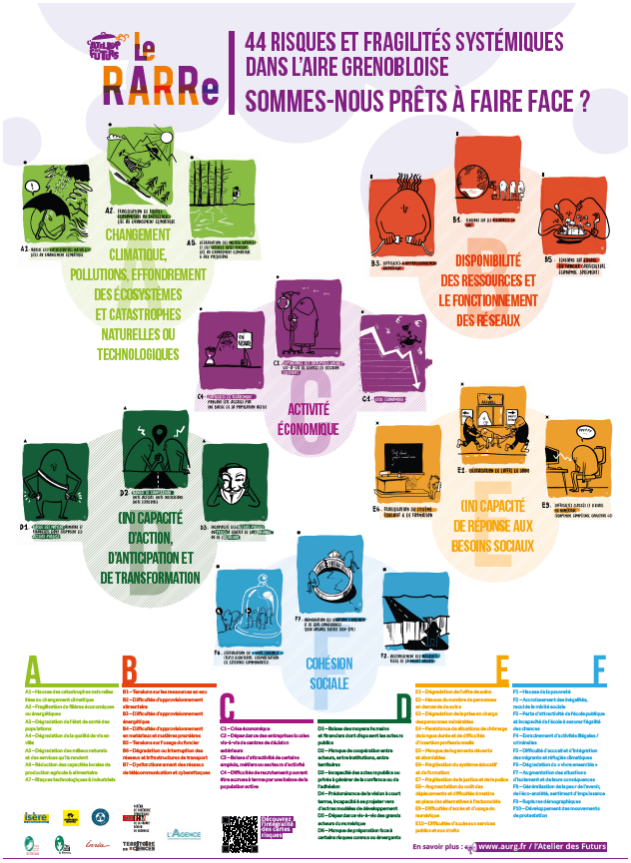

Figure 6: Overview of the 6 families of risks identified in the *l'Atelier des Futurs* initiative.

In 2023, 44 risks were identified as relevant to the Grenoble area. They are grouped into 6 thematic families (see Figure 6):

- Climate change, pollution, ecosystem collapse and natural or technological disasters
- (Un) availability of ressources and (dys) functioning of networks
- Economic activities
- (In) ability to act, anticipate and transform
- (In) capacity to respond to social needs
- Social cohesion

A questionnaire was created, tested, and then submitted to three panels of stakeholders (elected officials, citizens, business owners). The goal is to understand how these risks are perceived by the population, in terms of gravity, likelihood (or being already in existence), possibility to act against them, the effect of actions already in place, the differentiation between local and global impacts of risks, etc. The collected responses are currently being analyzed. First results as well as the philosophy of the overall project, will be presented on 6 February 2024 to a forum for elected officials of the Grenoble area, and the first edition of the planned yearly local risk report is planned for spring 2024. This first edition will present the full analysis of the results obtained with the risk perception survey, as well as a description of the above cited risks, including a description of scientific or other knowledge on them, especially pertaining to the local impacts.

8.2 Historical and current evolution of the EROI for oil and gas

Participants: Louis Delannoy, Pierre-Yves Longaretti, Emmanuel Prados.

As fossil fuels are exploited, they become more difficult to access and require more energy to extract. The continued decline in the EROI (energy return on (energy) investment) of oil and gas is therefore of concern, as these two energy sources still account for 52% of global energy consumption. However, these ratios are measured at the primary energy stage and should rather be estimated at the final or useful stage, where the energy is closest to the reality of economic processes. Following this principle, the EROI of fossil fuels are today comparable to or even lower than those of renewable energies (including short-term energy storage technologies in the calculation). This is part of the emerging consensus of the net energy analysis community, but its dissemination is hampered by frequent misunderstandings about EROI inherited from the lack of a formal methodology before the 2010s. To address this, we present the various steps that led to this emerging consensus, synthetize the EROIs of oil and gas at the primary, final, and useful stages from 1971 to 2019, and discuss the implications for the low-carbon transition [15]. This work is based on our previous works on EROI, such as [6, 7, 42].

8.3 Study of an economy under contraction

Participants: Albert Bouffange, Jean-Yves Courtonne, Jérémie Klein, Agnès Labrousse, Guillaume Mandil, Mathieu Mangeot.

This work is based on the internships of Jérémie Klein and Albert Bouffange [50]. Both of them have continued their work in the STEEP team as PhD students.

The Cuban special period is one of the rare cases in history when a country's economy suffered a sharp contraction in its supplies of raw materials essential to its metabolic functioning. This happened after the collapse of the USSR in 1991, which was Cuba's main trading partner, when the island saw its imports of several raw materials plummet. Major changes were made to cope with this shock. To study the territory during this period, flow data and coefficients from the Food and Agriculture Organization of the United Nation, the International Energy Agency, scientific and grey literature were collected. Then, using the data reconciliation tools of our team, analyses of material and energy flows enabled us to take a closer look at the Cuban metabolism before and after the collapse of the USSR. An approach by the economic actors (formal and informal) have made it possible to highlight the question of the organization mode for the agricultural system, highlighting the role of institution and their various links in the agricultural system. Overall, the island of Cuba saw its oil supply fall by more than 60% between 1989 and 1993, and its fertilizer supply by more than 70%. Differences by economic sector were highlighted, with some sectors particularly affected materially, such as transport. Via a number of social indicators (Gini index, life expectancy, quality of education, access to electricity, etc) the state of satisfaction of human needs was studied. We can see that the quality of energy, education and healthcare services has been only slightly affected by the severe energy constraints. Political choices can therefore be made to prioritize the satisfaction of needs, even in times of crisis. However, by comparing energy intensity at this period with low-consumption scenarios, we show some limits to how the Cuban case can serve as a basis for thinking about an ecologically sustainable society. It seems to be still too much dependant to fossil fuels. This historical case study allows us to imagine what could happen to our economies in the event of an energy contraction, the extent to which our human needs can or cannot continue to be met, and the questions of social organization that such an event would entail.

8.4 Territorialization of planetary boundaries

Participants: Guillaume Mandil, Gwendoline de Oliveira Neves, Damien Rieutor.

The aim of Damien Rieutor's PhD thesis is to provide a framework for downscaling the concept of planetary boundaries to the territorial level. This concept is an undeniable success of Earth system science. This success has attracted the attention of other scientific fields and sectors, notably public institutions, transforming reflections on local implementation of the concept into a major scientific and societal issue. Numerous attempts to implement the concept on a sub-global scale have raised a number of questions about this approach, and have highlighted the difficulties of operationalizing 'Planetary Limits' locally. These difficulties are due mainly to the dominant approach employed, which seeks above all to spatialize the Planetary Limits framework. The literature review we have carried out in this work examines this approach with regard to the distinction between the framework of Planetary Limits (biophysical dimension, spatial vision) and the concept of Planetary Limits (sociological dimension, territorial vision). Our results show that, by focusing on the biophysical aspects of the framework, it obscures the anthropological objectives of the concept and reduces the importance of the social specificities of the context. In this way, we demonstrate the limits of spatializing the framework. It hinders the concept's local operationalization, weakening its appropriation by territorial stakeholders and maintaining inconsistencies between the concept's global essence, its sub-global translation and local socio-biophysical specificities.

