RESEARCH CENTRE

Inria Center at Université Grenoble Alpes

IN PARTNERSHIP WITH:

CNRS, Université de Grenoble Alpes

2022

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

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Project-Team STEEP

Creation of the Project-Team: 2015 December 01

Keywords

Computer sciences and digital sciences

A3.3.2. – Data mining

A6.1. – Methods in mathematical modeling

A9.6. – Decision support

Other research topics and application domains

B3.1. – Sustainable development

B3.1.1. – Resource management

B3.4. – Risks

B3.4.3. – Pollution

B3.5. – Agronomy

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B9.6.9. – Political sciences

B9.9. – Ethics

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2 Overall objectives

> "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 [39] 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 [56, 45]. 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 [43, 44, 49]. 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.

3 Research program

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 work on LUCC (Land Use and land Cover Change) modeling which is complementary.

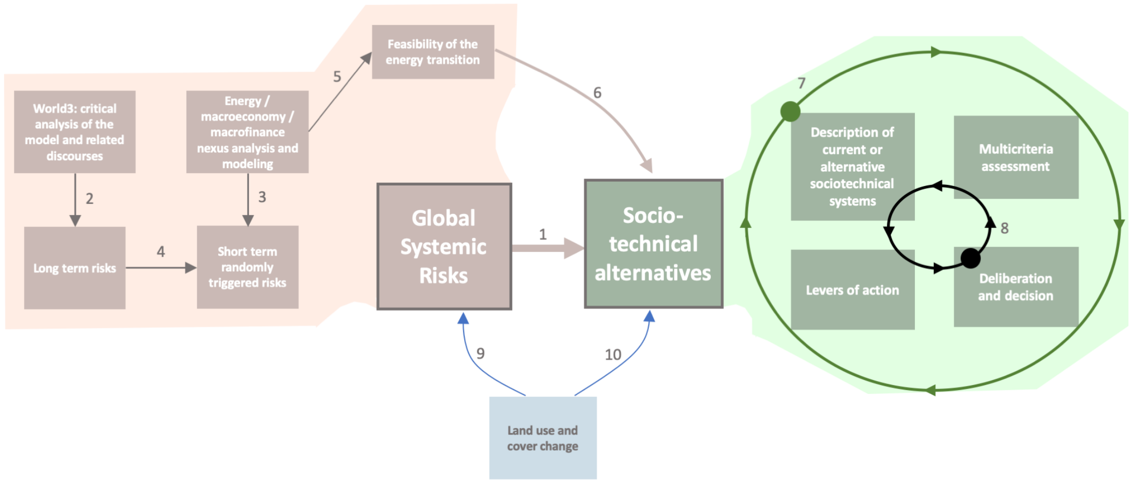

Figure 1: Sketch of the team structure: building blocks of the two research axes and logical connections. The orange and the green areas respectively depict the contents of the Global Systemic Risks axis (GSR) and of the Sociotechnical Alternatives axis (STA). Participatory processes can (and should) 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.

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 [53, 48] or in social sciences [40]. 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 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 Fig. 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 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 [54, 53]. The re-analyses of [57, 58] and [37] 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.

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

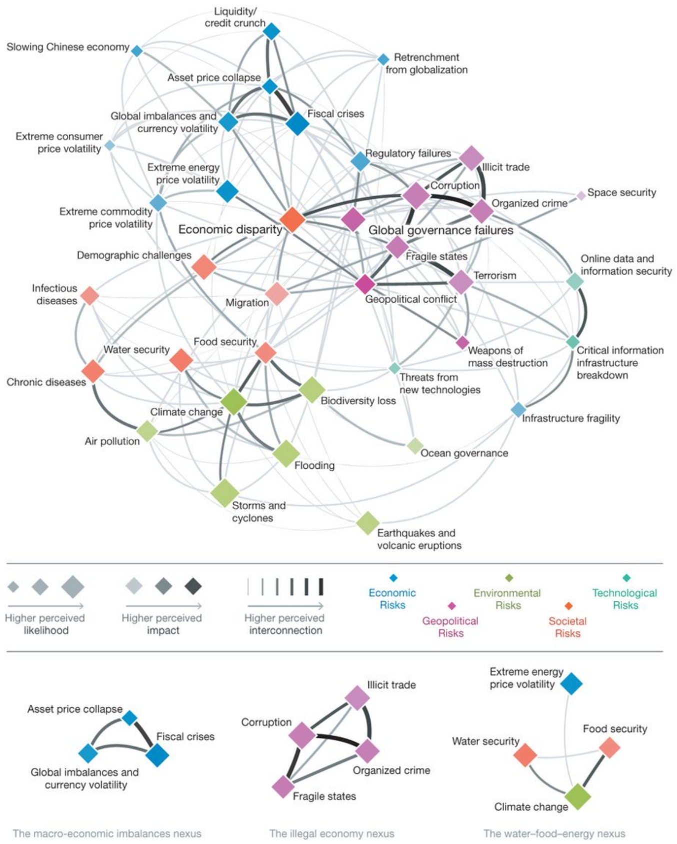

Figure 2: Global systemic risks and their interconnections according to the 2011 World Economic Forum report (reproduced in [48]). These risks are assessed by expert opinion and the importance attributed to them reflects in part cyclical concerns.

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 [47, 52, 38]), 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 coupled 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 [42] 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.).

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,

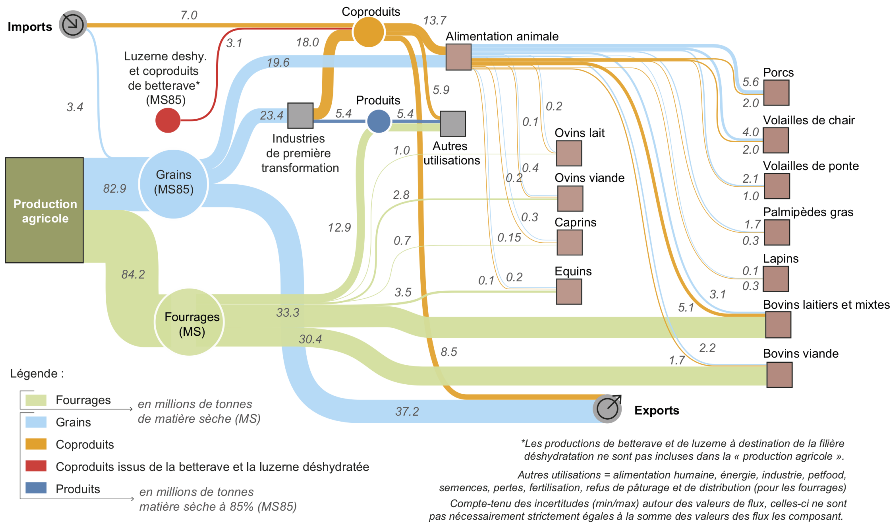

Figure 3: Example of a Sankey diagram resulting from a single-scale SC-MFA: Agriculture raw materials fed to livestock in France in 2015 (millions of tonnes) [41].

- 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 [46]. 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.

