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MODELLING FOR LOCAL SCALE SUSTAINABILITY AND DECISION-MAKING SUPPORT: REFLECTIONS AND DIFFICULTIES

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This paper is about integrated modelling for decision-making support to sustainability policies at local scales. By “local scales” we mean sub-national scales like cities, employment catchment areas, or slightly larger scales like *départements* and *régions*, for France. The goal of this article is to share a certain number of our motivations, outlooks and experiences we acquired via the creation of our research group, which tackles this complex topic. In a first step, we identify three scientific domains that we consider to play a key role in local scale sustainability and for which improvement in available knowledge is crucial. In a second part, we discuss challenges and difficulties one is confronted with when one wants to work on the context considered here.

1. Sustainability at local scale and modelling

Sustainable development is often formulated in terms of a required balance between the environmental, economic and social dimensions, but public policies addressing sustainability are in practice dominantly oriented towards environmental issues in Western countries. However, the numerous and interrelated pressures exerted by human activity on the environment make the identification of sustainable development pathways arduous in a context of complex and sometimes conflicting stakeholder and socio-ecological interactions.

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 process, with more than half the human population living in cities, an ever-increasing trend. 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 peri-urban growth. This phenomenon has both social and environmental consequences, like an increased vulnerability of some population categories or a fragmentation of ecological habitat, as it implies an increase in 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 crop-land and a fragmentation of ecological habitat, with negative effects on biodiversity. Controlling urban sprawl is therefore a key sustainability issue and the increasing concerns about climate change and upheaval in the market price of fossil fuels raise many questions about urban energy consumptions while reviving the debate on the desirable urban structures and their determinants.

The issues just described require a panel of policy measures at all institutional levels, as they illustrate the existence of both local-local and local-global feedback loops. The regional (sub-national) and more local levels are of particular importance for the transition to sustainability, especially in a “think global/act local” approach that is up to now mostly oriented towards local climate and territorial energy plans. In this context, more 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.

Advances on those problems are hampered by multiple bottlenecks of various kinds; some are social, others are economic or political (…) but a number of them are also scientific, as lack of knowledge does not allow us to understand the phenomena involved and to identify the main drivers and sources of problems, as well as appropriate leverages for public policy. Proposing reliable alternatives is a challenge in such a context. These difficulties are moreover amplified by the strong interdependence of the various dimensions of the problem. Interdisciplinary and systemic integration appears to be fundamental to make progress on sustainability issues. Modelling appears as an efficient tool to promote scientific communication and structure stakeholder interactions on sustainability issues.

The goal of this article is to share a certain number of our motivations and outlooks about integrated modelling for decision-making support to sustainability policies at local scales. In a first step, we identify three scientific domains that we consider to play a key role in local scale sustainability and for which improvement in available knowledge is crucial: urban economy, and related transportation and land use issues; material flow analysis and ecological accounting; and ecosystem services modelling. We think that these domains are basic building blocks that are indispensable in order to carry out an integrated analysis and practical courses of action on these issues. Of course, our objective here is not to list all important domains - we are far from being exhaustive - but to offer a perspective on what might be best bets for a correct identification of first steps towards an effective sustainability transition. The above three scientific domains make up the core of the research project of our group, STEEP[1], a team of INRIA Grenoble Rhône-Alpes, and of SOCLE3[2], an informal

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[1] http://steep.inrialpes.fr/

[2] http://socle3.obs.ujf-grenoble.fr/

interdisciplinary group gathering a number of researchers covering all key fields to bring off such a project. In a second part, we discuss the challenges and difficulties one is confronted with when one wants to work on the context considered here. As an example, we also mention briefly how we manage them in our project.

2. Key domains in a perspective of integrated modelling at local scales

As mentioned above, three key domains have been identified; they are essential mainstays in local decision-making support based on systemic sustainability analyses. These domains are presented here, ordered from socio-economic aspects to more environmental ones.

2.1. Urban economy and integrated land use and transport modelling

Modern urban regions are highly complex entities. The understanding of the phenomena underlying urban sprawl and peri-urbanization is a key element to control the dynamics structuring urban space. Clearly, urban transport systems are intricately linked to urban structure and the distribution of activities, i.e., to land use. Urbanization generally implies an increase in travel demand. Cities have traditionally met this additional demand by expanding the 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.

