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Combining narratives and modelling approaches to simulate fine scale and long-term urban growth scenarios for climate adaptation

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A B S T R A C T

Although climate scientists explore the effects of climate change for 2100, it is a challenging time frame for urban modellers to foresee the future of cities. The question addressed in this paper is how to improve the existing methodologies in order to build scenarios to explore urban climate impacts in the long term and at a fine scale. This study provides a structural framework in six steps that combines narratives and model-based approaches. The results present seven scenarios of urban growth based on land use strategies and technological and socio-economic trends. These contrasted scenarios span the largest possible world of futures for the city under study. Urban maps for 2010, 2040 and 2100 were used to assess the impacts on the Urban Heat Island. The comparison of these scenarios and related outputs allowed some levers to be evaluated for their capacity to limit the increase of air temperature.

1. Introduction

Exploring the future is essential if efficient land management policies are to be defined with mid-to long-term perspectives (Godet, 1986; Godet and Roubelat, 1996; Peterson et al., 2003; Amer et al., 2013). The use of qualitative scenarios and quantitative models is therefore becoming a common approach (Veldkamp and Lambin, 2001; Verburg et al., 2004; Kok et al., 2004; Lambin and Geist, 2006). The coupling of scenarios and models is still uneasy and remains a great challenge due to the different philosophies and assumptions underlying them (van Vliet et al., 2010). The term 'scenario' is widely use in various disciplines and may have several meanings such as model outputs, narratives or simulations. In this study, scenario is defined as a narrative, i.e. an imaginative and qualitative description of the future. When focusing on linking scenarios with Land Use and Cover Change (LUCC) models, three types of approaches can be distinguished, each with its own advantages and drawbacks.

The first one, called hereafter 'model-based approach' consists of scenarios based on a quantitative approach and assimilated to model outputs. In this case, scenarios are defined by a set of input parameters, which are varied to provide contrasts among them (Paegelow et al., 2014). The simulated outputs, relying on an exploratory inference, are quantitative (e.g. economic indices, 2D or 3D maps) and are often used as input to feed environmental models (Alcamo, 2008). However, by definition, they depend on the model theory and architecture, which limits the range of possible futures that can be explored (Mas et al., 2014).

The second approach, called 'narrative-based', favours the production of highly imaginative scenarios that are not limited by the issue of which models may eventually be used afterwards. Scenarios are first co-constructed with interested parties or by experts

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in a participatory mode (Strengers et al., 2004; Alcamo, 2008; Kok and van Delden, 2013; Kok et al., 2014). These scenarios are assimilated to qualitative narratives that include a wide diversity of futures, highlighting various land use strategies and interactions. They use exploratory or anticipatory assumptions, with potentially strong breaks with past trends. Spatially explicit models, when they are used, provide virtual views of the future landscape by allocating future LUCC to illustrate the narratives. This approach requires the development of specific models or the coupling of models according to the selected assumptions and the processes that may occur in the defined scenarios. Such an approach assumes that models may not be path-dependent (Brown et al., 2005) and challenges their calibration (Kok, 2009), validation and architecture (Houet et al., 2015). This corresponds to the Storyline And Simulation (SAS) approach defined by Alcamo (2008) which:

- first, defines the narratives;
- second, uses an appropriate model to allocate future LUCC;
- is dedicated to an integrated assessment of environmental impacts.

The third approach, called ‘intimately coupled narratives & models’, consists of possible combinations of the first two in developing a scenario. Models can be used in a participative way in order to co-construct the narratives with local participants and stakeholders (Rouan et al., 2010; Gourmelon et al., 2008). The same (or other) model(s) can then be used to assess management strategies on future LUCC as suggested by the companion modelling framework (Etienne, 2011). This approach and the model(s) that may be developed, depend strongly on the site specificities and the involvement of the various players. The scenarios provided will be more adapted to, and probably more effective for, involved stakeholders. This ‘intimately coupled narratives & models'approach integrates the other two as it combines both qualitative/quantitative approaches and inductive/deductive inferences. It can belong to the SAS approach as models are used to help defining players' strategies and environmental stakes, as a first step towards building the narratives.

