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Activity Report 2014

Team STEEP

Sustainability transition, environment, economy and local policy

IN COLLABORATION WITH: Laboratoire Jean Kuntzmann (LJK)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Earth, Environmental and Energy Sciences

Table of contents

Team STEEP

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Creation of the Team: 2010 January 01.

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2. Overall Objectives

2.1. Overview

STEEP started in January 2010, initially as an Inria “Action Exploratoire” (2010+2011). It is currently an “équipe centre” of Inria Grenoble - Rhône-Alpes and is also affiliated with the Jean Kuntzmann laboratory (LJK [1]). The process of creating an EPI (équipe projet Inria) is underway and planned to be completed in 2015.

[1] http://ljk.imag.fr/

STEEP is an interdisciplinary research team devoted to systemic modelling and simulation of the interactions between the environmental, economic and social factors in the context of a transition to sustainability at local (sub-national) scales. Our goal is to develop decision-making tools to support decision makers in the implementation of this transition by developing simulation and optimization programs. In other words, our objective is to set up some mathematical and computational tools which enable us to provide some parts of the answer to the challenges *how to operate the sustainable development at local scales? and which local governance for environmental public policies?*.

This theme is new at Inria, but also for the researchers of STEEP who previously worked in other fields. Elise Arnaud, Emmanuel Prados and Peter Sturm worked on computer vision and Pierre-Yves Longaretti is a physicist. Some STEEP staff are still in the process of their own thematic transition.

The work of STEEP follows several research directions, covering different application domains; these are described in “Scientific Foundations” and “Application Domains” respectively.

2.2. Sustainable development: issues and research opportunities

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 a decreasing food security, important population movements (such as climate refugees) and explosive geopolitical tensions.

Sustainable development is often formulated in terms of a required balance between its 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 to some extent 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). Environmental problems have only recently been the object of media attention and public awareness. Most efforts bear on developing technological solutions. However, it is now clear that this will not be sufficient. 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.

The risks associated with delayed reaction and adaptation times make the situation urgent. Delayed reactions significantly increase the probability of overshoot of the planet carrying capacity followed by uncontrolled and irreversible evolution on a number of fronts . 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.

Although environmental challenges are monitored worldwide, the search for appropriate lines of actions must nevertheless take place at all institutional levels, in particular at local scales.At such scales, the proximity and smaller number of stakeholders allows decision makers to reach a consensus much more easily than at national or international scales. The failure of the recent Copenhagen summit (and for that matter of all climate summits since the adoption of the Kyoto protocol in 1997) is a good illustration of the difficulties encountered in international negotiations. There are significant possibilities for operations at local scales, and the emergency of the situation gives the “think locally to act globally” logic an essential opportunity.

As of now, local decision levels have real political and economic leverage, and are more and more proactive on sustainability issues, either independently or in coordination through nationwide or European networks (we can refer for example to the European GMO-free Regions Network [2] or to the Network of European Regions for a Competitive and Sustainable TouRism [3]). Also, we think that two local scales are going to be increasingly dominant in the near future: urban areas (more exactly the employment areas of main cities) and “regions”

[2] http://www.gmo-free-regions.org
[3] http://www.necstour.eu

(such as régions in France, Länder in Germany or Cantons in Switzerland). In particular, the sustainability of urban areas is one of the key issues of this century. As focal points of human activity, urban areas concentrate and amplify environmental pressures in a direct or indirect way.

Urbanization is a global and an ever-increasing trend process, with more than half the human population living in cities. Although urbanized areas still represent a very small fraction of the total terrestrial surface, urban resource consumption amounts to three-fourths of the annual total in energy, water, building materials, agricultural products etc., and pollution and waste management is a growing concern for urban planners worldwide. In France, for example, even if resource intensity (materials use divided by GDP [4]) has been reduced by half since the 70s, the actual material use (total and per inhabitant) has remained essentially constant, and household wastes have grown by 20% since 1995. Greenhouse gas (GHG) emissions have been reduced by a few percent since 1990, but the transportation share (a major issue on this front) has been steadily growing over the same period.

Furthermore, urban sprawl is a ubiquitous phenomenon showing no sign of slackening yet, even in countries where rural depopulation has long been stabilized. Urban sprawl in industrialized countries is largely driven by residential suburban growth. This phenomenon has both social and environmental consequences. First it implies an increase of daily mobility. In a context of high dependency on private cars and uncertainty on energy prices, this translates into an increased vulnerability of some population categories. It also induces an increase in greenhouse gas emissions, as well as an irreversible loss of cropland and a fragmentation of ecological habitat, with negative effects on biodiversity. The increasing concerns about climate change and upheaval in the market price of fossil fuels raise many questions about urban energy consumption while reviving the debate on the desirable urban structures and their determinants. Controlling urban sprawl is therefore a key sustainability issue.

Let us mention here that cities cannot be sustainable by themselves and that from this point of view, it does not make sense to focus on the municipality scale ("*communes*"). We think that it is very important to work at larger scales, typically, at employment catchment areas complemented by the adjacent agricultural and natural zones they are dependent on (that would correspond to the smallest scale for which a systemic analysis could make sense). Nevertheless, let us emphasize that because of resource imports and waste exports (e.g. GHG emissions), for any limited territory, the considered area will always depend on and impact other more or less distant territories. This is one of the key issues when trying to assess local sustainability.

Finally, let us note that the numerous and interrelated pressures exerted by human activities on the environment make the identification of sustainable development pathways arduous in a context of complex and sometimes conflicting stakeholders and socio-ecological interactions. This is why we also think that it is crucial to develop interdisciplinary and integrated approaches; consequently, our proposal tries to address the entire spectrum from scientific expertise to stakeholder decision-help.