Several models have been developed in the field of urban economics to understand the complex relationship between transportation and land use and to facilitate the urban planning process [Iacono'08]. Researchers have sought to better model the functioning of cities by developing tools that can simulate the supply and demand of transport and land use, the real estate market, and the behavior of economic agents. Land use and transport integrated (LUTI) modelling provides a means to illustrate prospective exercises in urban planning. These models constitute invaluable analysis tools for planners working on transportation and urban projects. They enable the simulation of public policies and the quantification of indicators describing the evolution of urban structure. Key factors such as transport congestion, energy consumption, CO2 emissions etc., can be evaluated or estimated, and different urban development scenarios can be tested in a quantitative manner.

Yet, very few local authorities in charge of planning issues make use of these strategic models, mostly because they are difficult to calibrate and validate, two critical steps where systematic improvement would increase the level of confidence in the obtained results. These limitations prevent dissemination in local agencies. It is therefore crucial to meet the need for better calibration (estimation of model parameters based collected data) and validation strategies and algorithms.

2.2. Ecological accounting and material flow analysis

One of the major issues in the assessment of the long-term sustainability of urban areas is related to the concept of “imported sustainability”. Indeed, any city brings from the outside most of its material and energy resources, and rejects to the outside the waste produced by its 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 quantifying both local and distant environmental impacts; greenhouse gas emissions are only one aspect of this question.

In order to produce such an assessment for a given territory or urban area, one must first establish different types of ecological accounting: one must identify and quantify the different types of material and energy uses on the one hand, and the different types of impact associated with these uses [Billen’08]. The first task is the object of Material Flow Analysis (MFA), while the second is more directly related to the logic of Life Cycle Analysis (LCA). One of the major challenges here is to obtain reliable MFA data at the *région* and *département* scales, either directly, or through appropriate disaggregation techniques. The MFA methodology is now quite established at the national level, but still in its infancy at the regional or urban ones. The major difficulty is that economic accounting is nearly always performed in monetary units and not physical ones, and specific databases must be created to this effect, from a number of diverse data sources. On the impact side, the major difficulty is due to the fact that quite a few of the relevant flows are difficult to track throughout the planet in the modern globalized economy, and related impacts difficult to quantify. Finally, relevant decision help tools must be constructed, for decision-makers to evaluate social/environmental trade-offs.

It is nowadays essential to progress on this theme with three major aims in mind: 1) creating comprehensive databases enabling such analyses; 2) developing methodologies and models resolving scaling issues, and developing algorithms allowing to rigorously and automatically obtain the adequate assessments (in particular through an understanding and a careful treatment of the main sources of uncertainty); 3) providing a synthetic analysis of environmental impacts associated with the major material flows, at various geographic levels (employment catchment area, *département* and *région*, for France).

2.3. Eco-system services

Long-term sustainability is closely related to the underlying ecosystems, on various fronts: production of renewable resources (either energy or biomass), waste and pollutant resorption, local and global climate regulations etc. These various functions constitute the “ecosystem services” provided to society by our natural environment [Daily’97, Kareiva’07]. The reduction of the adverse impacts of urban areas on the environment is linked not only to limiting urban sprawl and making more efficient use of the available resources, but also to developing a better grasp of the interrelations between urban/peri-urban areas and their agricultural and semi-natural surroundings. In particular, reducing distant impacts while making a better use of local resources is a major challenge for the coming decades. In this context, it is important to develop generic modelling frameworks for ecosystem services, and to study their behavior under various scenarios of coupled urban/environment evolutions.

3. Challenges and difficulties

The modelling envisioned in our research group aims at combining a number of different aspects of economic analyses and analyses of the environmental impact associated with urban/rural/natural areas coupled evolutions under various social and environmental drivers. The required level of systemic and interdisciplinary analysis is one of the strongest and most ambitious points of this research, but also constitutes its most challenging aspect. The first aspect of this issue relates obviously to the various backgrounds of the involved researchers. Indeed, economists specialized e.g. in territorial economics have at first little common background with experts of the impact of climate change on the migration of species, except their desire to build a common framework. In our experience, the key point is not simply to elaborate a common vocabulary, but to develop an insider’s look into the internal logics of the various lines of questioning involved. This is in fact a particularly rewarding experience, both in terms of widening everyone’s scope and breadth of analysis, but also in strictly practical terms; indeed, quite often in this type of interdisciplinary project, the problem is to identify the right level of complexity one must aim at to construct a modelling framework that is both informative for researchers as well as for stakeholders, and yet still manageable. The most important problem is not expertise, but integration of knowledge.