8.5 Analysis of public policies dedicated to building waste

Participants: Jean-Yves Courtonne, Quentin Desvaux, Catherine Figuière, Guillaume Mandil.

Since November 1st, 2020, Quentin Desvaux has been involved in a CIFRE PhD thesis with the STEEP team, the CREG lab and the DPCTD (Direction de la Prévention, de la Collecte et du Traitement des Déchets) of Grenoble Alpes Métropole. The goal is to support the local authority in deploying a waste management strategy for the construction sector that is consistent with the specific features of its territory. The year 2023 was devoted to completing the work undertaken: finalizing the analysis of construction waste management and processing channels (based in particular on the team's material flow analysis tools); operational implementation of policy measures; coordination of working groups; perpetuation of the dynamics initiated with the stakeholders involved; restitution, promotion and dissemination of Quentin's work through public institutions. This work is a contribution towards the decompartmentalization of the academic and professional sectors. A journal article has been submitted recently.

8.6 Water and work flows in the French agriculture

Participants: Jean-Yves Courtonne, Hannah Gelblat-Laugier.

Hannah Gelblat conducted her master's internship in the context of Ademe's SCALABLE project where the STEEP teams and INRAE (Lessem Lab) are involved. She explored data sources related to water and labor used by the French agriculture sector. Regarding water, irrigation needs (blue water) were assessed based on plant needs and rainfall (under the current climate and a 2050 climate scenario). It emphasizes the role seasonality plays to account for water needs. Regarding labour time, bottom-up approaches (based on data from the Chambres d'Agriculture) were compared with top-down approches (based on EXIOBASE environmental and social extensions) and show a large uncertainty range.

8.7 Numerical tools for data and parameter reconciliation

Participants: Alexandre Borthomieu, Jean-Yves Courtonne, Vincent Jost, Guillaume Mandil, Mathieu Mangeot, Olivier Mauviel, Peter Sturm.

Data reconciliation is an important building block for MFA (material flow analysis) and other problems with a similar structure, such as in chemical plant modeling. The goal is to construct a consistent representation of, for instance, an economic supply chain or a set of processes (production processes, chemical ones, etc.) that are related through flows (of materials, substances, goods, etc.). This representation usually has a graph structure and numerical values to be determined usually concern the mentioned flows as well as technical coefficients characterizing the processes. These values are determined from data, which are often only partially available, subject to uncertainties, and incoherent. The data reconciliation problem entails the estimation of coherent numerical values from such data, using constraints, such as mass preservation, aggregation constraints, or others that might be available (such as known inequalities between certain values). Data reconciliation can be followed up by an estimation of the values' uncertainty. In our applications, uncertainties are usually represented by uncertainty intervals. The above mentioned constraints often allow to narrow down given uncertainty intervals – we speak of "interval reduction" here [26]. This year we have developed several methods for interval reduction. We also set up a benchmark for the interval reduction problem, including test data, ground truth and visualization methods (see Section 7.1.4).

Data reconciliation is used in representing an *observed* supply chain or other set of interrelated processes. STEEP also aims at developing tools to conceive, model and assess *potential* socio-technical alternatives (STA's), e.g. for territorial prospective exercises. When modeling STA's, reconciliation problems also appear, but they are of a different nature. The construction of an STA relies on choosing involved processes (such as transformation processes in agro-food chains or industrial production processes) and connect them according to the material or other flows they are related through. Now, for any given type of production, several alternative processes may be available (such as organic and conventional agriculture) and it is natural for a user to think of an STA in terms of relative shares between such alternative processes. Obviously, when defining desired shares for different sets of alternatives processes, the induced flows among all them are in general not coherent. This creates the need of a new reconciliation problem: instead of operating on flow values, it operates on the mentioned relative shares. We speak of parameter reconciliation [32]. We have developed and compared two mathematical formulations for parameter reconciliation (differing in the type of cost function used) and started to develop a software on top of them that shall enable interactive construction of STA's (STA-Explorer, see Section 7.1.2).

8.8 Serious games for the exploration and analysis of sociotechnical alternatives

Participants: Mathilde Boissier, Jean-Yves Courtonne, Ariane Dauvergne, Nils Ferrand, Vincent Jost, Achraf Kerzazi, Emmanuel Krieger, Mathieu Mangeot, Roger Pissard, Peter Sturm.

Accounting in biophysical flows is one grid of analysis providing insights on the sustainability of sociotechnical alternatives. These tools are indeed relevant to highlight systemic effects (interdisciplinary understandings, spatial and temporal scales) on resources and important pressures to consider for the transformation of territories. Yet, this biophysical flow vision remains for expert use only, whereas one of the challenges of transition territories is to involve the populations in participatory processes. Among diverse participatory tools, serious games have long since proven their ability to sensitize to sustainability issues, facilitate learning and support changes. We aim to develop several games to play with material and energy flows while discussing the futur of their territories. This involves every stage of modeling (capturing reality into a biophysical and governance model, making this model simple enough to be played with, and bring back this model into the real world to collectively transform a territory's organization), game design as well as lab and field experiments. After developing two simple games in 2022 (see last year's report and [25]), we have designed a modeling framework – TransKey – based on social metabolism, see [24]. Software implementation of a TransKey simulation platform has started this year (see Section 7.1.3), with the support of Roger Pissard and Laurence Boissieux from the Inria Grenoble SED service. A first fully playable version of a single-user game has been completed (see Figure 7 for a screenshot). After internal tests, it was tested through user experiments based on a taylor-made experimental protocol. These tests were carried out by the Floralis service of Université Grenoble Alpes in

the last three months of 2023. The gathered experimental and qualitative data have started to be analyzed at the time of writing of this report.

Another serious game was developed during the internship of Ariane Dauvergne [51]. Its goal is to sensitize players to the role of economic and power relations in the growing environmental and social crises.