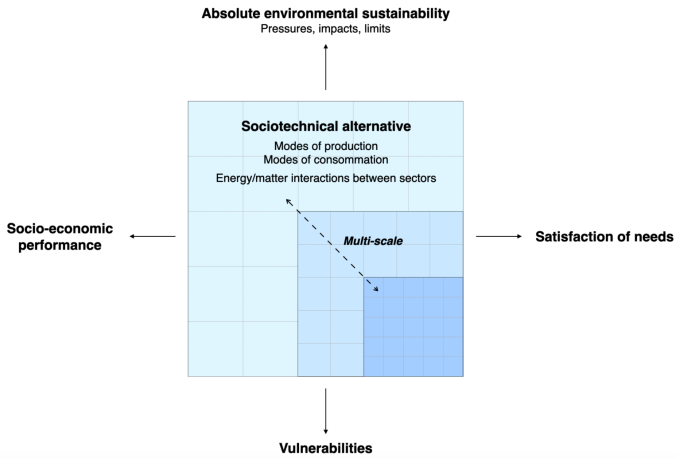

Figure 4: Schematic overview of research questions and concepts underlying sociotechnical alternatives. Center: targeted sociotechnical alternatives are typically of multi-scale nature. Borders: the four dimensions to be considered in evaluating sociotechnical alternatives (see text).

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 maneuver and means of action available to us to act against them. It is an "applicative" project as such. Listing its fields of application does not really make sense. However, we can isolate parts of our activities that fit into specific scientific fields and communities. This is what we do here in a non-exhaustive way.

4.1 Ecological accounting for sectorial pressure assessment

One of the major issues in the assessment of the long-term sustainability of territories is related to the concept of "imported sustainability". Cities in particular bring in from the outside most of their material and energy resources, and reject to the outside the waste produced by their activity. The modern era has seen a dramatic increase in both volume and variety of these material flows and consumption as well as in distance of origin and destination of these flows, usually accompanied by a spectacular increase in the associated environmental impacts. A realistic assessment of the sustainability of territories requires to quantify both local and distant environmental impacts; greenhouse gas emissions are only one aspect of this question. Such an assessment brings to light the most relevant direct and indirect lines of action on these issues. In this respect, it is useful to introduce the alternative concepts of consumer versus producer responsibility (or point of view).

The producer point of view is the most useful to pinpoint relevant direct lines of actions on environmental pressures due to production. In other respects, any territory imports and exports goods and services from and to the rest of the world. The consumer point of view provides information on the indirect pressures associated with these exchanges, as production responds to a final demand. Tracking the various supply chains through the analysis of the structure of the local economy and its relations and dependencies to the external world allows us to identify critically important contributions to environmental pressures; this also enables us to define fair environmental indicators in order not to attribute environmental pressures to producers only (whose responsibility is the easier to quantify of the two). In this approach, the producer responsibility follows directly from the measurement of its energy and material uses, while the consumer responsibility is established indirectly through an allocation of the impacts of production to the final consumers, but this second mode of allocation is to some extent virtual and partly subjective.

STEEP is pursuing its research program on this theme with three major goals: 1) Creating a comprehensive database enabling pressure analyses; 2) Developing methodologies and models resolving scaling issues, and developing algorithms allowing us to rigorously and automatically obtain adequate assessments; 3) Providing a synthetic analysis of environmental pressures associated to the major material flows, at various geographic levels (employment catchment area, *département* and *région*, for France), with the explicit aim of incorporating this type of information in the public decision process on environmental issues, via specifically designed decision-help procedures.

4.2 Urban economy and land use/land cover changes: assessment of spatial distributions of the pressures

The preceding section was focused on territorial metabolism, in particular on the analysis of supply chains. Here territories are examined with a more prominent emphasis on their spatial dimension, with attention to: the spatial distribution of local pressures previously identified (from a land use point of view), and the modeling of future land use and activity location (from an economic point of view). These two questions correspond to very different modeling strategies: the first one is more statistical in nature, extrapolating future land use from past evolution combined with global territory scenarios; the other one has a more fundamental flavor and focuses on an understanding of the processes driving urbanization. For this, we focus more precisely on the question of household and businesses choices of localization, as well as on spatial fluxes within the territory (transportation of goods and persons). The critical point here is to understand and manage urban sprawl and its environmental effects (GHG emission, loss of arable land, ecosystem fragmentation, and so on).

LUCC (Land Use/Land Cover Change) models are mostly used in environmental sciences, e.g. to evaluate the impact of climate change on agriculture, but they can also be used to analyze urban sprawl. There is a variety of models, static or dynamic, grid- or agent- based, local or global, etc., and with varying degrees of sophistication concerning spatio- temporal analysis or decision structures incorporated in the model.

The models of interest here are statistical in nature but spatially explicit. Following decades of development, they are robust, versatile and mature. In principle, agent-models have a larger potential for representing decision processes, but in practice this advantage results in a loss of universality of the models. Among the most well-known and most mature models, one can mention the CLUE family of models, DINAMIC, or LCM (Land Change Modeler). These models are well described in the literature, and will only be briefly presented here.

These models analyze change in land use in a statistical way; they are structured around three different modules:

- The first module determines the probability of change of pixels of the territory (pixels are typically tens to hundreds of meters in size).
- The second module defines the global changes between the various land uses of interest per time step (usually, a few years), based on global scenarios of evolution of the territory under study. These first two modules are independent of one another.
- The last module distributes changes of land use in an explicit manner, pixel per pixel, at each time step, on the basis of the information provided by the first two modules.

Probabilities of change are calibrated on past evolution, from the differences between two past maps of land use in the more favorable cases, or from a single map otherwise (under the assumption that the logic of occupation changes is the same as the logic of land use at this single date). Such changes are then characterized in a statistical way with the help of modeling variables identified by the modeler as having potential explaining or structuring power (typically, a few to a dozen variables are used for one type of land use change). For example, in the case of urban sprawl, typical explaining factors are the distance to existing urbanized zones or distances to roads and other means of transportation, elements of real estate costs, etc. Global scenarios are quantified in terms of global changes in land use over the whole studied area (e.g., how many hectares are transformed from agricultural to urban uses in a given number of years, how does this evolve over time...); this is done either from academic expert knowledge, or from information provided by local planning agencies. Whenever feasible, models are validated by comparing the model predictions with actual evolution at a later date. Therefore, such models need from one to three land use maps at different dates for calibration and validation purposes (the larger the number of maps, the more robust and accurate the model). A large array of statistical tools is available in the literature to perform the calibration and validation of the model.

The horizon of projections of such models is limited in time, typically 20-30 years, due to the inherent uncertainty in such models, although they are occasionally used on longer time-scales. Climate change constraints are included, when needed, through scenarios, as it is not in the scope of such models to incorporate ecological processes that may translate climate change constraints into land cover change dynamics. Note that on such short time-scales, climate change is not dominated by the mean climate evolution but by decade variations which average out on longer time-scales and are not modeled in the global climate models used e.g. for IPCC (Intergovernmental Panel on Climate Change) projections for the end of the century; as a consequence, the various IPCC climate scenarios cannot be distinguished on such a short time horizon.