STEEP, with its strong background in various areas of applied mathematics and modeling, can be a game changer in three connected key domains: urban economy, and related transportation and land use issues; material flow analysis and ecological accounting; and ecosystem services modeling. The group potential on these fronts relies on its capabilities to strongly improve existing integrated activity / land use / transportation models at the urban level on the one hand, and on the other, to build new and comprehensive decision-help tools for sustainability policies at the local and regional levels, in particular through the analysis of strategic social–environmental trade-offs between various policy options.

3. Research Program

3.1. Development of numerical systemic models (economy / society /environment) at local scales

[4] Gross Domestic Product (GDP) is defined as an aggregate measure of production equal to the sum of the gross values added of all resident institutional units engaged in production.

The problem we consider is intrinsically interdisciplinary: it draws on social sciences, ecology or science of the planet. The modeling of the considered phenomena must take into account many factors of different nature which interact with varied functional relationships. These heterogeneous dynamics are *a priori* nonlinear and complex: they may have saturation mechanisms, threshold effects, and may be density dependent. The difficulties are compounded by the strong interconnections of the system (presence of important feedback loops) and multi-scale spatial interactions. Environmental and social phenomena are indeed constrained by the geometry of the area in which they occur. Climate and urbanization are typical examples. These spatial processes involve proximity relationships and neighborhoods, like for example, between two adjacent parcels of land, or between several macroscopic levels of a social organization. The multi-scale issues are due to the simultaneous consideration in the modeling of actors of different types and that operate at specific scales (spatial and temporal). For example, to properly address biodiversity issues, the scale at which we must consider the evolution of rurality is probably very different from the one at which we model the biological phenomena.

In this context, to develop flexible integrated systemic models (upgradable, modular, ...) which are efficient, realistic and easy to use (for developers, modelers and end users) is a challenge in itself. What mathematical representations and what computational tools to use? Nowadays many tools are used: for example, cellular automata (e.g. in the LEAM model), agent models (e.g. URBANSIM), system dynamics (e.g. World3), large systems of ordinary equations (e.g. equilibrium models such as TRANUS), and so on. Each of these tools has strengths and weaknesses. Is it necessary to invent other representations? What is the relevant level of modularity? How to get very modular models while keeping them very coherent and easy to calibrate? Is it preferable to use the same modeling tools for the whole system, or can we freely change the representation for each considered subsystem? How to easily and effectively manage different scales? (difficulty appearing in particular during the calibration process). How to get models which automatically adapt to the granularity of the data and which are always numerically stable? (this has also a direct link with the calibration processes and the propagation of uncertainties). How to develop models that can be calibrated with reasonable efforts, consistent with the (human and material) resources of the agencies and consulting firms that use them?

Before describing our research axes, we provide a brief overview of the types of models that we are or will be working with. As for LUTI (Land Use and Transportation Integrated) modeling, we have been using the TRANUS model since the start of our group. It is the most widely used LUTI model, has been developed since 1982 by the company Modelistica, and is distributed *via* Open Source software. TRANUS proceeds by solving a system of deterministic nonlinear equations and inequalities containing a number of economic parameters (e.g. demand elasticity parameters, location dispersion parameters, etc.). The solution of such a system represents an economic equilibrium between supply and demand. A second LUTI model that will be considered in the near future, within the CITiES project, is UrbanSim [5]. Whereas TRANUS aggregates over e.g. entire population or housing categories, UrbanSim takes a micro-simulation approach, modeling and simulating choices made at the level of individual households, businesses, and jobs, for instance, and it operates on a finer geographic scale than TRANUS.

On the other hand, the scientific domains related to eco-system services and ecological accounting are much less mature than the one of urban economy from a modelling point of view (as a consequence of our more limited knowledge of the relevant complex processes and/or more limited available data). Nowadays, the community working on ecological accounting and material flow analysis only proposes statistical models based on more or less simple data correlations. The eco-system service community has been using statical models too, but is also developing more sophisticated models based for example on system dynamics, multi-agent type simulations or cellular models. In the ESNET project, STEEP will work in particular on a land use/ land cover change (LUCC) modelling environments (LCM from Clark labs [6], and Dinamica [7]) which belongs to the category of spatially explicit statistical models.

[5] http://www.urbansim.org

[6] http://www.clarklabs.org/products/Land-Change-Modeler-Overview.cfm

[7] http://www.csr.ufmg.br/dinamica/

In the following, our two main research axes are described, from the point of view of applied mathematical development. The domains of application of this research effort is described in the application section, where some details about the context of each field is given.

3.2. Model calibration and validation

The overall calibration of the parameters that drive the equations implemented in the above models is a vital step. Theoretically, as the implemented equations describe e.g. socio-economic phenomena, some of these parameters should in principle be accurately estimated from past data using econometrics and statistical methods like regressions or maximum likelihood estimates, e.g. for the parameters of logit models describing the residential choices of households. However, this theoretical consideration is often not efficient in practice for at least two main reasons. First, the above models consist of several interacting modules. Currently, these modules are typically calibrated independently; this is clearly sub-optimal as results will differ from those obtained after a global calibration of the interaction system, which is the actual final objective of a calibration procedure. Second, the lack of data is an inherent problem.

As a consequence, models are usually calibrated by hand. The calibration can typically take up to 6 months for a medium size LUTI model (about 100 geographic zones, about 10 sectors including economic sectors, population and employment categories). This clearly emphasizes the need to further investigate and at least semi-automate the calibration process. Yet, in all domains STEEP considers, very few studies have addressed this central issue, not to mention calibration under uncertainty which has largely been ignored (with the exception of a few uncertainty propagation analyses reported in the literature).