The chosen approach in the present study belongs to the SAS approach to build quantitative contrasted scenarios of city evolution. It constitutes a concrete application of the theoretical scheme of the Land System theory described by Kok et al. (2004) where participation and models are tightly linked to explore the future. These authors pointed out that most of the applications (before 2004) relied greatly on the ‘model-based’ approach. In this study, the focus is on the methodology, which provides a structural framework for benefiting from the respective advantages of the participatory and the modelling approaches.

The research reported in this paper aims to propose a framework for building quantitative and highly imaginative scenarios. It is applied to urban growth and impact studies and must fulfil the following objectives:

- cover a period of time up to one century. A perspective over half a century at least, if not a century, is required to account for and anticipate the contrasting effects on climate change of greenhouse gas emission scenarios, which are expected to differ markedly after 2050. Such a long-term approach is quite challenging considering the traditional urban planning exercises that commonly look only 20–30 years ahead, and it can only be applied through innovative prospective reflection.
- be able to integrate discontinuities (crises), into impact research. Even if high or low trend assumptions of future changes are considered as a reference baseline, exploring contrasted futures can be more fruitful to help decision makers to anticipate (un) expected events (Godet and Roubelat, 1996, 2000).
- provide quantitative scenarios applicable to a town as a whole, at the resolution of the urban block which is the relevant scale for urban planners to adapt and intervene on climate and energy consumption issues In France, for instance, public policies in this sense were set up in the period from 2000 to 2010 (see, for example, the French National Adaptation Plan[1]) for the next 20 years approximately. Worldwide, town authorities are confronted today with the need to define long-term territorial development strategies to limit the impacts of combined urban growth and climate change.

This paper presents the overall methodology used to build qualitative scenarios of land use change drivers, defined through a participatory framework, and coupled with multiple models allowing quantitative assessment of their impact on the urban climate and energy consumption. Section 2 details the innovative methodology based on six steps. It pays particular attention to the description of the variables identified in the participatory scenario building process and their links with the economic, geographic and architectural models then used to simulate the urban growth. Section 3 presents the 'quantified narrative' scenarios that we produced, which show a great diversity of possible futures. While examples concerning the city of Toulouse, France, studied in our ACCLIMAT project (Masson et al., 2014) will be presented, this original study is intended to contribute to any further methodological meta-study on this issue, and is applicable to any city and for other impacts. In section 4, the method is discussed with respect to the SAS approach and Fuzzy Set theory. Its interest also lies in the scenarios generated, providing key insights to help decision-makers in the definition of strategies for adapting to climate change at the city scale.

2. Combining narratives and models

The methodology developed to combine narrative and model-based approaches can be divided into six steps (Fig. 1):

1. Identify the main variables of sectors whose evolution will be studied, and their possible contrasting assumptions;
2. Combine assumptions into consistent sectorial scenarios (worldwide trends, local trends, land use planning strategies, technology trends);
3. Combine sectorial scenarios into integrated systemic scenarios;
4. Link scenario-driving variables to models input data;
5. Build quantitative projections for each type of input data;
6. Enrich the narrative with the quantitative data

Narratives were based on a participatory approach or the use of external prospective studies and projections. Participatory workshops were dedicated to the identification and combination of the variables needed for the scenario building process that were consistent with the scope of the study. Based on the pre-defined sectorial and systemic scenarios and the identification of suitable and useful models, variables defined as inputs to models were distinguished from those helpful to an understanding of the context and circumstances of the narratives. Finally, the simulated outputs were used to illustrate and quantify some of the context variables of the narratives.

The main novelty of our work lies in a step-by-step combination

[1] http://www.developpement-durable.gouv.fr/The-national-climate-change.html.