With regard to LUCC, the STEEP team has been involved for five years in the ESNET project whose funding came to a close in July of 2017, but the scientific production of the project is still underway. This project bears on the characterization of local Ecosystem Services networks; the project has been coordinated by LECA (Laboratoire d'Ecologie Alpine), in collaboration with a number of other research laboratories (most notably, IRSTEA Grenoble, besides our team), and in close interaction with a panel of local stakeholders; the scale of interest is typically a landscape (in the ecologic/geographic sense, i.e., a zone a few kilometers to a few tens of kilometers wide). The project aims at developing a generic modelling framework of ecosystem services, and studying their behavior under various scenarios of coupled urban/environment evolution, at the 2030/2040 horizon, under constraints of climate change. The contribution of the STEEP team is centered on the LUCC model that is one of the major building blocks of the whole project modelling effort, with the help of an ESNET funded post-doctoral researcher. In the process, areas of conceptual and methodological improvements of statistical LUCC models have been identified; implementing these improvements will be useful for the LUCC community at large, independently of the ESNET project needs.

4.3 Territorial foresight studies

The direct application of research axis Sociotechnical Alternatives (see previous section) lies in foresight studies for territories. Tools and methodologies we are developing are aimed at decision-aiding. One aspect is to help stakeholders to structure their foresight exercises, for instance by asking them to explicitly express their objectives and allowing them to design sociotechnical alternatives. Another aspect is to provide tools and concepts for assessing these alternatives, according to different dimensions. An overarching issue is the embedding of these tools and activities in participative processes.

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 digitial 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

Archipel conference. We organized the first edition of a transdisciplinary conference on "Systemic risks, trajectories and levers for action". It was intended as a first step towards the constitution of a scientific collective that will allow the emergence of questions, salient points, frameworks of thought, methods and tools to deal with systemic risks, and more globally with the future of our societies. The conference gathered 167 attendees from many disciplines. The next edition is already planned for 2024. For more details, refer to 10.1.1.

Anthropocene FACTS project. In 2022, we could make a first "real-life test" regarding our Anthropocene FACTS project, through a one-week thematic school held in Grenoble that brought together 50 participants from various disciplines. The event was a success and allowed to gather feedback on the first generation of contents for and on the general relevance of, the planned pedagogic platform and community on the Anthropocene. More details are given in 10.2.1.

Startups. The incubation of the FNI (Future Needs Invest) startup commenced in 2022 and the startup Terriflux launched in 2021 consolidated throughout 2022.

6.1 Awards

Best student paper of the 2022 International Conference on Geographical Information Systems Theory, Applications and Management [18].

Award from the Polytechnique engineering school for the master thesis of Léa Vienot [36].

7 New software and platforms

7.1 New software

7.1.1 Layout of Sankey diagrams

Keywords: Data visualization, Visualization, Sankey diagram, Flow visualization

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: 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.

Contact: Peter Sturm

Participants: Joanna Maurin, Peter Sturm, Jean-Yves Courtonne, Julien Alapetite

7.1.2 Sankeytool

Name: Web app for drawing Sankey diagrams

Keywords: Data visualization, Visualization, Sankey diagram, Flow visualization

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.

News of the Year: End of the AF Filières project sponsored by Ademe. Beginning of incubation of the Terriflux company inside the startup studio program of Inria.

URL: http://terriflux.fr

Contact: Julien Alapetite

Participants: Jean-Yves Courtonne, Julien Alapetite

7.1.3 Clumpy

Name: Comprehensive Land Use Models in Python

Keywords: Land use and cover change, LUCC, Spatially explicit model, Geostatistic, GIS

Functional Description: Clumpy is a land use and cover change model (a python package) which aims to be used in sustainability and environmental sciences. It allows to observe past changes statistics, set future contrasted scenarios and allocate simulated future land use maps according to those projections. From past land use maps and some explanatory variables, the software calibrates the model through machine learning methods (kernel density estimations, nearest neighbors for now). Explicit probabilistic values are returned and can be then adjusted to contrasted scenarios set by the user. It is finally possible to allocate a simulated land use map in order to provide decision materials for public stakeholder. Other land use and cover change model softwares such as Dinamica EGO, CLUE and LCM are compared to Clumpy in papers to come.

URL: https://gitlab.inria.fr/fmazy/clumpy/

Contact: Francois Remi Mazy

Participants: Francois Remi Mazy, Pierre-Yves Longaretti

7.1.4 SC-MFA

Name: Supply Chain Material Flow Analysis

Keyword: Optimisation

Scientific Description: The scientific methodology (described in detail in the thesis of Jean Yves Courtonne 2016) is summarized in the following. It consists of modeling, reconciliating and downscaling of flow data, typically flow data pertaining to supply chains. The existence of multiple units (physical units such as mass or volume, equivalence units, monetary, environmental pressures) is taken into account, enabling the fusion of environmental, monetary and supply assessments. The methodology takes also into account uncertainties and their reconciliation, allowing to highlight areas with poor information. The geographical downscaling ensures the coherence of results across territories and scales.

Functional Description: The software performs data reconciliation by constraints optimization. It works on Excel sheets and can be run through the command line or from a web application.

News of the Year: End of AFM Filières ademe project. Beginning of company Terriflux inside the startup studio program of Inria.

URL: http://www.flux-biomasse.fr

Contact: Jean-Yves Courtonne

Participants: Jean-Yves Courtonne, Julien Alapetite

Partner: Alapetite Julien

8 New results

8.1 Energy Consumption and Transition

Participants: Louis Delannoy.

Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency. To maintain perpetual economic growth, most energy transition scenarios bet on a break in the historical relationship between energy use and gross domestic product (GDP). Practical limits to energy efficiency are overlooked by such scenarios, in particular the fact that high-income individuals tend to buy goods and services that are more energy intensive. Detailed assessments of the energy embodied in regional final consumption are needed to better understand the relationship between energy and GDP. In [14], we calculate the energy necessary to produce households and governments' final consumption in 49 world regions in 2017. We correct prices at the sector-level and account for the energy embodied in the whole value chain, including capital goods. We find that high-income regions use more energy per unit of final consumption than low-income ones. This result contradicts the common belief that a higher GDP is correlated with a better efficiency and questions the feasibility of mainstream energy transition scenarios based on universal GDP growth.

Dynamic modeling of global fossil fuel infrastructure and materials needs: Overcoming a lack of available data. The low-carbon energy transition requires a widespread change in global energy infrastructures which in turn calls for important inputs of energy and materials. While the transport and electricity sectors have been thoroughly analyzed in this regard, that of the hydrocarbon industry has not received the same attention, maybe in part due to the difficulty of access to the necessary data. To fill this gap, we assemble public-domain data from a wide variety of sources to present a stock-flow dynamic model of the fossil fuels supply chain. It is conducted from 1950 to 2050 and along scenarios from the International Energy Agency. We estimate the concrete, steel, aluminum and copper requirements for each segment, as well as the embedded energy and CO2 emissions through a dynamic material flow analysis (MFA) model. We find that (i) the material intensities of oil, gas and coal supply chains have stagnated for more than 30 years; (ii) gas is the main driver of current and future material consumption; and (iii) recycled steel from decommissioned fossil fuels infrastructures could meet the cumulative need of future low-carbon technologies and reduce its energy and environmental toll [16]. Furthermore, we highlight that regional decommissioning strategies significantly affect the potential of material recycling and reuse. In this context, ambitious decommissioning strategies could drive a symbolic move to build future renewable technologies from past fossil fuel structures.

8.2 Analysis of the robustness of the World3 model and of the realism of the discourses on it

Participants: Mathilde Jochaud du Plessix, Serge Fenet, Pierre-Yves Longaretti.