Besides uncertainty analysis, another main aspect of calibration is numerical optimization. The general state-of-the-art on optimization procedures is extremely large and mature, covering many different types of optimization problems, in terms of size (number of parameters and data) and type of cost function(s) and constraints. Depending on the characteristics of the considered models in terms of dimension, data availability and quality, deterministic or stochastic methods will be implemented. For the former, due to the presence of non-differentiability, it is likely, depending on their severity, that derivative free control methods will have to be preferred. For the latter, particle-based filtering techniques and/or metamodel-based optimization techniques (also called response surfaces or surrogate models) are good candidates.

These methods will be validated, by performing a series of tests to verify that the optimization algorithms are efficient in the sense that 1) they converge after an acceptable computing time, 2) they are robust and 3) that the algorithms do what they are actually meant to. For the latter, the procedure for this algorithmic validation phase will be to measure the quality of the results obtained after the calibration, i.e. we have to analyze if the calibrated model fits sufficiently well the data according to predetermined criteria.

To summarize, the overall goal of this research axis is to address two major issues related to calibration and validation of models: (a) defining a calibration methodology and developing relevant and efficient algorithms to facilitate the parameter estimation of considered models; (b) defining a validation methodology and developing the related algorithms (this is complemented by sensitivity analysis, see the following section). In both cases, analyzing the uncertainty that may arise either from the data or the underlying equations, and quantifying how these uncertainties propagate in the model, are of major importance. We will work on all those issues for the models of all the applied domains covered by STEEP.

3.3. Sensitivity analysis

A sensitivity analysis (SA) consists, in a nutshell, in studying how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model inputs. It is complementary to an uncertainty analysis, which focuses on quantifying uncertainty in model output. SA's can be useful for several purposes, such as guiding model development and identifying the most influential model parameters and critical data items. Identifying influential model parameters may help in divising metamodels (or, surrogate models) that approximate an original model and may be simulated, calibrated, or analyzed more efficiently. As for detecting critical data items, this may indicate for which type of data more effort must be spent in the data collection process in order to eventually improve the model's reliability. Finally, SA can be used as one means for validating models, together with validation based on historical data (or, put simply, using training and test data) and validation of model parameters and outputs by experts in the respective application area. All these uses of SA will be considered in our research.

The first two applications of SA are linked to model calibration, discussed in the previous section. Indeed, prior to the development of the calibration tools, one important step is to select the significant or sensitive parameters and to evaluate the robustness of the calibration results with respect to data noise (stability studies). This may be performed through a global sensitivity analysis, e.g. by computation of Sobol's indices. Many problems will have to be circumvented e.g. difficulties arising from dependencies of input variables, variables that obey a spatial organization, or switch inputs. We will take up on current work in the statistics community on SA for these difficult cases.

As for the third application of SA, model validation, a preliminary task bears on the propagation of uncertainties. Identifying the sources of uncertainties and their nature is crucial to propagate them via Monte Carlo techniques. To make a Monte Carlo approach computationally feasible, it is necessary to develop specific metamodels. Both the identification of the uncertainties and their propagation require a detailed knowledge of the data collection process; these are mandatory steps before a validation procedure based on SA can be implemented. First, we will focus on validating LUTI models, starting with the CITiES ANR project: here, an SA consists in defining various land use policies and transportation scenarios and in using these scenarios to test the integrated land use and transportation model. Current approaches for validation by SA consider several scenarios and propose various indicators to measure the simulated changes. We will work towards using sensitivity indices based on functional analysis of variance, which will allow us to compare the influence of various inputs on the indicators. For example it will allow the comparison of the influences of transportation and land use policies on several indicators.

4. Application Domains

4.1. Introduction

In the context described in the previous sections, we can distinguish two connected and complementary strategies for analyzing environmental pressures: a sectorial approach and a spatial one. The first one is more directly connected to ecological accounting, the second one has more direct relations to urban economy and land cover modelling. Let us start by describing the former.

4.2. Ecological accounting for sectorial pressure assessment

One of the major issues in the assessment of the long-term sustainability of urban areas is related to the concept of "imported sustainability". Cities 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 urban areas 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.

Four methods stand out:

- Material Flow Analysis (MFA)
- Input-Output Analysis (IOA)
- Life-Cycle Analysis (LCA)
- Ecological Footprint (EF)

Each of these is based on a well-defined structuring element: mass conservation for MFA, measure of industrial inter-dependencies for IOA, identification of all the steps from cradle to grave for LCA, measure of biocapacity demand for EF. The different methods have preferred areas of application. For example, EF is more relevant for analyzing primary production such as agricultural staples, wood, etc. IOA is more focused on whole industrial sectors, while LCA is geared towards end-user products, taken as functional units; finally, primary materials (such as metals), waste and emissions are more easily characterized through MFA. Methodological choices are driven by the type of question one needs to address, data availability and collection method and the spatial scales under consideration. Indeed, data can be used in two different ways: bottom-up or top-down. The bottom-up data is more precise, but in general precludes comprehensiveness; on the contrary, the top-down data is by nature more comprehensive, but is not suited for a detailed, fine-scale analysis of the results.

STEEP has already initiated 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.

4.3. 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).

Land Use/land Cover Change models (LUCC)

LUCC 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 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 is involved in the ESNET project, bearing on the characterization of local Ecosystem Services NETworks; the project is 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 Land Use/Land Cover Change (LUCC) model that will be 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 may be useful for the LUCC community at large, independently of the ESNET project needs.