Data collection is critical for this type of research, and the relevant data are often, if not proprietary, at least confidential, and accessible only under the conclusion of confidentiality agreements with the organizations and institutions in charge of the constitution of the databases at the local level (nationwide data are in general more easily accessible, but naturally less detailed). In this respect, our project benefits in particular from its close partnership with the promoter of the ANR AETIC project[3], and from various collaborations that are now in an advanced stage of discussion, for socio-economical data collection and sharing; on another front, one of the project partners (LECA, *Laboratoire d'Ecologie Alpine*[4], Grenoble) in particular has a strong expertise on natural/agricultural ecosystems data collection, and numerous partnerships for access to the relevant data. Finally, data are often incomplete and inhomogeneous; also, the required amount of data depends exponentially on the number of sectors (both economic and geographic) and the dynamics of scales one wishes to model. Compromises are needed at all stages, in order to make the data as homogeneous as possible. Such constraints on the database elaboration are essential for model calibration and validation.

Let us conclude this quick overview of potential bottlenecks by briefly mentioning two important technical issues. The first one is model integration. This issue has very generic aspects, such as designing module interfaces so that the output of one module is indeed the required input of another. This may need extensive restructuring of existing modules or even modelling logic. Also, very pragmatic problems, such as interfacing models developed on different platforms, may become quite challenging in themselves. The second problem is related to the visualization of the data and of the model output, for the modellers on the one hand and for exchanges with stakeholders and policy makers on the other hand. This visualization need covers two different aspects: an explicit visualization of model results in terms of, e.g., evolution of land-use and land-cover, which can be performed in a usual way through an appropriate use of GIS (geographical information systems) techniques; and, more critically perhaps, a manageable representation of policy options in terms of policy objectives and the various social/environmental compromises entailed by these policy options. This last aspect of the problem constitutes in itself a field of research in fast expansion.

The remainder of this section is focused on some issues that are more specific to the type of modelling of interest in our research group, i.e., decision help in a sustainability perspective at the local geographic levels (from the employment catchment area to the *région*).

3.1. Scales

The choice of modeled scales must result from compromises between scientific questions and decision-help objectives. On the scientific side, first, the scales one needs to model vary with the question one wants to address. For example, in urban

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[3] http://projet-aetic.upmf-grenoble.fr/

[4] http://www-leca.ujf-grenoble.fr/

planning issues, both in terms of housing tract planning or transportation infrastructure, the relevant modelling scales are defined by the most important (in numbers as well as traveled distance) commuting trips. This point has long been recognized by local planning agencies, which now consider urban planning at the level of a *communauté de commune* or more recently, *Schémas de Cohérence Territoriaux (SCoT).* This scale is adapted, but its administrative boundary, which results from discussions and negotiations, may not reflect the logic of transportation problems. Also, in practice, it usually includes many other considerations. For the analysis of impacts associated with material and energy flows, French *régions* are probably best adapted, in particular in a logic of relocalization of economic activities in a context of increasing energy prices and desired reduction of GHG emissions. On the other end of the spectrum, ecosystem services analysis often requires modelling at very fine scales, in order to analyze, e.g., species habitat fragmentation and connectivity. In practice, the approach that has been adopted in our project is to study some well-defined and limited areas at very fine scales, and characterize these services at larger scales in a coarser way.

On the public policy side, two questions arise: identifying correctly what elected representatives and agencies *may* do, and what they actually *can* do; the difference between the two arises from the fact that on the one hand they may not realize that they actually possess some leverages on various problems, and on the other because some of their actual official domains of action may be impeded by various extraneous considerations (some of them briefly mentioned in the next paragraph). Finally, the relevant political leverage may not exist at the scale where the problem arises, as the "subsidiary principle" is still far from being efficiently applied at all decision levels in Europe and in France.

3.2. Model complexity and modularity, and decision-help

In all such modelling efforts, one must bear in mind that political decisions must often, if not always, be reached in the absence of complete scientific, social, and economic information on the problems at hand. On the one hand, the political time scale, like it or not, is not the time scale of research; on the other hand, asking for more scientific information is more often than not a way to maintain the existing *status quo* and gain time.

In this context, a balance between strictly scientific objectives and the final aim of public policy decision help must be found: a too elaborate model will be unusable in practice by stakeholders and policy-makers, especially that their dashboards are often very limited and qualitative. Furthermore, stakeholder interests and sometimes conflicting lobbying (even at the most local levels) often weighs more than providing correct and relevant scientific information. In this context, even perfect knowledge of the scientific determinants of the problems to be addressed at the political level is no guarantee that problems are correctly anticipated and possible win-win lines of actions identified and implemented.