This work has been centered around the PhD of Mathilde Jochaud du Plessix, that focuses on the evaluation of the quantitative robustness of the conclusions of the authors of the model. After having developed an instrumented version of the World3 model in Python [50], Mathilde produced a detailed analysis of the interaction dynamics at the heart of the model. She first focused on the alternating periods of growth and degrowth of the variables of interest by using several state-of-the-art methods [51]. Then, in order to objectively characterize the dynamics of the feedback loops linking these variables through time, she adapted and then mobilized the recent Loop Eigenvalue Elasticity Analysis method. This method induces a strong combinatorial explosion that was avoided by decomposing the global model into independent subsets. This decomposition led to five submodels that were analyzed independently. She produced a very detailed study, focusing on both the mathematical aspects of the method, and on the interpretation of the results in terms of relevance regarding the initial variables of the model. For example, in the agricultural sector several intertwined timescales were identified through the interplay of the feedback loops, varying from 10 years (fertility regeneration of the lands) to 600 years (fertility degradation due to persistent pollution). Mathilde also analyzed the dynamics of each variable of interest at the light of the co-dependency structure revealed by this work.

Thus, Mathilde Jochaud du Plessix not only produced an extensive sensitivity and loop dominance analysis of the model (see figure 5), but also elaborated an original method of characterization of the dynamical endogeneity of system dynamics model variables to evaluate the respective role of the model parameters and retroaction loops on the observed dynamics. These results are currently being written for publication, accompanied by an overall critical analysis of various popular discourses, in science and in the general public.

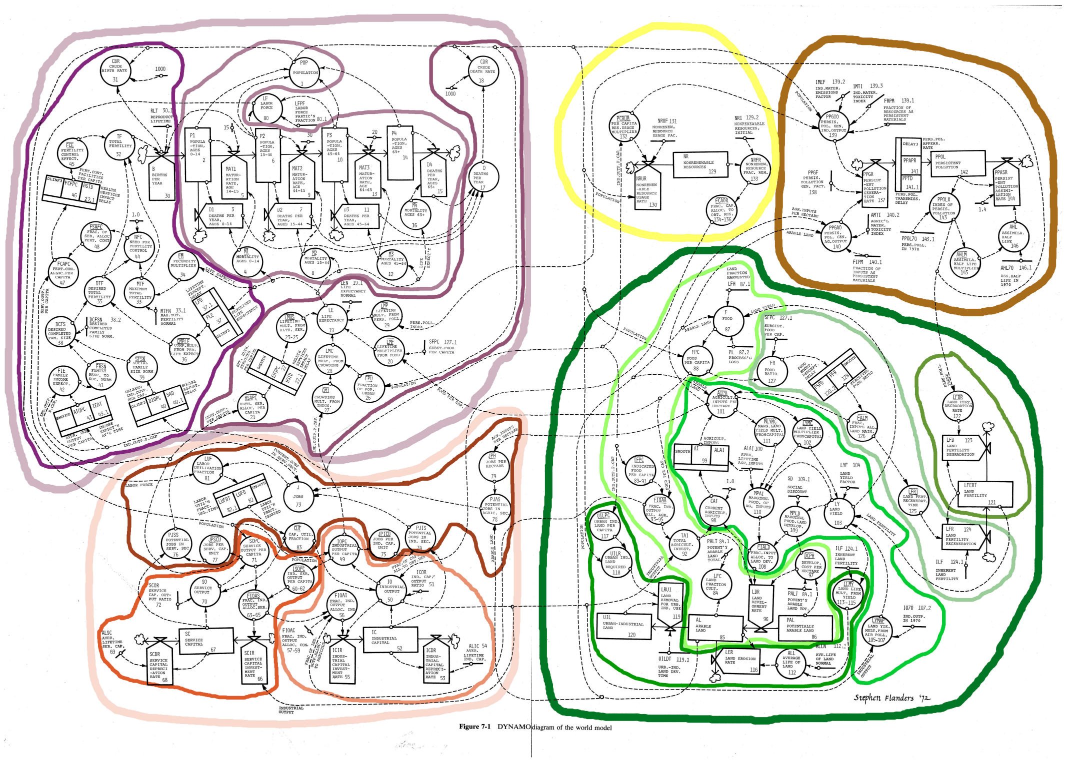

Figure 5: Main feedback loops of the World3 model and variables responsible for different subsets of the overall dynamics. [Details become more visible when zooming in the PDF file].

8.3 Land Use and Cover Change Modelling

Participants: François-Rémi Mazy, Pierre-Yves Longaretti.

Towards a Generic Theoretical Framework for Pattern-Based LUCC Modeling: An Accurate and Powerful Calibration-Estimation Method Based on Kernel Density Estimation. Several modeling strategies have been proposed to study Land Use and Land Cover changes (LUCC). However, substantial discrepancies have been noted between different models for the same problem, questioning their overall reliability and reproducibility. To address this challenge, we elaborate a generic, formally correct, theoretical framework for pattern-based LUCC modeling, which is implemented in our own software, CLUMPY (Comprehensive Land Use [and cover] Modeling in PYthon). In [17] we focus on calibration. We devise a kernel density calibration-estimation method (Bayes-eKDE) that is shown on synthetic artificial data to be both accurate and algorithmically efficient. We also introduce a generic evaluation method that allows us to compare the calibration efficiency of existing models. The gain in precision and computational time of our calibration method is precisely quantified in this way.

A Formally and Algorithmically Efficient LULC change Model-Building Environment. The use of spatially explicit land use and land cover (LULC) change models is widespread in environmental sciences and of interest in public decision-help. However, it appears that these models suffer from significant biases and shortcomings, the sources of which can be mathematical, conceptual or algorithmic. In [18], we formalize a modeling environment that distinguishes a calibration-estimation module from an allocation module. We propose an accurate calibration-estimation method based on kernel density estimation and detail an unbiased allocation algorithm. Moreover, a method of evaluation of LULC change models is presented and allows us to compare them on various fronts (accuracy, biases, computational efficiency). A case study based on a real land use map but with known (enforced) transition probabilities is used. It appears that the estimation error of the methods we propose is substantially improved over the best existing software. Moreover, these methods require the specification of very few parameters by the user, and are numerically efficient. This article presents an overview of our LULC change modeling framework; its various formal and algorithmic constituents will be detailed in forthcoming papers.

8.4 Analyzing the vulnerabilities and capabilities of wealth creation activities in the Maurienne valley in the French Alps

Participants: Michela Bevione, Jean-Yves Courtonne, Pierre-Yves Longaretti, Quentin Desvaux.

Alpine valleys constitute fragile environments and are very sensitive to environmental change. Current trends constitute major upheavals challenging these communities' adaptation abilities. Coupling quantitative modeling and qualitative social sciences analyses is necessary to provide insights on sources of vulnerability but such endeavors remain rare in the scientific literature. In [15] we present a metabolism-capabilities-vulnerabilities framework, which describes local communities and their environment as a network of wealth creation activities. We apply this framework to one of the main farming activities in the Alpine valley of Maurienne, the production of Beaufort cheese. We describe how stakeholders are involved in the supply chain and then quantify the economic and environmental aspects of the flows. We introduce the concept of 'territorial capabilities' to analyze the ability of stakeholders to cope with change through a reorientation of their activities. We highlight that while current environmental pressures do not seem to exceed local environmental limits, climate change is likely to be a source of future vulnerability. On the socioeconomic side, the analysis points out the dependence on subsidies and the aging of the workforce as other potential threats to this activity. Conversely, the local cooperatives system appears to be the main asset in vulnerability reduction.