Models for Land-Use and Transportation Interactions (LUTI)

Urban transport systems are intricately linked to urban structure and activities, i.e., to land use. Urbanization generally implies an increased travel demand. Cities have traditionally met this additional demand by extending transportation supply, through new highways and transit lines. In turn, an improvement of the accessibility of ever-farther land leads to an expansion of urban development, resulting in a significant feedback loop between transportation infrastructure and land use, one of the main causes of urban sprawl.

Transportation models allow us to address questions generally limited to the impacts of new infrastructures, tolls and other legislation on traffic regulation [8], on user behavior [9], or on the environment [10]. LUTI models (Land-Use and Transport Integrated models) can answer a much broader spectrum of issues. For example, they allow us to understand how the localization of households and of economic activities (which generate transportation demand) adapt to changes of transportation supply. They also allow us to assess the impacts of such changes on the increase in real estate value, or more generally on their effects on the economic development of a specific sector or neighborhood. An economic vision interprets all these interactions in terms of equilibrium between demand and supply. Modelling the localization of households and employments (companies) relies on capturing the way stakeholders arbitrate between accessibility, real estate prices, and attractiveness of different areas.

State of the art and operability of LUTI models.

The first model that proved able to analyze the interactions between transport and urbanization was developed by Lowry. Since then theories and models have become increasingly complex over time. They can be classified according to different criteria. A first classification retraces the historic path of these theories and models. They can be associated with one or several of the approaches underlying all present theories: economic base theory and gravity models, Input/Output models and theory of urban rent, and micro-simulations. A second possibility consists in classifying the models according to their aims and means.

Significant scientific progress has been made over the last thirty years. Nevertheless, modelling tools remain largely restricted to the academic world. Today, only seven models have at least had one recent application outside academia or are commercialized or potentially marketable, in spite of the important needs expressed by the urban planning agencies: Cube Land, DELTA, MARS, OPUS/UrbanSim, PECAS, TRANUS and Pirandello.

To guide their choice of a modelling framework, users can rely on various criteria such as the strength of the theoretical framework, the quality and the diversity of the available documentation, the accessibility of the models (is the model freely available? is the code open source? is the software regularly updated and compatible with the recent operating systems?), the functionality and friendliness of user interfaces (existence of graphic user interface, possibility of interfacing with Geographic Information Systems), existence of technical assistance, volume and availability of the data required to implement the model, etc. For example, among the seven models mentioned above, only two are open source and mature enough to meet professional standards: TRANUS and UrbanSim [11]. These two models are very different but particularly representative of the main current philosophies and trends in this scientific domain. Their comparison is informative.

STEEP implication in LUTI modelling.

As yet, very few local planning authorities make use of these strategic models, mostly because they are difficult to calibrate and validate. Systematic improvement on these two critical steps would clearly increase the level of confidence in their results; these limitations hinder their dissemination in local agencies. One of the major goals of STEEP is therefore to meet the need for better calibration and validation strategies and algorithms. This research agenda lies at the core of our projects CITiES ("*ANR Modèles Numériques*") and TRACER (Ecos Nord Venezuela). As for LUTI modeling, we have been using the TRANUS model since the creation of our team. We have also been working on UrbanSim from the beginning of the CITiES project. In

[8] Congestion, cost and time spent for the transport, etc.
[9] Changes in modality choice
[10] CO2 emissions, air pollution, noise nuisance, etc.
[11] http://www.urbansim.org

this framework we work in close collaboration with AURG [12], the local urban planning agency of Grenoble (*Agence d'Urbanisme de la Région Grenobloise*) in order to better understand and to improve the relevance of these tools for such territorial agencies.

5. New Software and Platforms

5.1. REDEM: REDuction Of GHG EMission software

Participant: Emmanuel Prados.

REDEM software (REDuction of EMissions) is a tool designed for the benchmarking of national GHG emission reduction trajectories. We have developed REDEM in collaboration with EDDEN Laboratory (Patrick Criqui and Constantin Ilasca). The actual version of the software is implemented in Visual Basic under Microsoft Excel in order to facilitate handling and diffusion to climate/energy economists. The work related to this software has been published in [5].

5.2. Wassily

Participants: Julien Alapetite, Jean-Yves Courtonne.

In collaboration with the association "Groupe de Réflexion sur les Empreintes Ecologiques Locales" (eco-data.fr), STEEP contributes to the development of Wassily (in tribute to Wassily Leontief who first designed the relevant concepts), to perform input-output analyses applied to environmental issues (see section 4.2). The purpose of this software is to automatize most of the work of standard input-output analysis and to visualize the results in a user-friendly way in order to efficiently address the related key environmental questions.

The software is structured in three different modules:

- the database module stores all the input-output data coming from Eurostat, OCDE, Insee or other sources.
- the computation module performs the input-output calculations
- the visualization module displays the results in a synthetic manner.

The database module is based on the SQlite format and makes use of SQL to manipulate the various tables involved in the process. The goal of this module is to provide a normalized data interface for the computation module, from various types of input-output data which are often stored as Excel sheet on web sites.
The computation module is based on QT and C++ and deals mostly with matrix manipulation.
The visualization module is based on a JavaScript library called D3 and allows the user to visualize the results in a number of different ways, such as bar charts, pie charts, sankey diagrams to name a few. The integration between the C++ and JavaScript pieces of code is performed with QTScript.

5.3. QGIS_Tranus_Reports

Participants: Patricio Inzaghi, Emmanuel Prados, Peter Sturm.