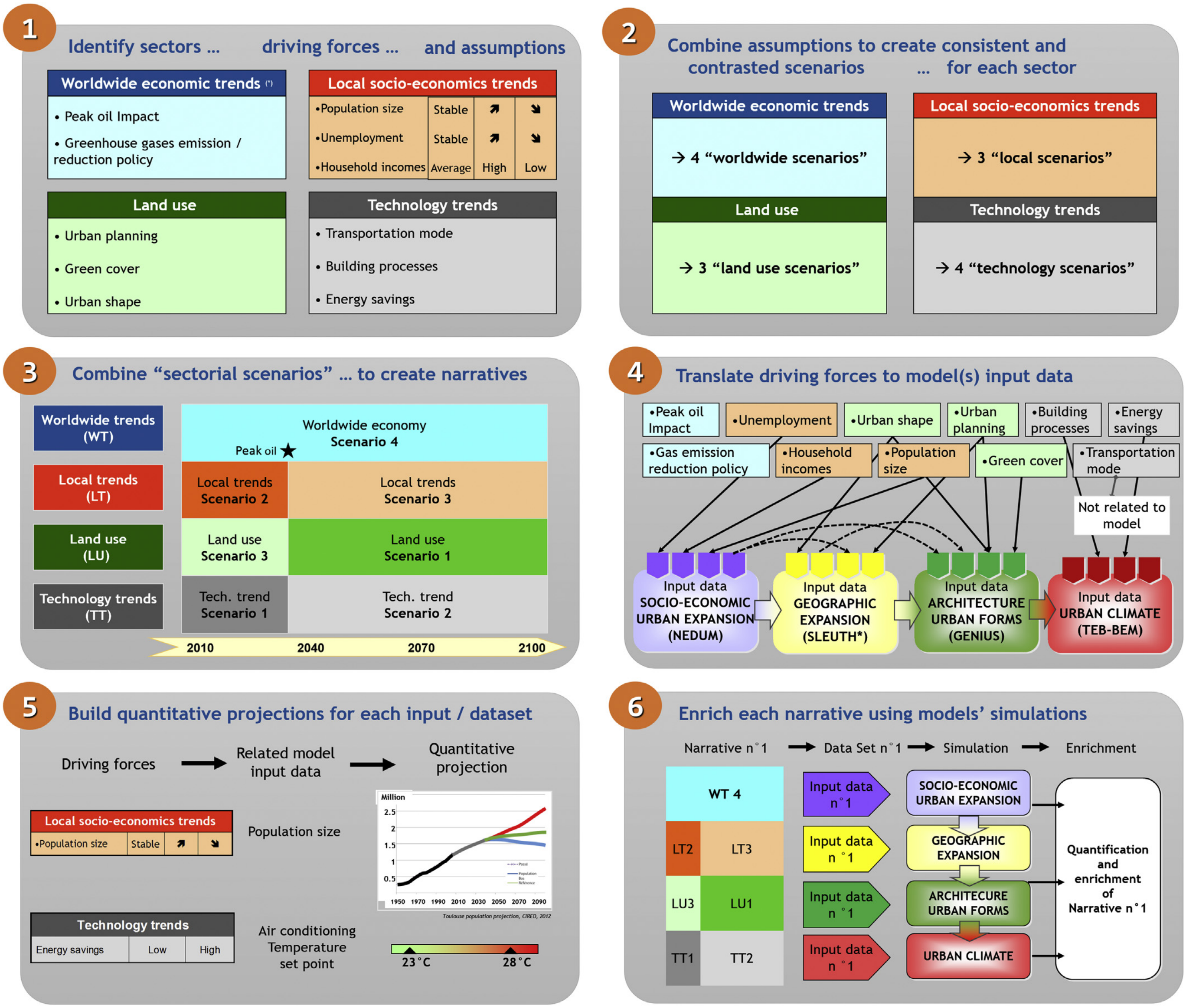

Fig. 1. From narratives to numerical models: a six-step methodological approach.

of various existing methods (participatory scenario method, models, etc.) which, taken independently, would not be used to best advantage.