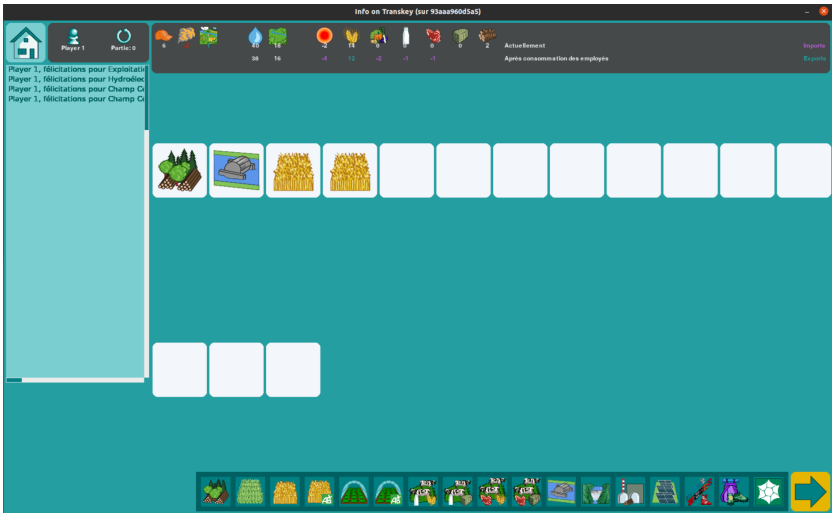

Figure 7: Screenshot of the first game developed based on the TransKey framework.

8.9 Participatory exercises in territories

Participants: Mathilde Boissier, Jean-Yves Courtonne, Nils Ferrand, Emmanuel Krieger, Peter Sturm.

Since about 2021, we have started to work towards the creation of participatory exercises, to assist in the face of transition challenges in territories. See [30] for a brief overview of our philosophy. We have been working on two territories, as follows.

The first project is the PETR du Grand Briançonnais (Pôle d'Equilibre Territorial et Rural – Briançonnais, Ecrins et Guillestrois Queyras), a so-called intercommunalité (grouping of 3 *communautés de communes*, comprising a total of 36 municipalities), located in the French Alps. This territory experiences recurring conflicts around the construction of hydroelectric power stations in mountain rivers, usually opposing energy producers, elected officials and NGO's dedicated to nature preservation. On this background, the presidency of the PETR launched the initiative of a territory-wide participatory process, to be steered by STEEP and Nils Ferrand's group at INRAE, covering the issues of energy, biodiversity, water, and territorial development. The year 2022 had seen the launch of the project with individual interviews and first meetings to better understand the territorial context and initiate the participatory process. Simple Sankey diagrams illustrating energy flows on the territory (created using the software described in Section refbil-3723) had also been put to the test. In 2023, procedural work has been conducted to formalize the project, helping the PETR to get funding from the Banque des Territoires (granted in the end of 2023). Based on this funding, the PETR and Inria are currently setting up a formal collaboration agreement to subtend the participatory exercise, expected to last throughout 2024 and 2025. In 2023, we have also conducted workshops to make stakeholders organize the participation (PrePAR approach), guiding them through a collective decision process about the next steps of the dialogue. A charter defining the common objectives and groundrules is also in progress. This procedural step should end in the beginning of 2024, making way for scientific and dialogue workshops directly related to resource management. The project has been presented to elected officials and other stakeholders of the territory, in November 2023, see 10.3.5.

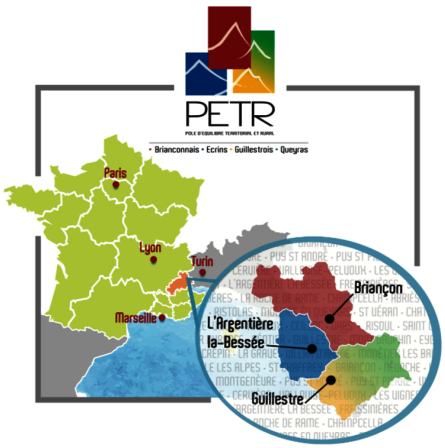

Figure 8: The territory of the PETR du Grand Briançonnais (Pôle d'Equilibre Territorial et Rural – Briançonnais, Ecrins et Guillestrois Queyras).

The second territory is the greater Grenoble area and the perimeter of the programmed participative process is the establishment of an interterritorial food plan (Projet Alimentaire inter-Territorial (PAiT) de la grande région Grenobloise). Within the Scalable project (see Section 9.3.2), STEEP is involved both in quantitative/analytical modeling and in the development of a participative approach. During 2023, two workshops have been organized (one on the milk sector and the other on the large culture sector). During these workshops, the results of the quantitative modeling realized thanks to surveys have been presented and discussed to evaluate the sectors' vulnerabilities and levers for action. This was also the opportunity to mix different stakeholders (economic operators of the sectors and project managers for the territorial collectivities). Finally, an additional aim was to get some insights about how the biophysical quantitative models can support dialogue and transitions.

8.10 Research group "Contremodélisation"

Participants: Mathilde Boissier, Guillaume Mandil, Mathieu Mangeot, Sophie Wahnich.

Created during the conference Archipel 2022, the group Contremodélisation focuses on modeling and the social impact of models. Around 15 researchers meet up once a month to collectively open up a critical and constructive space for questioning a model's life cycle in its entirety (order, context and design choices, use and impacts), right up to the very relevance of modeling. This group provides an opportunity to share practices and analysis grids in order to build an inter- and trans-disciplinary framework for putting modeling to the test. Finally, the aim is to involve the modeling community and society in this critical work through practical, training and teaching activities.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Participation in other International Programs

- Serge Fenet is involved in a collaboration with the University of Lausanne (UNIL), Department of Ecology and Evolution (Jérôme Gippet) and the University of Helsinki, Organismal and Evolutionary Biology Research Program (Charles Rocabert), working on the development of the MoRIS model of propagation of invasive species.

9.2 International research visitors

9.2.1 Visits to international teams

Research stays abroad

Léon Fauste

Visited institution: ICTA Lab (Institut de Ciència i Tecnologia Ambientals), Universitat Autònoma de Barcelona

Country: Spain

Dates: 3 weeks in June 2023

Context of the visit: Léon worked under the supervision of Mario Giampietro and Raúl Velasco-Fernández on a model to help determine what level of food autonomy is reachable for a given territory and, conversely, what is the smallest scale where a given autonomy can be reached.

Mobility program/type of mobility: Research stay

Enzo Baquet

Visited institution: Unisanté, Université de Lausanne

Country: Switzerland

Dates: September 2023 to February 2024

Context of the visit: This visit is done in the context of the research on systemic risks on the health sector, cf. Section 8.1.3.

Mobility program/type of mobility: Research stay

9.3 National initiatives

9.3.1 LINDDA – Living INfrastructure to Design responsible Digital technology for Agroecological transition

Participants: Mathilde Boissier, Jean-Yves Courtonne, Nils Ferrand, Guillaume Mandil, Mathieu Mangeot, Peter Sturm.