In this respect, the elaboration of multi-criteria and multi-stakeholders decision procedures is of paramount importance, and must be developed in parallel with more strictly scientific lines of questioning. An expert in these issues is involved in our group for these reasons, and this aspect of the question requires fostering interactions with local stakeholders and decision-help agencies right from the start of the intended research project. More generally, implication of stakeholders, in particular of decision-makers and institutional actors, is required for a correct upstream focus of some of the project's objectives and downstream use of its results. This makes model modularity a critical feature in order to address different and possibly conflicting stakeholder preoccupations. In all cases, the model inputs and outputs must be largely simplified in discussions with stakeholders and policy makers. It is the role of the multi-criteria decision-help experts to establish the right level of simplification in coordination with stakeholders on the one hand, and the scientific experts on the other, and to "fill in" the gaps if necessary. The question of the visualization of the model and of the various policy options is particularly critical as well.

3.3. A challenging framework for modelling science

Before describing some key challenges more specific to modelling aspects, we provide a brief overview of the types of models already developed in those fields.

As for LUTI (Land Use and Transportation Integrated) modelling, we can cite the TRANUS model (one of the most widely used LUTI models), which has been developed since 1982 by the company Modelistica[5], 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 popular LUTI model is UrbanSim[6]. Whereas TRANUS aggregates over e.g. entire population or housing categories, UrbanSim takes a micro-simulation approach, modelling 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.

The scientific domains related to eco-system services and ecological accounting, are much less mature than the one of urban economy and LUTI modelling. Nowadays,

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[5] http://www.modelistica.com/english

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

the community working on ecological accounting and material flow analysis only proposes statistical models based on more or less simple data correlations. The ecosystem services community has been using statistical models too, but is also developing more sophisticated models based for example on system dynamics, multi-agent type simulations or cellular models. Here, we can cite for example the widely used land cover model CLUE-S[7] which belongs to the last category.

Now, let us focus on three key challenges more directly related to modelling issues.

3.3.1. 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 mentioned above, 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).

Here the challenges are related to two major issues connected with calibration and validation of models: (a) defining a calibration methodology and developing relevant and efficient algorithms to facilitate the parameter estimation of considered models [Nocedal’99, Conn’09]; (b) defining a validation methodology and developing the related algorithms (this is complemented by sensitivity analysis, see the following paragraph). 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.

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[7] http://www.ivm.vu.nl/en/Organisation/departments/spatial-analysis-decision-support/Clue

3.3.2. 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 [Saltelli'08]. 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 devising meta-models (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.

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.

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 meta-models. 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.

3.3.3. Modelling of socio-economic and environmental interactions

Considering the assessment of socio-economic impacts on the environment and ecosystem service analysis, the problems encountered here are intrinsically interdisciplinary: they draw on social sciences, ecology or Earth sciences. The modelling of the considered phenomena must take into account many factors of different nature which interact *via* various 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. The spatial processes involve proximity relationships and neighborhoods, like for example, between two adjacent parcels of land. The multi-scale issues are due to the simultaneous consideration in the modelling, 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. Multi-scale approaches can also be justified by the lack of data at the relevant scales. This is for example the case for the material flow analysis at local scales for which complex data disaggregations are required.

At this stage, it is crucial to understand that the scientific fields considered here are far from being mature. For example, the very notions of ecosystem services or local ecological accounting are quite recent and at best partially documented, but advances in those fields are essential, and will be required to identify transition paths to sustainability. Nowadays, the analyses are only qualitative or statistic. The phenomena are little understood. It is then crucial here to do upstream research. It is to anticipate and to help the development of modelling tools that will be used tomorrow in these fields.

Developing 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; cellular automata, multi-agent models, system dynamics, or large systems of equations describing equilibrium models? 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 modelling tools for the whole system, or can we freely change the representation for each considered subsystem? How to easily and effectively manage different scales? How to get models which automatically adapt to the granularity of the data and which are always numerically stable? 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?

4. Conclusion

In this article we have shared a certain number of our motivations and outlooks about integrated modelling for decision-making support to sustainability policies at local scales. We have identified three scientific domains that play a key role in local scale sustainability and for which improvement in available knowledge is crucial and urgent: urban economy (and related transportation and land use issues), material flow analysis and ecosystem services modelling. Then, we have discussed challenges and difficulties one is confronted with when tackling these problems. The difficulties are multiple and of various types. Some of them are related to the very nature of the problem (interdisciplinary, scale delimitation) and require carrying out this exercise with a very specific state of mind (integration of knowledge being by certain aspects more problematic than expertise; interactions with stakeholders and decision-makers). Some of the difficulties are technical and even pragmatic (data, visualization, model interfacing). Finally, this problem also offers a very challenging framework for the modelling sciences, including applied mathematics and computer science. Model calibration and validation, as well as sensitivity analysis have largely been ignored until now, when they are really critical in this context. They are also extremely arduous and complex. In other respects, developing flexible integrated systemic models which are efficient, realistic and easy to use is a challenge in itself.

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