This software allows to graphically visualise data output by the TRANUS LUTI model (and possibly, of any other data of the same structure). In particular, this concerns any data items defined per zone of a modelled territory (productions, indicators, etc.). The software is designed as a plugin for the geographical information system platform QGIS and can be run interactively as well as by the command line or by a call from within another software. The interactive mode (within QGIS) allows the user to define graphical outputs to be generated from TRANUS output files (type of graphs to be generated – 2D or 3D – color coding to be used, choice of data to be displayed, etc.). Visualisation of data is done in the form of 2D graphs or 3D models defined using java-script. The software is about to be registered with the APP.

[12] http://www.aurg.org/

6. New Results

6.1. Highlights of the Year

This year has seen a number of major advances in the team research projects, on several fronts. The first one concerns the most important and time consuming project, namely integrated land use, activity and transport modelling (LUTI modelling). In this respect, the results described in 6.8 below constitute probably the first set of works contributing sophisticated numerical procedures to the calibration and validation of the TRANUS LUTI model.

The second significant breakthrough concerns the completion of a downscaling methof for Material Flow Analysis (MFA), a key aspect in the characterization and understanding of territorial metabolism for decision-help purposes (section 6.2).

Finally, the modelling effort on land use change for the ESNET project has now been mostly completed, and an operational LUCC model has been calibrated and validated for this project (section 6.3).

6.2. Downscaling Material Flow Analysis: the case of the cereals supply chain in France

The spatial reconstruction of the production, trade, transformation and consumption flows of a specific material can become an important decision-help tool for improving resource management and for studying environmental pressures from the producer's to the consumer's viewpoint. One of the obstacles preventing its actual use in the decision-making process is that building such studies at various geographical scales proves to be costly both in time and manpower. We propose a semi-automatic methodology to overcome this issue. First a supply chain model at the national level has to be designed. Supply and use tables are used to handle the data consistently. Finding the appropriate level of detail for both products and industries is an iterative process: with a small number of highly aggregated product categories, the study isn't likely to provide useful information while with a very detailed list of products and industries, finding input data, especially at local scales, won't be feasible. Secondly, national production, transformation, trade and consumption data have to be reconciled in order to respect the law of mass conservation: this is done through constraint optimization. Thirdly, regional supply and use tables are generated (either with direct data or through downscaling of national data using local proxies, e.g. employment statistics) and reconciled, taking into account the additional constraint that regional data must add up to national one.

We applied the methodology on the case of cereals and reconstructed the supply chain flows of the 22 French regions as well as the flows of four nested territories: France, the Rhône-Alpes région, the Isère département and the territory of the SCOT of Grenoble. Uncertainties of output data were estimated via Monte-Carlo simulations. We display the results using our Sankey diagram vizualisation tool. A research paper is in the reviewing process for one of the major journals in this field.

Future steps include coupling this model with economic (added value), social (local employment) and environmental (environmental pressures) aspects in order to provide new information to decision-makers at various administrative levels (from a group of cities to the national level).

6.3. Mapping and land use and land cover change for the ESNET project

The ESNET project (EcoSystem services NETworks) is a collaboration lead by LECA (Laboratoire d'ECologie Alpine, UJF) that aims at characterizing the ecosystem services of the Grenoble urban region (about 2/3 of the Isere département) at the 2040 horizon under various constraints of urban policy planning, changes in agricultural and forest management, and climate change impact on ecosystems. A preliminary task in this research program was the elaboration of very detailed maps (both in terms of land use and of resolution) of the study area at three different dates (1998, 2003 and 2009) based on available satellite and IGN data, in order to characterize past land use patterns as well as agricultural rotation patterns. These have been made and completed at Inria with the hiring of specialized engineers in these tasks, funded by the ESNET program. This exercice informs the next task (land use and land cover change – LUCC – modelling). Hosting this work at Inria was not only logical in terms of the available computer environment, but also useful in terms of visibility of Inria from outside planning agencies.

The LUCC model itself is developed partly at Inria (for modelling expertise) and partly at LECA (for expertise on ecological change drivers). The model development is now operational, thanks to a major effort on this front in 2014. Both transitions from non urban to urban and use and changes of agricultural practices are now calibrated and validated. The first scenario has been successfully simulated in terms of land use. The three other scenairios of the project are in the final stage of elaboration before simulation, so that the land use change simulation phase of the ESNET project should be completed by the end of April, 2015.

Two resarch papers are in the process of being written on the question of land use practices and their evolution in the study area, and a third one on issues of principle in land use modelling is also underway.

6.4. Benchmarking tools for the climate negotiation of GHG emission reduction trajectories

Climate negotiations related to global warming are another important issue of sustainable development. In this framework that is place at international scale we propose a benchmarking tool that is designed to avoid the main limitations of actual negotiation schemes. Our approach is based on the original Soft Landing proposition, made by Criqui and Kouvaritakis in the early 2000. We develop an up to date solution which improves the original idea mainly by introducing common but differentiated emission reduction profiles and by developing a dedicated algorithm for that purpose (called REDEM). To be compatible with global objectives, it is commonly accepted that for most developing regions, the national emission curves should admit a maximum and then should progressively decline. Similarly, we emphasize the fact that, in order to achieve the global objectives, all states will have to entail mitigation efforts, the intensity which may be measured by the rate of variation of the national emissions. At one point, the effort will reach a maximum, when the rate of variation in absolute value is at its maximum, and then decrease. In other words, there will also be a peak in the effort. Then we propose to base the benchmark on this peak of effort. This work has been done in collaboration with EDDEN Laboratory, in particular Patrick Criqui and Constantin Ilasca. It has been published in [5].