Project funded by PEPR program
Duration: 2022-2027 (5 years)
Coordinator: Muriel Mambrini (Learning Planet Institute), Peter Sturm for Inria partner.
Partners: Learning Planet Institute, CY School of Design, STEEP, Conservatoire National des Arts et Métiers, ITAP/Inrae, G-EAU/Inrae.
Keywords: agroecology, design, transition, participation.
Abstract: The project is part of a program on Agroecology and Digital. It will subtend our work on participation in the STA axis (Section 3.2) and will provide the opportunity to collaborate with experts in Design (for games, interfaces, intermediation). Further, the project will give us access to student groups for field work.

9.3.2 SCALABLE – Metabolism of agricultural biomass: multi-scale representations, vulnerability analysis and evaluation by local stakeholders

Participants: Mathilde Boissier, Jean-Yves Courtonne, Nils Ferrand, Sophie Madelrieux, Guillaume Mandil.

Project funded by ADEME
Duration: 2021-2024 (36 months)
Coordinator: Sophie Madelrieux (Inrae Grenoble), Jean-Yves Courtonne for Inria partner.
Partners: LESSEM (Inrae Grenoble), Auvergne-Rhône-Alpes Énergie Environnement, TerriFlux, Parc Naturel Régional de Chartreuse, STEEP (Inria Grenoble).
Keywords: agriculture value chains, multi-scale analysis, multicriteria analysis, vulnerabilities, participative evaluation.
Abstract: SCALABLE focuses on agricultural biomass, on the different transformation steps (supply chain) from production to consumption, at several geographical scales (national, regional, local). The projects aims at improving knowledge on material and organizational vulnerabilities of territories with respect to these supply chains: to what extent are the needs of the local population satisfied in a sustainable way, and without transferring vulnerabilities to other territories? This work will be conducted by coupling an analytical approach (use of descriptive models) with a deliberative approach (evaluation by local stakeholders). It will also lay a basis for assessing the relevant scales of relocation of the different sectors of the value chains.

9.3.3 TRAJECLIM – Resilience of a polar socio-ecosystem facing anthropic and climate change

Participants: Serge Fenet.

Project funded by CNRS
Duration: 2021-2023 (14 months)
Coordinator: Roman Teisserenc (Laboratoire Ecologie Fonctionnelle et Environnement, UMR5245), Serge Fenet for Inria partner.
Partners: UMR5503 (INP, Toulouse), UMR5245 (Université Paul Sabatier, Toulouse), UMR8212 (Gif-sur-Yvette), EA3816 (FoReLLIS, Poitiers), EA827 (Laboratoire d'Études et de Recherches Appliquées en Sciences Sociales, Toulouse), STEEP (Inria Grenoble).
Keywords: island model, systemic approach, résilience, systemic levers, storytelling.
Abstract: As a polar city of 5000 inhabitants created ex-nihilo in 1929, Igarka is a small urban island in the middle of Siberia that suffers from climate change, social decline (-75% of inhabitants), and industrial decline (linked to the cessation of forest exploitation at the end of the 20th century). However, the accounts of the inhabitants talk about both optimism and resilience in the face of these global trajectory bifurcations, mainly forced by the climatic repercussions of human activities, and by political context. Thus, in a sense, Igarka can be considered as a herald for our own territories and societies confronted to the current global changes. Preparing a Horizon Europe project, TRAJECLIM project wants to initiate an interdisciplinary analysis of Igarka's trajectory and its observed resilience, using multiple systemic approaches. It will rely on the study of the biogeochemical carbon and contaminants cycles, as well as indigenous, historical, literary and artistic narratives from the city inhabitants. It will produce a meta-analysis of the dynamics and bifurcation points the city had to deal with, as well as an inventory of the levers and tools of resilience invented by the population in the face of climate change.

9.3.4 SysPart – Participatory research into the use and impact of material flow models for forecasting the challenges of territorial transitions

Participants: Mathilde Boissier, Jean-Yves Courtonne, Nils Ferrand, Mathieu Mangeot, Sophie Wahnich.

Project funded by CNRS MITI (Mission for Transversal and Interdisciplinary Initiatives)
Duration: 2022-2023
Partners: Universite‘ Savoie Mont Blanc (Myriam Donsimoni).
Keywords: participation, material flow analysis, prospective, transition.
Abstract: This project subtended some of the research activities described in Sections 8.8 and 8.9.

9.3.5 BACCFIRE

Participants: Jean-Yves Courtonne.

Project funded by Ademe
Duration: 2022-2024
Partners: ONF, FCBA, INRAE, IGN and TerriFlux.
Keywords: Forestry and timber sector, storage, sequestration, substitution, material flow analysis, life cycle analysis.
Abstract: The goal is to better assess what role the forest-wood supply chain can play for climate mitigation.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Exergy Economics Workshop We co-organized, together with Paul Brockway of Leeds University, the 7th edition of the International Exergy Economics Workshop (IEEW2023), which was held from 10–12 July 2023 in Challes-les-Eaux, France. Over 40 researchers, mostly from Europe and the USA, met over 3 days to discuss the state and future of the research field of exergy economics, and its application to important topics including energy and material constraints, economic growth and policy.

Peter Sturm and Louis Delannoy were in charge of the local organization and Louis Delannoy participated to the programme committee.

Winter School on Sustainability Modeling of Complex Agroecological Systems In december 2023, we co-organized, together with Elisa Hittner and Sophie Madelrieux from INRAE, a winter school on Sustainability Modeling of Complex Agroecological Systems: Challenges and Alternatives to Current Approaches. The instructors were Mario Giampietro and Ansel Renner from Universitat Autònoma de Barcelona. The event, held in Grenoble, lasted 3 days and was attended by 20 participants, about two thirds of which were PhD students or post-docs.

Member of organizing committees

- Emmanuel Prados was a member of the organizing committee for the "Entreprendre dans l’anthropocène: Agir, travailler, entreprendre dans un monde en transition" days, organized on 29 and 30 March 2023 in Grenoble by the UGA Design Factory. See also this website.

Member of conference program committees

- Organized by STEEP in June 2022, the Archipel conference "Systemic Risks, Trajectories and Levers for Action" was a first step towards building a transdisciplinary scientific collective that would

bring to the fore questions, salient points, frameworks of thought, methods and tools for tackling current systemic risks, and more generally the futures of our societies. The second edition of the conference is scheduled for April 2024, but in order to maintain the initial momentum, the 2022 and 2024 program committees have proposed an intermediate meeting in June 2023 in Lyon. The purpose of these days was to help the working groups set up in 2022 to make progress in their collective work, and to present to the community the work already carried out during this first year. Serge Fenet, Emmanuel Prados and Sophie Wahnich took part in the programme committee.

10.1.2 Journals

Reviewer - reviewing activities

- Jean-Yves Courtonne was a reviewer for the following journals: Forest Ecosystems, Frontiers in Nutrition.