2.1. *Identifying main sectorial variables and their assumptions*

Although the 2100 time horizon is appropriate when dealing with the effects of climate change, it raises challenges and issues for modelling the future evolution of cities, for which scenarios have to consider multiple drivers. Moreover, given the complex interactions of all possible drivers, they have to be chosen clearly. A first participatory – brainstorming – workshop, including stakeholders, experts and scientists in climatology, urban planning, economy, modelling, architecture regrouping approximately 20 persons, was able to put together a list of potential long-term drivers of the 'city' system per sector. Driving variables were distinguished from dependent variables and classified in four multiscaled or thematic clusters, called 'sectorial scenarios' by stakeholders below: worldwide trends, local trends, land use planning, and technology trends. The number of drivers varied from one sector to another and was not limited but identifying key drivers allowed the number of variables to be limited. For example, considering the worldwide trends sector, the two main driving variables identified were the peak oil and the (in)existence of an international climate policy, since they will affect the economy of our study area directly (aerospace industry) or indirectly (transport) (Viguié et al., 2014). Local trends focus on demography and economy of the study area. For instance, demography and immigration variables were considered as local trends drivers as they influence the urban evolution of a given city. Land use planning consider only the drivers of land management strategies (for e.g. green belt, households' density, protected areas, etc.) that influence the design of urbans forms and extent. Technology trends concerns current and future innovations in transportation and building materials that may affect the town energy balance and energy consumption. To build contrasting futures, contrasting assumptions for each selected variable of each sector were listed and described. Driving variables and their contrasting assumptions are presented in Tables 1 and 2.

The main assumption on this step was that the methodology proposed for scenario development started by simplifying the complexity to a limited number of variables. This is a common approach in scenario building (Godet, 1986). Thus, the challenging aspect of creating, dealing with, and quantifying qualitative data captured in exploratory narratives developed by stakeholders is removed. The goal of the participatory workshop was to first determine these sectors and the associated potential key drivers but not, at that time, their possible values.

Note that, at this stage, there is no link with the models, so it is probable (and this is what occurred during the process) that some of the drivers cannot be considered by the models. The position assumed here of not limiting the discussions on the drivers to the capabilities of the models has two advantages:

- it allows richer narrative scenarios, even if some aspects will not be quantified, and
- this points out shortcomings in the modelling chains. A new model can then be added or developed: it was done for architectural evolution during our project. However, if the expertise is not present in the partnership, the impacts of these drivers is not quantified. This is what occurred for the transport network, which was not dynamically simulated by a model; only a simplified transportation model was used in the socio-economic expansion model. But this gave some clues for the interpretation of several aspects linked to such unmodelled drivers.

Once the drivers of each sector had been defined by the participatory workshop, the next task was to define possible scenarios for each of them even for those that would not be used by the models.

2.2. Building consistent sectorial scenarios

At that stage, several potential drivers for each sectors were considered pertinent to the problem at hand (respectively two drivers for the worldwide trends, seven for the local trends, nine for the land use planning and twelve for the technology trends – cf. Tables 1 and 2). Some scenarios then had to be identified for them. Classically, there are two ways to provide values for driving variables in the scenarios.

The first one is through a participatory workshop (focus groups), where experts, scientists and, if appropriate, decision makers and politicians, propose several and potentially contrasting possible futures for each aspect. The participants were guided to some extent by the results of the first participatory workshop, which drew attention to identified drivers only. This had the advantage of improving the efficiency of the discussions, without limiting the potentially innovative aspects of the scenarios. However, at that stage, there was still no vision of the scenario as a whole. Matrices of drivers/assumptions were built to help in the definition of consistent combinations by colouring one cell of the table – i.e. assumptions – for each driver.