6.5. On the acceptability of land use transport integrated models by French end users as operational tools: from understanding to daily use

Land Use and Transport Integrated models (LUTIs) are promising approaches for urban planning. There is large literature describing their technical architectures or using them in various scientific contexts. Yet little attention has been paid to expectations of practitioners (planners) and to the daily use of such models. There is clearly an important gap between research and practice: a daily use of LUTIs for the simulation of regional planning policies is still an exception in France, despite important research investments and recent interest of planning agencies., and this situation does not seem to be specific to France. We worked on sheding light on what would make them definitely accepted and more used by planners to evaluate a range of urban and transport policies. To do so, we have interviewed different types of end users in France to identify their motivations and barriers to use LUTI models, in addition to literature study and our own experience dealing with urban planning agencies. We have analysed the main obstacles that prevent LUTIs from being widely used by local authorities. It is important to identify that there are two main issues: 1) Do current LUTIs really answer the questions and practical issues territorial agencies are confronted with on a day-to-day basis? Do they match their interests and expectations? 2) Are current LUTIs suitable with respect to the constraints and limitations of local agencies? The main obstacles associated with these issues are: first, it is difficult to match rather generic models with very specific and varied end users questions; second, it is costly and heavy to implement and use a LUTI (capacity obstacles); third, there is no guarantee that results of a dedicated LUTI will have any impact on the policy design (decision making obstacles). The results of our analysis show demand for a far more bottom-up oriented approach: the models should consider objectives and general needs of end users to live up to their expectations. Only a closer collaboration between modelers and end users, and more efforts to integrate modeling into urban planning, will make LUTIs considered as relevant approaches.

This work has been done in collaboration with Mathieu Saujot (IDDRI) and Mathieu De Lapparent (IFSSTAR), and belongs to the work program of CiTIES project.

6.6. Replication procedure for grouped Sobol' indices estimation in dependent uncertainty spaces

Sensitivity analysis studies how the uncertainty on an output of a mathematical model can be attributed to sources of uncertainty among the inputs. Global sensitivity analysis of complex and expensive mathematical models is a common practice to identify influent inputs and detect the potential interactions between them. Among the large number of available approaches, the variance-based method introduced by Sobol' allows to calculate sensitivity indices called Sobol' indices. Each index gives an estimation of the influence of an individual input or a group of inputs. These indices give an estimation of how the output uncertainty can be apportioned to the uncertainty in the inputs. One can distinguish first-order indices that estimate the main effect from each input or group of inputs from higher-order indices that estimate the corresponding order of interactions between inputs. This estimation procedure requires a significant number of model runs, number that has a polynomial growth rate with respect to the input space dimension. This cost can be prohibitive for time consuming models and only a few number of runs is not enough to retrieve accurate informations about the model inputs.

The use of replicated designs to estimate first-order Sobol' indices has the major advantage of reducing drastically the estimation cost as the number of runs becomes independent of the input space dimension. The generalization to closed second-order Sobol' indices relies on the replication of randomized orthogonal arrays. The motivation of this work is to extend this methodology in presence of dependent inputs. Indeed, the case of correlated parameters has to be tackled with caution, as the calculation of single input indices does not provide anymore a proper information, that can be easily interpreted. One strategy is thus to define grouped indices for groups of correlated variables. We address this issue by proposing an approach based on replicated designs and randomized orthogonal arrays that enables to take into account dependency within inputs. We suppose that this dependency can be expressed through constraints. This approach can be used facing any set of constraints at the condition that one is able to provide points in the input space that verify the considered constraints. Guided by our application on a land-use and transport integrated model (LUTI) where some economical parameters are linked by order relations, we focus on the case of sets of linear ordered constraints. Thus we propose a sampling strategy based on the simplex geometric structure, that ensures a proper input space filling.

This work has been done in collaboration with Laurent Gilquin and Clementine Prieur (members of Moise Team), and belongs to the work program of CiTIES project. It is described in [18]. The proposed procedure will be soon applied to study the sensitivity of TRANUS model.

6.7. Specifications for the calibration of Simbad model

"Simbad" is a LUTI model developed by LET. In the context of the CITiESANR project, we have done a comprehensive and detailed study of the parameters of the model in order to fully specify the calibration process of the model. For example, we have specified the objects of interest and indicators, as well as satisfaction criteria. This work has been done in close collaboration with LET.

6.8. Calibration of the TRANUS Land Use Module

The setting up of a LUTI model requires, like most numerical models, at least one phase of parameter estimation. This is concisely referred to here as calibration, although the calibration of a LUTI model also entails other aspects such as the definition of spatial zones, of economic sectors, etc. The TRANUS LUTI model plus software, like many other existing models, come along with a relatively simple calibration methodology. Most LUTI models indeed perform parameter estimation in a piecewise fashion, by sequentially estimating subsets of parameters. While this reduces the mathematical and computational complexity of calibration, neglecting the interactions across different modules and their parameters, may result in a significant loss of a model's quality. A second issue is that TRANUS, like several other LUTI softwares, employs rudimentary numerical routines for parameter estimation. We aim at reducing these weaknesses.

To do so, we first defined a particular parameter estimation problem for TRANUS properly as an optimisation problem, based on an explicit cost function that is to be minimised (something lacking in many articles on LUTI calibration). Next, we developed a series of numerical estimation schemes to solve this optimisation problem. The main difficulty here was that the model is dynamic; by delving into the model's equations and structure, we were able to unwind the model's dynamics and to make it amenable to standard numerical optimisation by gradient descent type methods [4]. This was first done for the estimation of a particular subset of model parameters (the so-called shadow prices). We have recently started to work on the simultaneous estimation of these and other model parameters.