10.1.3 Invited talks

- Nils Ferrand gave an invited seminar at United Nations University, Macao, on Modeling for Change, Cross-Ethics and Stakeholders, 16 June 2023.
- Nils Ferrand gave an invited talk on "Exploring the design of participatory and transformative research, and research on participatory transformation" [59] at a workshop on Transformative Research at Australian National University, Canberra.
- Nils Ferrand gave a presentation on "Processus participatifs et engagement des chercheurs dans l'Appui aux Politiques Publiques dans les territoires" [58], INRAE, March 2023.
- Nils Ferrand gave a presentation on Processus décisionnels mobilisant des modèles de métabolisme dans le secteur forêts-bois at a seminar organized by Des Hommes et Des Arbres, Nancy, December 2023.
- Nils Ferrand gave a presentation on "Innovative pathways for an efficient co-design and extension of socio-environmental change between scientists and… others" [57] at the advanced training course on "Science-Policy Interface", Ghent University, December 2023.
- Peter Sturm gave an invited talk on "Rebound effects, efficiency, frugality, resilience: The importance of the questions one asks" at the Journées plénières du GdR IG-RV (Informatique Géométrique et Graphique, Réalité Virtuelle et Visualisation), Lyon, 2023.
- Peter Sturm (with Didier Mallarino) gave the opening address to the Doctoriades of Toulon University, December 2023.
- Peter Sturm participated to the round table "Which place for AI in the ecological transition?", held during the Journées de Recherche en Apprentissage Frugal, Grenoble, France, December 2023.
- Peter Sturm gave a presentation of the Framework Convention between Inria and the French Ministry of Culture at the workshop Art&Science as a research enabler, CEA, Grenoble, France, November 2023.
- Peter Sturm gave a keynote on "A historical survey of geometric computer vision" at the Journées Jeunes Chercheurs ORASIS, Carqueiranne, France, May 2023.
- Jean-Yves Courtonne gave a presentation on Material Flow Analysis methods and tools at the EVS Lab, Lyon, December 2023.
- Jean-Yves Courtonne gave a presentation on the stakes of the Anthropocene during the opening meeting of the CRAT-R project (Ideas Laboratory, CEA Grenoble), online, March 2023.
- Jean-Yves Courtonne gave a presentation on the STEEP team research program at the annual seminar of the DILS LAB (CEA-List), online, April 2023.

- Emmanuel Prados took part in the round table entitled "Organization of degrowth: what are we talking about?" organized by Grenoble INP - ENSE3 in conjunction with the PISTE training course "For a Sober Techno and Eco-Responsible Engineering" on 19 January 2023. This round-table discussion featured 3 speakers who are experts in degrowth from different perspectives (economic, social, philosophical, hard sciences, etc.)

- Emmanuel Prados was invited to speak at the seminar on nuclear disarmament organized by ICAN on 14 March 2023, in the session "Penser l'effondrement" ("Thinking about collapse").

- Emmanuel Prados was invited to lead a workshop as part of the seminar "Agir, travailler, entreprendre dans un monde en transition" ("Acting, working, undertaking in a world in transition") which took place on 29 and 30 March 2023 at the University of Grenoble.

- Emmanuel Prados has been invited to give a lecture and workshop on "Understanding the coming collapse: causes, consequences and room for manoeuvre" on 14 December 2023 at the University of Strasbourg as part of the lecture series "Se (re)construire dans un monde numérique: Penser les crises à venir et défis futurs".

- Pierre-Yves Longaretti was invited to give a seminar on "Frugality and rebound effects. Challenges, lock-ins, leverages." Labos1point5, January 10, 2023. .

- Pierre-Yves Longaretti has given an invited seminar in the ethics seminar program of IRMAR. "Sobriété. Enjeux, blocages, leviers." INSA and Rennes University, 10 novembre 2023.

10.1.4 Leadership within the scientific community

- Emmanuel Prados, Sophie Wahnich and Mathieu Mangeot have led and/or facilitated working groups as part of the Archipel community:
  - The "Sociotechnical alternatives in a perspective of radical transformation" group.
  - The "Draft Charter for the Archipel Community" group, which led to the drafting of the Archipel Community Charter.

10.1.5 Scientific expertise

- Formation à la transition écologique. Pierre-Yves Longaretti is member of the Rhône-Alpes scientific committee in charge of organizing training courses for all French public service executives, an initiative of the French government. Jean-Yves Courtonne, Pierre-Yves Long and Guillaume Mandil are part of the team of scientists who will be giving these training courses, which should cover at a basic level a panel of environmental issues, with a focus on climate change, resources and biodiversity.

- Emmanuel Prados and Jean-Yves Courtonne are members of the scientific committee of the city of Grenoble.

- Jean-Yves Courtonne is a member of the Steering Committee (COPIL) of the Territory consortium.

- Pierre-Yves Longaretti is member of the scientific committee of the Idée project (Innovation et Développement pour une Economie Environnementale, Grand Annecy)

- Guillaume Mandil is member of the scientific committe of the Parc Naturel Régional de Chartreuse since September 2020.

- Peter Sturm is member of the Steering Committee (COTECH) of *Atelier des Futurs* (see Section 8.1.4).

- Peter Sturm was member of the selection comittee for a Junior Professorship at INSA Lyon.

- Peter Sturm acted as expert for professorship promotions, The University of Hong Kong.

10.1.6 Research administration

- Nils Ferrand is member of the steering group of the *Projet Prioritaire International Forêts*, INRAE.
- Emmanuel Prados and Guillaume Mandil are members of the Campus D'Après initiative: a cross-disciplinary collective of academic researchers of the grenoble area who share a common goal: to better understand and reduce the direct and indirect environmental impact of research.
- Peter Sturm is member of the direction of Laboratoire Jean Kuntzmann since 2023.
- Jean-Yves Courtonne represents Inria at the Council of UFR IM2AG (Teaching Department *Informatique, mathématiques et mathématiques appliquées* of Université Grenoble Alpes).

10.2 Teaching - Supervision - Juries

10.2.1 Teaching

The Anthropocene FACTS project, initiated in 2020, has been paused in 2023, but its main objectives and activities have been taken over by the Design Factory department at UGA, where Guillaume Mandil, the principal STEEP contributor to Anthropocene FACTS, is involved. These activities include, in particular, the introduction of undergraduate-level teaching on ecological transition and sustainable development (TEDS) accessible to all UGA undergraduate courses, as well as a "train the trainer" program for teachers (from UGA and other universities in France).