The second way to set values for the drivers is to gather some information from other sources, without discussing it further in a participatory workshop. This information can come from literature or from external modelling. On the issue of environment and climate change mitigation or adaptation, the best example is the IPCC exercise, where climate change scenarios are modelled by many climate groups around the world, and can then be used by others either directly from the model outputs or through the information in IPCC reports (IPCC, 2007a, 2007b; IPCC, 2013).

During this project, we chose to define the sectorial driver scenarios in both ways. This shows that the two methods are not exclusive.

Firstly, the ‘Worldwide trends’ scenarios were built using the second method as in Viguié et al. (2014). The IMACLIM-R model, a multi-region and multi-sector model of the world economy (Waisman et al., 2012; Sassi et al., 2010; Crassous et al., 2006), was used to generate four contrasting scenarios. The method is described in S1 (Supp. Material 1).

Secondly, another workshop had the aim of building scenarios for the other three site-specific sectors, respecting the consistency of driving variables. We used exclusively a cross-impact analysis with stakeholders to do so. The objective was to describe a specific context, for each sector, that could occur at any time between present and 2100, over the whole time period or only during a shorter period. Thus, one sectorial scenario could be followed by another, and it was possible to introduce disruption in the city's evolution (e.g. a crisis). The cross-selection of the set of assumptions associated with each variable by consistency checking helped to design contrasting sectorial scenarios. In order to differentiate the occurrence of each sectorial scenario, each of them was represented by a logo. The sectorial land-use scenarios are illustrated in Table 3. All the narratives of sectorial scenarios are detailed in S2 (Supp. Material 2).

This participatory approach also allowed a much broader spectrum of futures to be imagined more easily than with the simple use of literature or external model outputs (where the range of possible futures is limited by what has already been modelled). This was a key aspect for imagining discontinuities such as crises in the scenarios, which is one of the objectives of our methodology. This is further described in the next step.

2.3. Building consistent systemic scenarios and their narrative

Based on alternative outcomes that were identified for each pertinent driver, it was still necessary to build a complete scenario with different outcomes occurring. In order to continue to provide as much liberty as possible in the definition of the scenarios, this was again done in a participatory way (focus groups). The objective was to provide a limited number of contrasting scenarios, some with ruptures, some without, that still kept their consistency.

Therefore, the work of the participants was to link the sectorial scenarios, checking the consistency between the drivers of each of them. In order to facilitate the process, the scenarios for worldwide trends that might influence a coherent story of the future evolutions in each sector were first defined.

Then, in order to provide a complete view of the scenario, the scenarios for each sector had to be associated with scenarios of the other sectors. This defined what we call 'systemic scenarios' in this paper. This last step proved to be somewhat easier, because there were fewer direct links between these broad sectors than among drivers within one sector. This reflects, for example, the fact that a politician may be able to choose the strategic urban expansion policy for their city while the worldwide economy goes one way or another. However the results of this policy may later be influenced by this worldwide economy.

During the present project, a third workshop was organized to build systemic scenarios: each was a chronological combination of coherent sectorial scenarios. One ‘worldwide trend’ scenario was chosen for each systemic scenario. It defined the general context over the whole time period. Numerous scenarios could have been

Table 1
Driving variables for the ‘worldwide economy’ sector. The definitions of scenarios is detailed in the supplementary material 1.

Variables	Assumption 1	Assumption 2
A. Peak oil	A.1. Low impact	A.2. High impact
B. International climate policy	B.1. No existence	B.2. Existence

Table 2
Driving variables for the 'local trends', 'land use' and 'technology trends' sectors.