8.5 Support for the choice of geographic scale in the manufacturing industry through constrained optimization

Participants: Léon Fauste, Jean-Yves Courtonne, Guillaume Mandil, Mathieu Mangeot, Peter Sturm.

The debate around relocalization is more and more active and arguments related to sovereignty, sustainability and environmental causes are evoked. The environmental pressures of a system can be studied through multiple indicators (built surface, CO2 emission, water consumption, ...) and sustainability can be studied through different indicators like productivity, resilience, reliability, adaptability or self-sufficiency. However some indicators can be in contradiction, which imposes the search for trade-offs and the choice of scale influences these trade-offs. For example, moving from a global to a local scale may degrade productivity but improve social, health or ethical indicators. There is therefore a real issue around the choice of geographic scale in the relocation of industries to find the scale that offers the best trade-offs. In [21], we propose to look at the productive industry with a decision support model where we can choose the scale at which the industry is organized and then, under this constraint, we optimize a set of indicators. This allows us to observe the losses and gains of one choice of scale compared to another.

8.6 Exploring the French economy with physical supply-use tables

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

An emerging research axis of the team intends to contribute to the design, evaluation and debate of socio-technical alternatives for the future (e.g., horizon 2050). “Expert” quantitative modeling makes it possible to guarantee the biophysical coherence of narratives (regarding flows of materials, energy and human work) and to tackle complex issues (e.g. trade-offs between social and environmental criteria, trade-offs between geographical scales...). In order for these alternatives to emerge in a democratic manner, the team is currently involved in both “expert modeling” and “participatory modeling” (where groups of citizens identify what they wish to model and create and evaluate their own alternatives). In [22] we focus on the latest developments on the “expert” side. We define a socio-technical alternative as a consistent arrangement of modes of production and modes of consumption. This includes biophysical and socio-political dimensions, but for the time being the emphasis is laid on the circulation of material, energy and human work between sectors and down to final consumption.

8.7 Analysis of the circulation of material flows in the Grenoble Alpes Métropole area: the missing links in the building sector

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

Based on the directives of its CODEC1, the DCTD2 of Grenoble Alpes Métropole (Grenoble Metropolitan Area) has initiated an ambitious approach aimed at reappropriating waste deposits by transforming local production systems. This local policy focuses in particular on the construction sector and is part of a national framework that is undergoing major changes, the objective of which is to structure a recycling sector specific to construction waste. Nevertheless, the lack of infrastructure for the production of recycled materials, combined with the lack of technical skills, accentuates the phenomenon of resource relocation, the associated environmental impacts and reduces the resilience of the territory. By promoting the extraction and reuse of secondary resources, the community wishes to implement sustainable alternatives to the logic of massive extraction of natural resources, while limiting the export of separated and sorted fractions to other regions or countries. It is within this framework of sector analysis that we reveal vulnerabilities that characterize the building sector as well as the prescriptions that will enable Grenoble Alpes Métropole to boost this chain of circulation of territorial secondary materials [23].

8.8 Multi-scale environmental evaluation of agricultural supply chains through coupling of LCA and MFA

Participants: Yazid Charkani, Jean-Yves Courtonne, Guillaume Mandil.

One of our foci is to evaluate the environmental footprint of agricultural sectors at the national and regional levels in France. To do so, we describe in [32] a coupling and harmonization work between material flow data based on the MFA (Material Flow Analysis) method and environmental impact data based on the LCA methodology (Life Cycle Analysis). A harmonization methodology between these two models has been proposed and tested on 4 commodities (wheat, oats, maize, milk). The regionalization has been tested on the milk sector, the results have revealed the transfer of impacts between territories due to the final consumption of the inhabitants.

8.9 Methodology for coupling LCA and the MATER model

Participants: Baptiste de Goër, Jean-Yves Courtonne, Guillaume Mandil.

Today, the main methodology used to analyze the environmental impacts of a given system is the Life Cycle Analysis (LCA). This multi-step and multi-criteria methodology is now established in the consensus as reliable in a prospective objective. In this context, huge databases have been set up. This is the case of Ecoinvent, a particularly complete Swiss LCA database. There is currently a challenge to associate these databases, and this methodology, with other prospective models, such as the MATER model proposed by a research team from the ISTerre laboratory (team led by Olivier Vidal). In [33] we present a methodology and software to group production chains present in Ecoinvent, so that these groupings correspond to the structure of the MATER model, in order to extract LCA data and reuse them in this new framework. The core of the work focuses on two elements: the development of a reliable clustering algorithm, and the testing system put in place to ensure this reliability.

8.10 Describing and designing socio-technical organizations through the biophysical description of territorialized supply chains

Participants: Emmanuel Krieger, Jean-Yves Courtonne, Guillaume Mandil, Mathieu Mangeot, Peter Sturm.

Humans are having more and more impacts on environment due to unsustainable consumption and production patterns, thus threatening the capacity of natural systems to support their long-term existence. To help reaching a desirable and sustainable societal organisation, it is notably helpful to estimate the desirability of possible alternatives to the current socio-technical organisation. To move forward in this direction, a systemic modelling tool which could enable actors to design their own projection of a socio-technical alternative, and to evaluate it with multi-criteria indicators, is considered here. Following the idea of laying the foundations for the realization of this model, [34] proposes to explore the biophysical description of territorialized supply chains. In this sense, Supply Chain – Material Flow Analysis is chosen among other tools to be used to describe biophysical economy through the establishment of six material based French national supply-chains which are non-metallic minerals, fossil fuels, metals, waste, water and energy supply chains. Furthermore, based on the establishment of the material flows of urban mobility, a draft of a first prototype, greatly simplifying the approach, is proposed to design urban transport alternatives as well as to proceed to an environmental assessment of these alternatives. This work thus further advances the project of creating a multi-supply chain and multi-scale systemic model by continuing to lay the foundations for describing the biophysical economy and by examining what a simplified prototype could do in terms of modelling, design and evaluation.

8.11 Energy and nitrogen footprints of French agriculture chains

Participants: Alexandre Pannier, Jean-Yves Courtonne, Julien Alapetite.

This work [35] is part of a research project funded by ADEME entitled SCALABLE. This project is based on the following two observations: on the one hand, the agri-food systems that produce and transform biomass of agricultural origin (meat, cereals, dairy products, vegetables, etc.) are increasingly globalized and on the other hand, these same systems are exposed to growing disturbances and stresses (economic, geopolitical, health, climatic). It therefore appears necessary to be able to assess the vulnerabilities of territories in terms of dependence on other territories, ecological footprint or competition in use for all biomass of agricultural origin. In this context, this work aims to assess the energy (inseparable from any human activity) and nitrogen (essential nutrient for plants and animals) footprints of agricultural sectors. It presents the methodology used to perform the energy and nitrogen flux analyzes and the graphical representations that were built to visualize the results. These graphical representations, in Sankey diagrams' form, will eventually serve as a decision-making tool for the actors of the concerned territories and sectors.