- Denis Dupré, Serge Fenet, Guillaume Mandil, and Mathieu Mangeot have regular teaching duties at the universities employing them.
- Jean-Yves Courtonne, Serge Fenet, Guillaume Mandil, Emmanuel Prados, and Peter Sturm: Les véritables enjeux environnementaux – compréhension, modélisations et outils quantitatifs, 30 hours, course plus project work, Master course, Ecole Centrale de Marseille.
- Jean-Yves Courtonne, Serge Fenet, Pierre-Yves Longaretti, Guillaume Mandil, Emmanuel Prados, and Peter Sturm: Les véritables enjeux environnementaux – compréhension, modélisations et outils quantitatifs, 24 hours course plus project work, MSTII Graduate School and L3 Computer science, UGA.
- Denis Dupré, Jean-Yves Courtonne, Guillaume Mandil: Science, Environnement, Société, Doctoral School (CED) UGA.
- Jean-Yves Courtonne : modélisation quantitative et analyse de flux de matière, 10 hours of tutoring for Master 1 students, IDDAT (IUGA, UGA).
- Jean-Yves Courtonne : intérêts composés et croissance exponentielle, 20 hours of courses and tutoring for Master 1 students, MIAGE (IM2AG, UGA).
- Peter Sturm, Emmanuel Prados, Jean-Yves Courtonne : évaluation environnementale et blocages à l'action, 24 hours of courses and tutoring for post-master students, TEET (ENSE3, Grenoble INP).
- Pierre-Yves Longaretti, "Changements globaux, limites planétaires, risques globaux". 6h lecture in the first year course "Enjeux energie, climat et ordre de grandeurs et analyse dimensionnelle" PHY208, UGA.
- Pierre-Yves Longaretti, "Réduction des impacts environnementaux: sobriété, croissance, découplage, effets rebond". 2h lecture at INSA Rennes (November 2023)
- Nils ferrand, Master course on Transition Design (UGA, 18h)
- Nils Ferrand, UN university course on participatory processes, United Nations University, Macao, 4h.

10.2.2 Supervision

- PhD defended this year: Louis Delannoy, "An exploration of the systemic risks emerging from the interaction between energy, finance and the economy", supervised by Pierre-Yves Longaretti and Emmanuel Prados. Defended on 14 September, 2023.

- PhD abandoned this year: Olivier Mauviel, "Méthodologie de conception d'alternatives socio-techniques", supervised by Peter Sturm, Jean-Yves Courtonne, Guillaume Mandil.

- PhD in progress: Enzo Baquet, "Analyse de la dynamique de propagation des perturbations intra et inter-sectorielle dans le contexte de crises à court terme", supervised by Serge Fenet, Pierre-Yves Longaretti, and Mathieu Mangeot.

- PhD in progress: Antonin Berthe, "Etude de la faisabilité de la transition énergétique. Modélisation des couplages énergie-matière.", supervised by Pierre-Yves Longaretti, Emmanuel Prados, Olivier Vidal (ISTerre).

- PhD in progress: Alexandre Borthomieu, "Méthodologie de description d'évaluation multicritère d'alternatives socio-techniques", supervised by Peter Sturm, Jean-Yves Courtonne, Vincent Jost (G-SCOP), Guillaume Mandil.

- PhD in progress: Albert Bouffange, "Penser les contractions matérielles pour la France en liant économie politique et flux de matière et d'énergie", supervised by Agnès Labrousse (Sciences-Po Lyon), Emmanuel Prados, and Pierre-Yves Longaretti.

- PhD in progress: Quentin Desvaux, "Re-conception de systèmes de production durables et territorialisés - apports croisés de l'écologie territoriale et de l'économie politique", supervised by Catherine Figuière (CREG), Guillaume Mandil, Jean-Yves Courtonne.

- PhD in progress: Léon Fauste, "Relocalisation d'industrie productive : une approche par les graphes et les contraintes", supervised by Christine Solnon (Lyon University), Mathieu Mangeot, and Jean-Yves Courtonne.

- PhD in progress: Jérémie Klein, "Outils numériques de modélisation fonctionnelle pour l'aide à la décision dans l'évaluation des transitions sous contraintes", supervised by Guillaume Mandil, Jean-Yves Courtonne, Peter Sturm, and Bernard Tourancheau (LIG).

- PhD in progress: Emmanuel Krieger, "Modélisation socio-technique de territoires : modèles numériques et jeux sérieux", supervised by Peter Sturm, Nils Ferrand, and Jean-Yves Courtonne.

- PhD in progress: Damien Rieutor, "Implémentation locale du concept des 'Limites Planétaires'. Méthodologie de transposition territoriale des spécificités du concept de Limites Planétaires pour évaluer la criticité environnementale locale", supervised by Guillaume Mandil, Gwendoline de Oliveira Neves (Universidad Pablo de Olavide, Seville, Spain).

Sophie Wahnich (co-)supervises several PhD theses outside of STEEP, one being related to our considerations on territorial issues: Karla Candeia, "Le mouvement des sans terre au Bresil", EHESS.

10.2.3 Juries

- Peter Sturm was reviewer of the PhD thesis of Torben Fetzer (University of Kaiserslautern-Landau, Germany).

- Peter Sturm is member of the *Comité de thèse* of Rémi Mourgues (Inria / GIPSA-Lab).

10.3 Popularization

10.3.1 Conference-debate series and YouTube-channel "Understanding and Acting"

In view of the global issues described in Section 2.1, we initiated in 2016 a series of conference-debates entitled "Understanding and Acting" (*Comprendre et Agir*) that examines these issues in order to help researchers and citizens to increase their awareness of the various issues at stake in order to initiate relevant individual and collective actions. From now on, the scientific community at large must realize that its duty also lies in helping citizens to better understand these issues. If the fraction of people in society whose privilege is to be paid to think about society's problems do not seize this opportunity in the critical times we face, who will? Researchers must become more involved in the search of socioeconomic alternatives and help citizens to implement them. The interactions between researchers and citizens have also to be reinvented.

Presentations typically last between 45 to 60 minutes; they are followed by a 45 minute public debate with the audience. The presentations are captured on video and then made directly accessible on the YouTube channel *Comprendre et Agir*. As of January 2024 the channel has about 11,200 subscribers and reached a total of over 936,000 viewings.

In 2023, we had the following conference-debates.

- Gabrielle Bouleau (LISIS/INRAE), Motifs de science, 17 january 2023.
- Florence Jany-Catrice (CLERSE-CNRS, Lille), Inflation, croissance, découplage : Quels enjeux politiques et techniques ?, 2 may 2023.
- Sophie Wahnich (STEEP and PACTE), La Démocratie est-elle un mythe ?, 25 may 2023.

10.3.2 "Faire face, Face cinéma" series

The STEEP team co-organizes with the *Design Factory* of Université Grenoble Alpes and the PACTE laboratory a series of screenings of documentaries or films dedicated to social-environmental issues called "Faire face, Face cinéma". The screenings are followed by a debate between the director (except in exceptional cases), the organizers and the public. This cycle is supported and animated in particular by Sophie Wahnich (STEEP) and Anne Delaballe (UGA Design Factory). In 2023, the following films and documentaries were screened: Athenian material (Laure Vermeersch), Les voies jaunes (Sylvestre Meinzer), and Brazil (Terry Gilliam).