Variables	Assumption 1	Assumption 2	Assumption 3
Driving variables for the 'Local trends' sector			
1. Demography (aging)	1.1 Aging population	1.2 Young population	
2. Demography (size)	2.1 Stable	2.2 Increasing	2.3 Decreasing
3. Attractiveness	3.1 High	3.2 Low	
4. Household size	4.1 Increasing	4.2 Decreasing	
5. Household income	5.1 Higher than mean European Union income	5.2 Lower than mean European Union income	
6. Income inequality	6.1 Higher than mean national inequality	6.2 Lower than mean national inequality	
7. Economy/Labor	7.1 High unemployment Diversified or specialized employment	7.2 Low unemployment Specialized employment	7.3 Low unemployment Diversified employment
Driving variables for the 'Land use planning' sector			
8. Governance	8.1 Weak, uncontrolled land use management	8.2 Bottom-up isolated initiatives with weak coherency	8.3 Strong, Regional scheme for land use management
9. Energy performance	9.1 Carbon-free city and close to energy independence	9.2 Subsidiary to National energy norms	9.3 Worse than mean performance of national cities
10. Urban extent/form	10.1 Controlled conurbation	10.2 Sprawled and scattered city	10.3 Archipelago city
11. Regulation of urban density/blocks	11.1 No control of urban density – (close-set) houses	11.2 Control of urban density – 2 to 5 storey (close-set) buildings	11.3 Control of urban density – high-rise buildings
12. Location of local services	12.1 Scattered within urban blocks	12.2 Urban zoning	
13. Transport network	13.1 No development	13.2 New roads infrastructures	13.3 Development of multi-modal infrastructures
14. Transportation type	14.1 Domination of private car	14.2 Domination of public transportation	
15. Daily travel (distance/bulk)	15.1 Increasing	15.2 Decreasing	
16. Green areas	16.1 Preserved for ecological issues, recreational and local food production	16.2 A reserve for urban development	
Driving variables for the 'Technology trends' sector			
17. Local resources	17.1 Local farming and supply chain	17.2 Regional farming and supply chain	17.3 Globalization
18. Energy generation system	18.1 Autonomous building	18.2 Smart grids	18.3 As usual
19. Evolution of energy uses in buildings	19.1 Integrated supply-demand process	19.2 Improvement of supply	19.3 Increasing energy consumption
20. Standards and regulations[a]	20.1 Rapid integrated environmental approaches	20.2 Rapid regulatory framework evolution	20.3 Slow regulatory framework evolution
21. Technological innovation[b]	21.1 Fast evolution	21.2 Slow evolution	21.3 Low culture of innovation
22. Technologies of transports	22.1 Fossil-fuel transports	22.2 Electric motors and alternative fuels	22.3 Alternative fuels
23. Transportation availability/offer[c]	23.1 Less than tendency	23.2 Similar to tendency	23.3 Larger than tendency
24. Building energy performance	24.1 Efficient and comfortable buildings	24.2 Efficient buildings	24.3 Inefficient buildings
25. Buildings materials for new buildings	25.1 Integrated processes (3D prints, etc)	25.2 Innovative bio-techniques (Wood/Vegetal materials)	25.3 Traditional techniques (masonry, reinforced concrete)
26. Improving existing building performance	26.1 New or integrated technical solutions	26.2 improved traditional	26.3 No incentive for renovation
27. Urban density and buildings morphology[d]	27.1 Dense urban forms	27.2 Extreme density (high-rise buildings, dense industries …)	27.3 Low density and individual houses
28. Uses of energies[e]	28.1 Pro-active	28.2 Thrifty use	28.3 Non-thrifty use

[a] 20.2 means that for specific environmental issues norms evolve rapidly; 20.1 supposes that new norms involve integrated environmental solutions (for e.g. positive energy building with waste disposal for heating).
[b] 21.1/21.2 means that people have awareness to technological innovations and adopt them rapidly or slowly while, for 21.3, awareness is low and traditional techniques and materials are preferred.
[c] 23.x concerns the availability/offer of new transportation technology (related to drivers 22 and 14).
[d] 27.1 means buildings that are adapted to natural conditions/hazards (wind/sun orientation, height …) and with energetic concerns.
[e] 28.1 means very thrifty. Users are aware of environmental concerns and impacts of their choice.

built while still respecting the consistency of the assumptions, i.e. verifying that assumptions or sectorial scenarios had compatible meanings and were not controversial. Participants were split into two focus groups which produce 4 and 5 scenarios respectively. The results from both were compiled. However, we defined a limited number (seven) of scenarios (Fig. 2) by keeping those that showed the most contrast or were the most similar for the two groups. This choice was motivated by the wish to present the largest possible world of futures and to assess their implication in the spatial evolution of Toulouse and the associated micro-climatic Urban Heat Island (UHI). Once the chronology of each systemic scenario had been defined, summarizing the occurrence of sectorial scenarios, the corresponding narratives could be built.