8.12 Serious games for the analysis of sociotechnical alternatives

Participants: Léa Vienot, Mathilde Boissier, Jean-Yves Courtonne, Vincent Jost.

At a time when politicians increasingly call on experts to decide on social issues, the French democratic crisis reflects in the citizens' mistrust of scientists. In a context of absolute environmental emergency, several planetary boundaries already being overstepped by the Western world, it seems necessary to rebuild confidence between the people, scientists and politicians. To rethink our consumption and production patterns and to design desirable alternatives to our current way of life, the society as a whole must take part in the profound societal decisions that await us. With this in mind, scientific research develops new tools capable of modelling socio-technical organizations, thanks to which vulnerabilities of these systems are highlighted. The aim of [36] is to work on translating these phenomena and risks from a scientific language to a form accessible to all. With this in mind, we investigated a possible method, which combines three dimensions: playfulness, materiality and minimality. To do so, we studied how knowledge transfer is explored in the practice of stakeholder participation. Serious games are studied as a relevant form to answer this need of transposition. The concept of lucidity and the way in which the ideas are represented in board games are used. This work led to the design of two serious games [36]; they can be downloaded here and here. Each of them includes a playing time, in which people engage in a playful situation to experiment the systemic effects, and a debrief, to enhance learning by taking a step back and connecting the game situation to reality. They were played with about 10 groups, with students or scientists, as well as general audiences (2022 edition of the *Fête de la Science* as well as game cafés).

8.13 Participatory exercises in territories

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

we spent the year 2022 to mount collaborations towards real-life participatory processes. This was achieved for two territories, each having its particular needs for such a process. The first is the PETR Briançon (Pôle d'Equilibre Territorial et Rural – Briançonnais, Ecrins et Guillestrois Queyras), a so-called *intercommunalité* (grouping 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. In July 2022 we have started to work on this. The first phase was to conduct individual interviews with about 35 actors, to gather information on what each one perceives as important issues (for themselves and/or the territory), on their objectives, their expectations on a participatory process, etc. A synthesis of these interviews was presented in a public meeting, which also included a first round of workshops mixing the different actors. During this phase, we also carried out 3 pre-experiments in order to better understand to what extent biophysical accounting tools could facilitate participatory processes. After participants made a short diagnosis about energy on their territory, they collectively analyzed a Sankey diagram (such as figure 3) related to energy flows on the PETR's territory. Besides a relational interest (meeting people and making people meet on the territory), these pre-tests were very useful to better design workshops that will later in the process be open to the whole territory. The next phase will be to make the relevant stakeholders arrive at a formal contractualization for the process (in particular, formal engagement of the public authorities), a charter defining the common objectives and groundrules as well as a framework of the different process steps they chose. The entire process is expected to last at least throughout 2023.

The second territory is the greater Grenoble area and the perimeter of the programmed participative process is the establishment of an interterritorial food plan. Within the Scalable project, STEEP is involved both in quantitative/analytical modeling and in the development of a participative approach. During stakeholder workshops which will take place in 2023, we will assess how they apprehend the models and indicators produced: What surprises them? What information is lacking? Do the models help them identify transformation strategies?

8.14 "Atelier des Futurs" Initiative, Grenoble Metropolitan Area

Participants: Antonin Berthe, Emmanuel Prados, Peter Sturm.

The local authorities of Grenoble and adjacent territories[2] have recently 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 (through Inria) is the first academic partner to join the initiative and sign 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). Its idea 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. Peter Sturm is member of the Steering Committee (COTECH) of *l'Atelier des Futurs* and the work on the Local Risk Report will involve several other members of STEEP.

8.15 Anomaly Detection Based on Sequence Indexation and CFOF Score Approximation

Participants: Serge Fenet.

This work focuses on the detection of anomalies in the message traces of the communication infrastructure of the information system of the French national railway company (SNCF) [28]. It shows that for this task a method can be designed by combining two recent and independent techniques. The first is the storage and indexation of time series in a tree called iSAX tree, and the second is an anomaly detection score named CFOF, that has been proven to resist to the concentration phenomenon in high

[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.

dimension. We show in this paper, that it is possible to use the information structure of the iSAX tree to quickly determine an approximation of good quality of the CFOF score. We show that the approximate score is close to the exact score on both synthetic and real industrial datasets, and the first feedback indicates that this score is relevant for triggering alarms related to the anomalies observed in the activity of the SNCF information system.

9 Partnerships and cooperations

9.1 International initiatives

9.1.1 Participation in other International Programs

- Pierre-Yves Longaretti has been involved in TARA (Transition adaptation research alliance); he animated the theme *Operationalizing reflexive sustainability* at the TARA Workshop in Bogor, Indonesia, November 2019.

- Serge Fenet is involved in the TRAJECLIM project with the Laboratoire Ecologie Fonctionnelle et Environnement of Toulouse INP, that focuses on the resilience of the current trajectory of a polar socio-ecological system facing climate and anthropogenic change.

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

9.2 International research visitors

9.2.1 Visits of international scientists

Other international visits to the team

Sabin Roman

Status: Post-Doc

Institution of origin: Cambridge Centre for the Study of Existential Risk)

Country: UK

Dates: 14-18 November

9.2.2 Visits to international teams

Research stays abroad

Jean-Yves Courtonne

Visited institution: Global Resource Use lab, Vienna University of Economics and Business

Country: Austria

Dates: September (one week)

9.3 National initiatives

9.3.1 LINDDA

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

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.
Abstract: The project is part of a program on Agroecology and Digital. It will subtend our work on participation in the STA axis (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: Jean-Yves Courtonne, Maxime Latgé, 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.

10 Dissemination

10.1 Promoting scientific activities

10.1.1 Scientific events: organisation

Archipel Conference. Between June 20 and 23, 2022, STEEP organized the Archipel 2022 conference in Grenoble, on «Systemic risks, trajectories and levers for action». This conference was a first step to constitute a transdisciplinary scientific collective that will allow the emergence of questions, salient points, frameworks of thought, methods and tools to deal with systemic risks, and more globally with the future of our societies. The conference comprised plenary sessions, symposia and workshops and gathered 167 attendees. It initiated a collaborative workgroup aiming at:

- bringing together a community of scientists from diverse backgrounds, adopting shared systemic approaches to global issues;
- starting to co-develop and consolidate frameworks of thought, knowledge and methodologies on global systemic risks, their assessment, and their mitigation;
- making concrete progress in the production and dissemination of knowledge.

The event brought together researchers from very different backgrounds and themes and also members of civil society, and the initial goal of launching a trans-disciplinary community around the challenges of the Anthropocene (planetary limits, systemic risks, levers for action) was successfully achieved. These four days have allowed the crystallization of a community emerging from various fields of "hard", social and health sciences. Several working groups were formed during this first conference, and the second edition is already planned for 2024, organized by INSA Lyon. An intermediate working day will also be organized in Lyon in spring 2023.

Workshop on strong sustainability trajectories. In 2022, Pierre-Yves Longaretti co-organized, with Jean-François Ponsot (economist at the PACTE/IEP lab, Grenoble) and Antoine Godin (chief economist, AFD, Paris) a two-day workshop on "Strong sustainability trajectories — between opportunities and vulnerabilities".