10.3.3 Articles and contents

- Louis Delannoy co-authored the article Une économie de guerre sera-t-elle nécessaire pour respecter l'Accord de Paris sur le climat ?, published in The Conversation [54].

10.3.4 Education

Systemic Risk Fresco. Systemic risks emerge from interactions within a system in which vulnerabilities are present. If elements of a system are sensitive and sufficiently intertwined, disrupting one or several of them can spread over the whole system, triggering chain reactions and feedback. Systemic thinking is not straightforward [83]. Courses in education are often specialized, focusing on one or few themes or objects. Students often go from one subject to the other, without linking them. "All other things being equal" type reasoning then implicitly arises. This kind of reasoning is consequently blind to interactions with – and vulnerabilities to – changes in other elements of a system.

Studying Global Systemic Risks logically implies systemic thinking. Four PhD students of the team (Alexandre Borthomieu, Antonin Berthe, Léon Fauste, and Mathilde Jochaud du Plessix) created a game to vulgarize this kind of thinking. The Global Systemic Risks fresco (*Fresque des risques systémiques globaux*) is a serious game aimed at broadening the understanding of this aspect. It enables participants to explore interactions within a system and the spreading of disruptions. The game is a visual and spatial representation of the core elements of western societies.

A session takes place in three stages: (i) the construction of the fresco, (ii) the exploration of breakthrough scenarios and (iii) a time of "return to reality". In the first stage, participants are invited to

construct a map of elements they consider important for society; they are guided to first think about primary needs, then means to answer such needs (such as education or a construction sector) and finally, “sectors” allowing to realize these means (energy and materials, finance and geopolitics, “the environment”). Links between all these elements represent dependencies (see Figure 9 for a sample outcome).

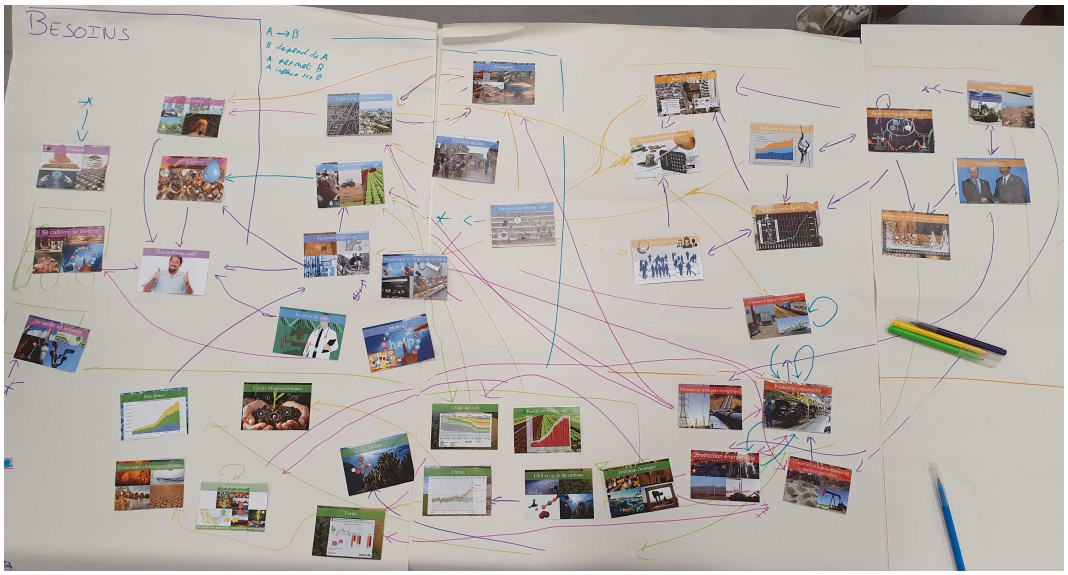

Figure 9: Structure designed by a group after phase I of the Systemic Risk Fresco workshop.

In the second stage, the thus established map allows to explore scenarios and questions such as how disruptions in one of the elements are links can spread through the system. The goal is to foster insight in the systemic nature of our socio-ecological system and to encourage participants to think about our needs in a new way, adapted to a degraded environment, and then eventually to create or imagine more resilient alternatives. As these topics are sources of discomfort and strong emotions, a workshop ends with a third stage, to share feedback on what they have just experienced, as well as a time for sharing emotions, which we believe is now essential for any research or knowledge creation around social and environmental issues that affect each person in different ways. Moreover, we believe that this time allows participants to be accompanied in the “return to reality” and to limit the feeling of powerlessness.

The Global Systemic Risks fresco has been employed in various workshops with different types of audience (scientists, students, general public) and we use it now routinely in several courses at university. It has also been demonstrated to members of the public authorities involved in the *l’Atelier des Futurs* initiative (Section 8.1.4), as an input to the preparation of the Local Risk Report for the Grenoble area.

For more details on the fresco, please refer to this report.

10.3.5 Interventions

- Nils Ferrand, Emmanuel Krieger and Peter Sturm showcased our emerging project on an energy – water – biodiversity dialogue in the Briançon area (see Section 8.9) at the *Conférence des Maires* of the PETR du Grand Briançonnais, on 17 november 2023, through an oral presentation and a booth. The audience consisted of elected officials (municipal, departmental) as well as employees of public services of the territory.

- Pierre-Yves Longaretti has been invited for a conference and public debate on "Frugality and rebound effects". Fête des possibles, Saint-Etienne, 28 septembre 2023.

- Several team members presented the system risks fresco at the 2023 edition of “Fête de la Science”, see here.

- Albert Bouffange gave an interview on shortcomings in the computation of GNP. 20 december 2023, on Radio Anthropocène (Lyon).
- Antonin Berthe was the invited researcher in the May 15 episode of the series "Vie de chercheur•e•s" on the twitch channel Chercheur•e•s de montagne. This series aims at popularizing research topics and at discussing with PhD students on their life within research labs and as PhD students in general.
- Mathilde Boissier gave an interview on Radio Imagine Briançon, 25 october 2023, to present the participatory project done with the PETR du Grand Briançonnais (see Section 8.9).
- Louis Delannoy gave an interview on Une 'économie de guerre' pour sauver le climat on the youtube channel PlanB.
- The work of Louis Delannoy on the EROI of fossil energy sources was cited several times in the episode Taux de retour énergétique : J.M. Jancovici dans l'erreur ? of the youtube channel Le Réveilleur.