2.4. Linking scenarios and models

In order to precisely quantify the impact of the driving forces in so many sectors, a large place was given to disciplinary models. While, technically, a single model could be used to simulate some impacts, we advocated the use, and even the coupling, of several models. This made it possible:

- to cover many of the drivers and sectors identified during the previous stages

Table 3
Sectorial land-use scenarios.

Sector	Method	Scenario	Narrative	Combined assumptions	Corresponding logo
Land use planning	Participative workshop	LU1	**Uncontrolled metropolis city** The 2010 urban management plan failed because of local political disagreements. As a result agricultural areas are converted into urban development (close-set and scattered houses) and environmental issues are not addressed. Municipalities favor their own development instead of sharing a common vision.	8.1; 9.3; 10.2; 11.1; 12.3; 13.1; 14.1; 15.1; 16.2	
		LU2	**Controlled *economicus* metropolis** Thanks to a regional management plan, the urban development is under control favoring economic interests. Green areas are used for urban development (with buildings) although a green-belt aims at limiting its extent. It also favors public transportation by increasing the city compactness.	8.3; 9.2; 10.1; 11.2 & 11.3; 12.1; 13.2; 14.2; 15.2; 16.2	
		LU3	**Controlled well-being metropolis** Thanks to a regional management plan, the urban development is under control favoring human well-being. Green areas are preserved and a green-belt aims at limiting the urban extent. Because of social values and existing constrains (city extension), decision makers favor individual housing (houses/small buildings) and transportation while funding for low emissions vehicles for example.	8.3; 9.1; 10.1; 11.2; 12.3; 13.2; 14.1; 15.1; 16.1	
		LU4	**Archipelago green regional capital** Stakeholders share a common vision which enables to depart from the current trend of urban development. For various environmental reasons (e.g. climate), future development is based on an archipelago design. Some municipalities aim at receiving all urban development (small and high-rise buildings) while others are dedicated for recreational and ecosystems services (food production, ecological corridors …). This ambitious program favors the development of public transportation and local social and economic services.	8.3; 9.1; 10.3; 11.2; 12.1; 13.3; 14.2; 15.2; 16.1	

• to provide coherent simulations of the process under study through the coupling between the models, each model evolving coherently with what the other models predicted.

The benefit of using coupled models in the prospective was twofold: (i) each disciplinary model was specialized in its field, and produced more accurate scenarios than the participatory method and (ii) only models enabled the different time-scales and spatial-scales of the processes involved in the different sectors to be taken into account. For instance, town expansion processes were considered at a 5- or 10-year time step while climatic impacts required seasonal or yearly analyses. Moreover, while a 1-km resolution was sufficient to study spatial patterns of urban growth when considering economic factors, territorial planning features required a finer resolution (100 × 100 m) in this study.

Next it was necessary to select appropriate models for the quantitative estimations.

Models were selected according to (i) their capacity to represent the physical, economic and LUCC processes the project aimed to focus on; (ii) their ability to take account of the key drivers present in the scenarios; (iii) the capacity of their numerical architecture to facilitate coupling (e.g., we chose software without a human interface and with free license only); and (iv) the expertise of the project partners.

As already mentioned above, some new models may need to be developed if a key aspect is not covered by the other models. Pre-existing models may also be adapted to enable coupling with the other model components of the modelling platform by:

- computing supplementary diagnostic fields that are expected as coupling fields by another model;
- changing the model design to avoid the calibration or equilibrium pre-staging phase in order not to be path-dependent according to the SAS approach (see for instance Houet et al., 2016).
- modifying the code of a model so that it can take an additional driver into account.