10.2 Teaching - Supervision - Juries

10.2.1 Anthropocene FACTS project

The Anthropocene FACTS project started in the STEEP team in 2018 following numerous requests from various universities to have team members come and teach a course on our research topics. These types of requests became too frequent starting in 2018, and we quickly realized that we would not be able to cope with them. Nevertheless, to help ensure that socio-environmental topics are taught broadly in higher education, we came up with this project. Its objectives are multiple:

- Make robust and diverse pedagogical contents available to educators who wish to teach about these issues.

- Make these contents as easy as possible to appropriate, in particular to non-specialists.
- Create an academic community to peer-review contents, share practices, methods, constructive criticism, difficulties encountered, experiences, etc.

In May 2022, we organized a one-week thematic school held in Grenoble brought together 50 participants: 25 university teachers and researchers who wanted to start teaching socio-environmental issues and 25 MSc students from many disciplines whose participation aimed at testing if the program was adapted to this audience. The event was a success. Feedback from participants allowed to validate the relevance of our project and provided very useful input for fine-tuning.

Since this thematic school, we have started to connect with related initiatives in France – indeed, in the last one or two years, more and more such initiatives are launched by scientists. We have established regular discussions with Labos1.5, *Enseigner le climat*, UVED, *Riposte Créative Pédagogique*, Ecocloud, etc. A common goal is the creation of a platform for sharing pedagogical resources (slides and associated notes, specifications of workshops and student projects, methods for facilitating debates, etc.), as well as the creation of a community that will maintain and enrich the platform and be available to give advice to educators who desire to start teaching systemic socio-environmental issues. Our project is in line with the recent announcement by the Ministry, of the goal that by 2025 a training on ecological transition shall be mandatory for all bachelor students in France.

10.2.2 Teaching

- Jean-Yves Courtonne, Serge Fenet, Pierre-Yves Longaretti, Guillaume Mandil, Régis Perrier, Emmanuel Prados, and Peter Sturm: *Les véritables enjeux environnementaux – compréhension, modélisations et outils quantitatifs*, 24 hours, course plus project work, Master course, Ecole Centrale de Marseille.
- Jean-Yves Courtonne, Serge Fenet, Pierre-Yves Longaretti, Guillaume Mandil, Régis Perrier, 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.
- Jean-Yves Courtonne, Guillaume Mandil: *Science, Environnement, Société*, Graduate School (CED) UGA.
- Denis Dupré, Serge Fenet, Guillaume Mandil, and Mathieu Mangeot have regular teaching duties at the universities employing them.

10.2.3 Juries

Peter Sturm was a reviewer of the PhD thesis of Nicolas Jacquelin (Université de Lyon) and chaired the PhD committee of Devesh Adlakha (Université de Strasbourg).

Peter Sturm was member of the recruitment committee for a professorship (INP Toulouse) and external expert for a promotion committee at The University of Hong Kong.

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, 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 November 2022 the channel has close to 10,000 subscribers and reached a total of over 825,000 viewings.

In 2022, we had the following conference-debates.

- Servane Mouton (Hospices civils de Lyon): Impacts of screens on health (*Impacts des écrans sur la santé*)
- Clément Féger (AgroParisTech): Can ecological accounting enable the emergence of an economy that respects the biosphere boundaries? (*Quelle(s)comptabilité(s) pour organiser les responsabilités pour la préservation de la biosphère ?*)
- Christophe Bouillaud (Institut d'études politiques de Grenoble): "It's politics, stupid!" On the few political mechanisms that led to climate and environmental chaos (1970-2030) (*"It's politics, stupid!" Sur les quelques mécanismes politiques ayant mené au chaos climatique et environnemental (1970-2030)*)

10.3.2 Internal or external Inria responsibilities

- Emmanuel Prados and Jean-Yves Courtonne are members of the scientific committee of the city of Grenoble. This committee is involved in the preparation of the events for “Grenoble 2022 European Green Capital”.
- Jean-Yves Courtonne is a member of the Steering Committee (COPIL) of the Terristory consortium.

10.3.3 Articles and contents

Book on World3 and the 1972 report “The Limits to Growth” to the Club of Rome. 2022 marks the 50th anniversary of the Meadows report on the limits to physical growth in a finite world [55], an iconic work in sustainability science. In order to celebrate and popularize it, the STEEP team coordinates the edition of a FAQ on this report, the underlying World3 model, and limits to growth in a broad sense. Four researchers (Louis Delannoy, Mathilde Jochaud du Plessix, Vincent Jost, Sophie Wahnich) interviewed peers and members of civil society 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 provide short chapters answering them. The finally produced book of about 120 pages 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 web publication is planned for the end of the year, and the paper publication – in agreement with the publishing house Excès – has been set for September 2023 in order to prepare the editorial work and the communication as well as possible.

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 [59]. 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. The Global Systemic Risks fresco was included as a participating workshop in the Archipel 2022 conference organized by the STEEP team (see section 10.1.1).

A workshop 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 6 for a sample outcome).

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 different workshops already and will be used by members of the public authorities involved in the *l'Atelier des Futurs* initiative (section 8.14), 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.

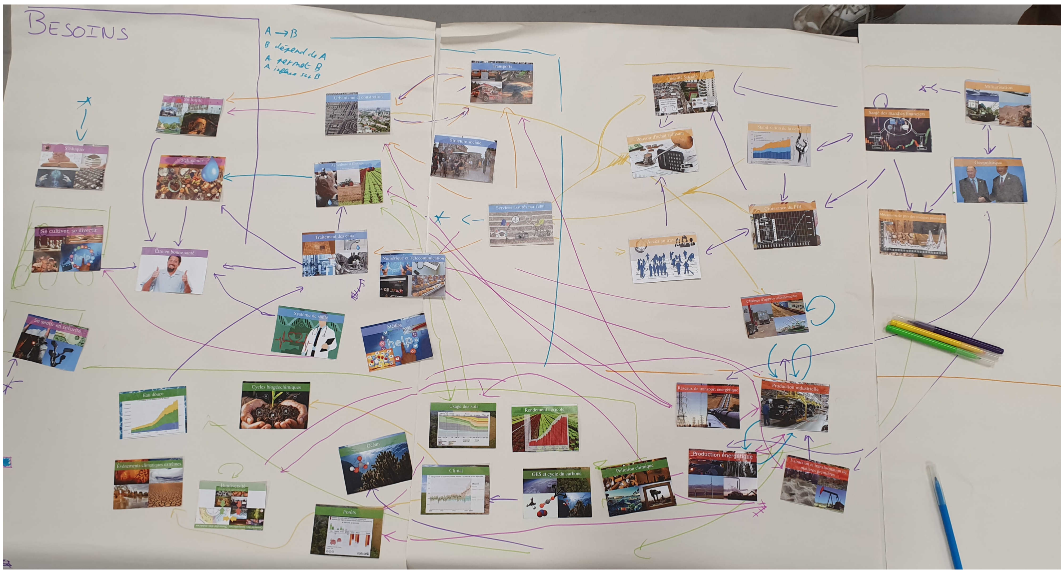

Figure 6: Structure designed by a group after phase I of the Systemic Risk Fresco workshop.

Faire face, Face cinéma. 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. The first session of this cycle took place on November 15, 2022 with the screening of "Soylent Green" by Richard Fleischer.