The following interventions were linked to this year's publication of the book "World3 et le rapport Meadows, les limites à la croissance – Question raisonnées pour aujourd'hui" [33] we coordinated (see Section 6.1):

- Sophie Wahnich, with Renaud Bécot (Laboratoire Pacte) and Hugo Le Boulzec (Gael/CNRS) animated a session at the 2023 edition of "Fête de la Science", on Les limites à la croissance : l'histoire sans fin: The limits to growth: the never-ending story. The aim was to discuss economic growth, environmental impacts and the incompatibility with the planet's diminishing resources.
- Emmanuel Prados, Sophie Wahnich, Serge Fenet, Pierre-Yves Longaretti and Guillaume Mandil took part in an "arts et sciences ambulation", on 16 November 2023 at the Université Grenoble Alpes to introduce the Meadows report on the limits to growth and as authors of the book [33] celebrating 50 years of the Meadows report. At this event, were also shown reproductions from the series entitled "à vos souhaits" by artist Anaïs Beaulieu that were used as illustrations in the book.
- Pierre-Yves Longaretti and Sophie Wahnich have been invited for a presentation followed by a debate around the book. Bookstore "Compagnie", Paris, 18 october 2023.

11 Scientific production

11.1 Major publications

[1] M. Bevione, N. Buclet, J.-Y. Courtonne and P.-Y. Longaretti. 'Socio-ecological transition, wealth creation and territorial metabolism: the case of the production of the AOC-labelled cheese Beaufort in the Maurienne Valley'. In: *ESEE 2019 - 13th International Conference of the European Society for Ecological Economics*. Turku, Finland, June 2019, pp. 1–4. URL: https://hal.inria.fr/hal-02430879.

[2] T. Capelle, P. Sturm, A. Vidard and B. Morton. 'Calibration of the Tranus Land Use Module: Optimisation-Based Algorithms, their Validation, and Parameter Selection by Statistical Model Selection'. In: *Computers, Environment and Urban Systems* 77 (Sept. 2019), 101146:1–13. DOI: 10.1016/j.compenvurbsys.2017.04.009. URL: https://hal.inria.fr/hal-01519654.

[3] J.-Y. Courtonne, J. Alapetite, P.-Y. Longaretti, D. Dupré and E. Prados. 'Downscaling material flow analysis: The case of the cereal supply chain in France'. In: *Ecological Economics* 118 (Oct. 2015), pp. 67–80. DOI: 10.1016/j.ecolecon.2015.07.007. URL: https://hal.archives-ouvertes.fr/halshs-01321742.

[4] J.-Y. Courtonne, J. Alapetite, V. Wawrzyiak and M. Bevione. 'The AF Filières project: application of PSUT frameworks for regional analyses of agriculture and forestry supply chains and footprints in France'. In: *ESEE 2019 - 13th International Conference of the European Society for Ecological Economics*. Turku, Finland, June 2019, pp. 1–4. URL: https://hal.inria.fr/hal-02430898.

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[6] L. Delannoy, P.-Y. Longaretti, D. Murphy and E. Prados. 'Assessing Global Long-Term EROI of Gas: A Net-Energy Perspective on the Energy Transition'. In: *Energies* 14.16 (Aug. 2021), p. 5112. DOI: 10.3390/en14165112. URL: https://hal.archives-ouvertes.fr/hal-03322866.

[7] L. Delannoy, P.-Y. Longaretti, D. Murphy and E. Prados. 'Peak oil and the low-carbon energy transition: A net-energy perspective'. In: *Applied Energy* 304 (Dec. 2021), pp. 1–17. DOI: 10.1016/j.apenergy.2021.117843. URL: https://hal.archives-ouvertes.fr/hal-03360253.

[8] L. Gervasoni, M. Bosch, S. Fenet and P. Sturm. 'A framework for evaluating urban land use mix from crowd-sourcing data'. In: *2nd International Workshop on Big Data for Sustainable Development*. Washington DC, United States: IEEE, Dec. 2016, pp. 2147–2156. DOI: 10.1109/BigData.2016.7840844. URL: https://hal.inria.fr/hal-01396792.

[9] J. Lenglet, J.-Y. Courtonne and S. Caurla. 'Material flow analysis of the forest-wood supply chain: A consequential approach for log export policies in France'. In: *Journal of Cleaner Production* 165 (Aug. 2017), pp. 1296–1305. DOI: 10.1016/j.jclepro.2017.07.177. URL: https://hal.archives-ouvertes.fr/hal-01612454.

[10] E. Prados, P. Criqui and C. Ilasca. 'A Benchmarking Tool for the International Climate Negotiations'. In: *AAAI-15 Special Track on Computational Sustainability*. Austin, United States: AAAI, Jan. 2015, pp. 95–100. URL: https://hal.inria.fr/hal-01101210.

[11] C. Rocabert, S. Fenet, B. Kaufmann and J. Gippet. 'Accounting for the topology of road networks to better explain human-mediated dispersal in terrestrial landscapes'. In: *Ecography* (12th Dec. 2023). DOI: 10.1111/ecog.07068. URL: https://hal.science/hal-04449314.

[12] Z. Steep, S. Wahnich and L. Delannoy. *Les limites à la croissance.Meadows : questions raisonnées*. Voix publiques. excès, 10th Oct. 2023. URL: https://hal.science/hal-04360218.

[13] C. Vannier, A. Bierry, P.-Y. Longaretti, B. Nettier, T. Cordonnier, C. Chauvin, N. Bertrand, F. Quetier, R. Lasseur and S. Lavorel. 'Co-constructing future land-use scenarios for the Grenoble region, France'. In: *Landscape and Urban Planning* 190 (2019), p. 103614. DOI: 10.1016/j.landurbplan.2019.103614. URL: https://hal.archives-ouvertes.fr/hal-02405231.

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11.2 Publications of the year

International journals

[15] L. Delannoy, E. Aramendia, P.-Y. Longaretti and E. Prados. 'Évolution historique et tendancielle de l'EROI du pétrole et du gaz'. In: *Annales des mines - Série Responsabilité et environnement* (July 2023), pp. 1–12. URL: https://hal.science/hal-04262020.

[16] L. Delannoy, M. Auzanneau, B. Andrieu, O. Vidal, P.-Y. Longaretti, E. Prados, D. J. Murphy, R. W. Bentley, M. Carbajales-Dale, M. Raugei, M. Höök, V. Court, C. W. King, F. Fizaine, P. Jacques, M. K. Heun, A. Jackson, C. Guay-Boutet, E. Aramendia, J. Wang, H. Le Boulzec and C. A. Hall. 'Emerging consensus on net energy paves the way for improved integrated assessment modeling'. In: *Energy & Environmental Science* 17.1 (2024), pp. 11–26. DOI: 10.1039/D3EE00772C. URL: https://hal.science/hal-04328785.

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