This work is done in collaboration with Arthur Vidard from the MOISE Inria project-team and Brian Morton from the University of North Carolina at Chapel Hill.

6.9. State of the Art on the Calibration and Validation of LUTI Models

One of the tasks of the CITiES project is to construct an extensive state of the art report on the calibration and validation of LUTI models. We coordinate this effort, which involves all partners of CITiES, together with the project partner LVMT (Nicolas Coulombel). It consists of the definition of a taxonomy, of an extensive literature research and of a critical analysis of this literature. A short publication that explains the goals of this effort and some intermediate findings, has been presented in [3]. The completion of this task is expected for the first semester of 2015.

7. Bilateral Contracts and Grants with Industry

7.1. Bilateral Contracts with Industry

The PhD thesis of Jean-Yves Courtonne is co-sponsored by ARTELIA and Inria, via a bilateral contract.

Related to the former computer vision research activities of team members, we still had one contract with EADS Astrium Satellites (now Airbus Defence and Space), where we appear as sub-contractor: DECSA (DGA).

8. Partnerships and Cooperations

8.1. Regional Initiatives

In 2012, we started an informal collaboration with Serge Fenet from the University of Lyon (LIRIS lab), which among others accompanied Brindusa Smaranda's MSc thesis. In 2013, a project we submitted to the IXXI Complex Systems Institute of the Rhône-Alps region, together with the CERAG lab, was accepted. The project is about modeling and data mining applied to territorial ecology.

8.2. National Initiatives

8.2.1. ANR

CITiES (*Calibrage et valIdation de modèles Transport - usagE des Sols*)
Program: "*Modèles Numériques*" 2012, ANR
Duration: 2013 – 2016
Coordinator: Emmanuel Prados (STEEP)
Other partners: LET, IDDRI, IRTES-SET ("Systemes and Transports" lab of Univ. of Tech. of Belfort-Montbéliard), IFSTTAR-DEST Paris (formerly INRETS), LVMT ("*Laboratoire Ville Mobilité Transport*", Marne la Vallée), VINCI (Pirandello Ingenierie, Paris), IAU Île-De-France (Urban Agency of Paris), AURG (Urban Agency of Grenoble), MOISE (Inria project-team)
Abstract: Calibration and validation of transport and land use models.

8.2.2. FRB (Fondation pour la Recherche sur la Biodiversité)

ESNET (Futures of ecosystem services networks for the Grenoble region)
Program: "Modeling and Scenarios of Biodiversity" flagship program, Fondation pour la Recherche sur la Biodiversité (FRB). This project is funded by ONEMA (*Office National de l'Eau et des Milieux Aquatiques*).
Duration: 2013 – 2016
Coordinator: Sandra Lavorel (LECA)
Other partners: EDDEN (UPMF/CNRS), IRSTEA Grenoble (formerly CEMAGREF), PACTE (UJF/CNRS), ERIC (Lyon 2/CNRS)
Abstract: This project explores alternative futures of ecosystem services under combined scenarios of land-use and climate change for the Grenoble urban area in the French Alps. In this project, STEEP works in particular on the modeling of the land use and land cover changes, and to a smaller extent on the interaction of these changes with some specific services.

8.3. International Initiatives

8.3.1. Participation In other International Programs

TRACER (*TRANUS, analyse de la calibration et des erreurs, retours sur Grenoble et Caracas*)
Program: Ecos-NORD
Duration: 2012 – 2014
Coordinator: Mathieu Saujot (IDDRI)
Other partners: University of Caracas (Venezuela)

8.4. International Research Visitors

8.4.1. Visits of International Scientists

Brian Morton

Date: May 2014 - Jul 2014

Institution: University of North Carolina at Chapel Hill (USA)

8.4.1.1. Internships

Jayasi Mehar

Date: May 2014 - Jul 2014

Institution: IIIT-D (Inde)

Solange Blundi

Date: Jul 2014 - Jan 2015

Institution: Universidad de Buenos Aires (Argentina)

Luciano Gervasoni

Date: Jun 2014 - Dec 2014

Institution: Universidad Nacional del Centro de la Provincia de Buenos Aires (Argentina)

Patricio Inzaghi

Date: Jul 2014 - Jan 2015

Institution: Universidad de Buenos Aires (Argentina)

Abdelrahman Ahmed Mohamed

Date: Mar 2014 - Jul 2014

Institution: Nile University (Egypt)

Iman Boukhriss

Date: Mar 2014 - Aug 2014

Institution: INSA (Lyon)

9. Dissemination

9.1. Promoting Scientific Activities

9.1.1. Scientific events selection

9.1.1.1. member of the conference program committee

Peter Sturm was Associate Editor for the IEEE/RSJ International Conference on Intelligent Robots and Systems and member of the Program Committee of the German Conference on Pattern Recognition.

9.1.2. Journal

9.1.2.1. member of the editorial board

Peter Sturm is Associate Editor of the IEEE Transactions on Pattern Analysis and Machine Intelligence, the Journal of Mathematical Imaging and Vision, and the Image and Vision Computing Journal.