Other. Team members contributed to several sections of the INRAE–Inria White Book on Agriculture and Digital Technology [25, 26, 27, 29].

Louis Delannoy and Emmanuel Prados wrote an article entitled Les lois de la physique rendent la sobriété inévitable, published by Reporterre.

Louis Delannoy wrote an article for Mother Pelican, Hydrocarbons: Consume More to Produce Less.

Team members wrote a paper on the particular role of violence in a "science of collapse" [31].

Peter Sturm gave an invited talk (plus short paper) at ROADEF 2022 on the topic of efficiency in Operational Research [19].

10.3.4 Interventions

- Jean-Yves Courtonne was invited by BPI Coq Vert to give a talk to 100+ business owners on the limits of circular economy. BPI (*Banque Publique d'Investissement*) is the French public investment bank, a major national actor in supporting innovation for the French economy.
- As a follow-up to the previous event, Jean-Yves led a workshop gathering about 15 participants on Material Flow methodology and use for decision-making.
- Pierre-Yves Longaretti gave a talk on systemic risk modeling with Louis Delannoy and Antonin Berthe (PhD students, STEEP). *Strong sustainability trajectories* workshop, Grenoble, June 2022.
- Emmanuel Prados gave a plenary guest conference entitled "Understanding the unprecedented dangers and risks we are now facing, addressing these issues (causes, consequences, room for maneuver) from a scientific and socio-political perspective" at the 2nd Days of the Engineer, Actor of Transitions which took place from November 21 to 24, 2022.
- Emmanuel Prados gave a course within an inter-union training day on *Urgence environnementale et sociale : agir collectivement pour vivre mieux*, Grenoble, 6 october 2022.
- Pierre-Yves Longaretti gave a conference at the "Les conf' allant vert" organized by UGA Design Factory, the 19th January 2022. Title "Collapse risks: nature, assessment, perspectives".
- Sophie Wahnich gave a conference at the "Les conf' allant vert" organized by UGA Design Factory, the 10th March 2022. Title "Utopia of language and utopia of history, a meetings".
- Emmanuel Prados gave a 3 hours course to the 2nd year students of the Ensimag engineering school in the framework of the "Numérique Responsable" ("Responsible Digital") module (last course of the module having an opening objective on the political, ethical issues, and the actors' games) [April 26, 2022].
- Peter Sturm animated a joint workshop of two national research networks, on Operations Research (GdR Recherche Opérationnelle) and AI (GdR IA), on "How to evolve one's research activities to give them more sens?", Lyon.
- Peter Sturm and Mathilde Jochaud du Plessix intervened in the 2022 edition of Pint of Science, an international general audience initiative. They gave talks on their work in a bar in downtown Grenoble.
- Louis Delannoy gave a conference on *Le taux de retour énergétique : talon d'Achille de la transition bas-carbone et témoin d'injustice climatique* at the RSE Seminar of Université Grenoble Alpes
- Louis Delannoy gave a general audience conference Le taux de retour énergétique : talon d'Achille de la transition bas-carbone et témoin d'injustice climatique, invited by the *Shifters*.
- Louis Delannoy gave a podcast on Ressources fossiles : pénuries en vue ?, for Ozé.
- Two high school classes from Lycée de l'Albanais, Rumilly, France (about 60 students, aged 15 to 17) and their teachers visited STEEP for an entire day. Team members gave presentations on our research but also on general topics related to the Anthropocene. The visit was prepared in advance: the students watched videos of some of our online conferences and prepared detailed lists of questions, on our research, on environmental and social issues, on the work of a scientist, etc. Thus, seminar-style presentations were complemented by open discussions structured around the students' questions.

- Mathilde Boissier and Mathieu Mangeot participated in the workshop Crossing knowledge with everyone jointly organized by ATD Quart Monde, CNAM and CNRS (via the GIS Démocratie et Participation) for research into the crossroads of knowledge with people living in poverty, Saint Denis, France.
- Mathieu Mangeot gave a course on Limits to growth, planetary boundaries and the Doughnut theory to first grade students of Savoie Mont Blanc University, Chambéry, France.

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.

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11.2 Publications of the year

International journals

[14] B. Andrieu, O. Vidal, H. Le Boulzec, L. Delannoy and F. Verzier. 'Energy Intensity of Final Consumption: the Richer, the Poorer the Efficiency'. In: *Environmental Science and Technology* 56.19 (20th Sept. 2022), pp. 13909–13919. DOI: 10.1021/acs.est.2c03462. URL: https://hal.archives-ouvertes.fr/hal-03787921.

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International peer-reviewed conferences

[18] F.-R. Mazy and P.-Y. Longaretti. 'A Formally and Algorithmically Efficient LULC change Model-Building Environment'. In: GISTAM 2022 - International Conference on Geographical Information Systems Theory, Applications and Management. Lisbon, Portugal, 27th Apr. 2022, pp. 1–12. URL: https://hal.inria.fr/hal-03626612.

[19] P. Sturm. 'Efficience : Quels Liens avec la Résilience et la « Sobriété » ?' In: ROADEF 2022 - 23ème congrès annuel de la Société Française de Recherche Opérationnelle et d'Aide à la Décision. Villeurbanne - Lyon, France, 23rd Feb. 2022, pp. 1–2. URL: https://hal.archives-ouvertes.fr/hal-03597201.

National peer-reviewed Conferences

[20] J.-Y. Courtonne, M. Boissier, A. Borthomieu, L. Fauste, V. Jost, E. Krieger, G. Mandil, M. Mangeot, O. Mauviel, C. Solnon and P. Sturm. 'Des outils numériques d'aide à la décision pour la conception et l'évaluation participative d'organisations alternatives de l'économie'. In: ROADEF 2022 - 23ème congrès annuel de la Société Française de Recherche Opérationnelle et d'Aide à la Décision. Villeurbanne - Lyon, France, 23rd Feb. 2022, pp. 1–2. URL: https://hal.archives-ouvertes.fr/hal-03595273.

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Conferences without proceedings

[22] A. Borthomieu, J.-Y. Courtonne, V. Jost, E. Krieger, G. Mandil, M. Mangeot and P. Sturm. 'Exploring the French economy with physical supply-use tables'. In: 14th ISIE SEM Conference : Transforming socio-economic metabolism in times of multiple crises. Vienne, Austria, 19th Sept. 2022. URL: https://hal.archives-ouvertes.fr/hal-03672578.

[23] Q. Desvaux. 'Analysis of the circulation of material flows in the Grenoble Alpes Métropole area: the missing links in the building sector'. In: XIème Congrès de l'Association Française d'Économie Politique « Qu'est-ce qu'un système économique et social soutenable ? » Amiens, France, 28th June 2022. URL: https://hal.archives-ouvertes.fr/hal-03885898.

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Scientific book chapters

[25] V. Bellon Maurel, P. Bonnet, I. Piot-Lepetit, L. Brossard, P. P. Labarthe, P. Maurel and J.-Y. Courtonne. 'Digital technology and agroecology: opportunities to explore, challenges to overcome'. In: *Agriculture and Digital Technology: Getting the most out of digital technology to contribute to the transition to sustainable agriculture and food systems*. White book INRIA 6. INRIA, 2022, pp. 76–97. URL: https://hal.inrae.fr/hal-03606035.

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Reports & preprints

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