9.2. Teaching - Supervision - Juries

9.2.1. Teaching

E. Arnaud, Image processing, 18h, M2, University of Grenoble, France.

E. Arnaud, Statistics for biologist, 39h, L1, University of Grenoble, France.

E. Arnaud, Advising students on apprenticeship, 15h, M2, University of Grenoble, France.

P. Sturm, Computer vision, 13.5h, M2, University of Grenoble, France.

9.2.2. Supervision

PhD in progress:

Thomas Capelle, Research on optimization methods for setting up integrated models of transportation and land use, started in October 2013, P. Sturm and A. Vidard (MOISE)

Jean-Yves Courtonne, Analyse d'impacts environnementaux et aide à la décision sur des territoires locaux, du bassin d'emploi à la région, started in xxx, P.-Y. Longaretti and D. Dupré (CERAG)

Laurent Gilquin, Sensitivity analysis of a macroeconomic LUTI model, started in October 2013, E. Arnaud and C. Prieur (MOISE)

Anthony Tschirhard, Calibration and sensitivity analysis of a micro-simulation LUTI model, Oct 2012, E. Prados, E. Arnaud, P. Sturm

9.2.3. Juries

E. Prados, Reviewer of PhD thesis, Bruno Belin, University of Nantes angers Le Mans (title: “Conception interactive d’environnements urbains durables à base de résolution de contraintes”).

P. Sturm, President of the AFRIF Thesis Award Committee (French Association for Research in Pattern Recognition and Interpretation)

P. Sturm, Reviewer of habilitation thesis, Xavier Savatier, Université de Rouen

P. Sturm, Reviewer of PhD thesis, Behrooz Nasihatkon, The Australian National University

P. Sturm, President of PhD thesis, Julian Quiroga, Grenoble University

P. Sturm, President of PhD thesis, Lilian Calvet, Université de Toulouse

10. Bibliography

Publications of the year

Articles in International Peer-Reviewed Journals

[1] P. DUTTA, E. ARNAUD, E. PRADOS, M. SAUJOT. *Calibration of an Integrated Land-Use and Transportation Model Using Maximum-Likelihood Estimation*, in "IEEE Transactions on Computers", January 2014, vol. 63, n^{o} 1, pp. 167-178 [*DOI :* 10.1109/TC.2013.168], https://hal.inria.fr/hal-00748555

[2] R. PERRIER, E. ARNAUD, P. STURM, M. ORTNER. *Estimation of an Observation Satellite’s Attitude using Multimodal Pushbroom Cameras*, in "IEEE Transactions on Pattern Analysis and Machine Intelligence", September 2014, 14 p. [*DOI :* 10.1109/TPAMI.2014.2360394], https://hal.inria.fr/hal-01093238

International Conferences with Proceedings

[3] P. BONNEL, N. COULOMBEL, E. PRADOS, P. STURM, E. ARNAUD, C. BOITTIN, L. BOUZOUINA, J. CABRERA DELGADO, T. CAPELLE, J. DELONS, L. GILQUIN, V. HILAIRE, M. DE LAPPARENT, D. NGUYEN-LUONG, J.-P. NICOLAS, M. SAUJOT, A. TSCHIRHARD, A. VIDARD. *A survey on the calibration and validation of integrated land use and transportation models*, in "Symposium "Towards integrated modelling of urban systems"", Lyon, France, October 2014, https://hal.inria.fr/hal-01093254

[4] T. CAPELLE, P. STURM, A. VIDARD. *Formulating LUTI calibration as an optimisation problem: example of Tranus shadow-price estimation*, in "Symposium "Towards integrated modelling of urban systems"", Lyon, France, October 2014, https://hal.inria.fr/hal-01093248

[5] E. PRADOS, P. CRIQUI, C. ILASCA. *A Benchmarking Tool for the International Climate Negotiations*, in "AAAI-15 Special Track on Computational Sustainability", Austin, United States, January 2015, https://hal.inria.fr/hal-01101210

[6] E. PRADOS, M. SAUJOT, A. TSCHIRHARD, J. CABRERA DELGADO, M. DE LAPPARENT. *Involving end-users in calibration and validation processes: A key factor to favor transfer of integrated models*, in "Symposium "Towards integrated modelling of urban systems"", Lyon, France, October 2014, 4 p. , https://hal.inria.fr/hal-01101228

Scientific Books (or Scientific Book chapters)

[7] P. STURM. *Calibration of a non-single viewpoint system*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00759938

[8] P. STURM. *Fisheye lens*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00759935

[9] P. STURM. *Focal length*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00759934

[10] P. STURM. *Image plane*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00784185

[11] P. STURM. *Omnidirectional vision*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00789333

[12] P. STURM. *Optical axis*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00788369

[13] P. STURM. *Pinhole camera model*, in "Computer Vision: A Reference Guide", K. IKEUCHI (editor), Springer, 2014, https://hal.inria.fr/hal-00794084

Research Reports

[14] E. PRADOS, P. CRIQUI, C. ILASCA. *Mathematical formulation of REDEM algorithm for National soft landing CO2 trajectories under global carbon budgets*, Inria, September 2014, n^{o} RR-8601, 18 p. , https://hal.inria.fr/hal-01069604

Scientific Popularization

[15] E. PRADOS, E. NEVEU. *Mathématiques et algorithmique pour l'aide à planification territoriale*, 2014, 3 p. , Article rédigé dans le cadre de l'ARP MathsInTerre, https://hal.inria.fr/hal-01101254

Other Publications

[16] E. ARNAUD, E. BLAYO, G.-H. COTTET, A. HAMON, K. LE CALVEZ, M. NODET, B. THIBERT. *APP pour les maths en L1*, June 2014, Journée APP, https://hal.inria.fr/hal-01096838

[17] P. CRIQUI, C. ILASCA, E. PRADOS. *National Soft Landing CO2 trajectories under global carbon budgets*, March 2014, https://halshs.archives-ouvertes.fr/halshs-00980101

[18] L. GILQUIN, C. PRIEUR, E. ARNAUD. *Replication procedure for grouped Sobol' indices estimation in dependent uncertainty spaces*, July 2014, https://hal.inria.fr/hal-01045034