Scenarios can influence the models in two ways: directly when scenario variables are inputs of a model, and via coupling of the model with another, which is itself influenced by the scenario. Sectorial scenarios are translated into data that are used as model inputs.

The modelling chain used in the ACCLIMAT project is described in Masson et al. (2014). The city expansion was modelled by two coupled economic (NEDUM, Viguié et al., 2014) and geographic (SLEUTH*, Clarke et al., 1997; Houet et al., 2016) models, while architectural evolutions at block scale were modelled by GENIUS (Bonhomme et al., 2016; Tornay et al., 2015). The energy consumption and microclimate impacts were simulated by the TEB model (Masson, 2000).

For example, local trend scenarios provided population size, household incomes, etc. for the economic model NEDUM; land-use scenarios provided urban planning, urban land demand, etc. for the geographic model SLEUTH* intimately coupled to NEDUM and urban greening policy for the urban block model GENIUS (see for instance, step 4 in Fig. 1). Technology trend scenarios influenced both GENIUS (building uses, renovation rate, etc.) and TEB (thermal policy, energy source, energy use and performance, etc.). Additionally, models could be indirectly influenced by outputs of another model located upstream in the modelling workflow. For instance, the urban density, modelled by the expansion coupled models, influenced the architectural forms simulated by GENIUS.

Depending on the system under study, the modelling chain could be more or less complex. However, the structuration of all the scenarios in the same way, each with values for each driver in each sector, allowed the input values to be determined for the quantitative models. This was another key input of our methodology, and especially stage 1 (determination of pertinent drivers through a participatory workshop) because, while it allowed narrative, all scenarios contained the same type of information, and nothing was missing, from one scenario to another, to feed the models.

2.5. Building quantitative projections for each type of input data of each systemic scenario

Each systemic scenario had aspects of a backcasting scenario, i.e. targeting a (un)desirable situation in the future through the participative process. However, while the final size and pattern of the city remained unknown until the simulation was done, each assumption was scenario dependent. This meant that each assumption had to be defined quantitatively accordingly to the systemic scenario. The evolution of some assumptions could make the model input variables evolutive. For example, urban densification was promoted first by limiting the urban area with the design of a green-belt, and then by promoting collective buildings instead of individual houses. In summary, the narrative defined influential drivers and their timeline while models simulated the quantitative pathway and images of the targeted (un)desirable future in an exploratory way.

All assumptions required for the modelling were quantified or mapped. Then, they were debated, modified and eventually approved, again through a participatory approach.

For instance, during our project, the local demographic projections were derived from existing national projections made by the French Demographic Institute and adapted for Toulouse on the basis of past demographic trends. For example, a ‘crisis’ scenario expected decreasing attractiveness leading to a decline in population while the ‘excellence’ local trends scenario applied the national demographic trend to local demographic growth. The ‘complementary’ local trends scenario expected an increase in Toulouse's attractiveness, leading to a continuous inflow of new residents. As another example, the ‘uncontrolled urban form’ territorial management strategy was defined by the same restrictions as those currently in place, while the ‘controlled urban form’ defined a green belt to limit the urban expansion and the ‘archipelago urban form’ expected that only a few communities would absorb arrivals and urban development.

2.6. Enriching the narrative with the quantitative data

As an iterative process, the narratives defined in step 3 (cf. § 2.3.) were then enriched with quantitative information simulated by the models. The models' outcomes were used to improve the description of the *image* of the city and its possible evolution.

3. Results: a set of seven contrasting scenarios

This section presents results provided directly by the application of our methodology to build quantitative-narrative scenarios of the future evolution of a city in the very long term (one century). The case studied was the city of Toulouse, in south-west France, but this methodology could be used for other cities in the world, and also for other issues involving the construction of scenarios.

The results present the seven scenarios, i.e. the narratives, their translations into urban maps and their related impact indicators (urban forms and climate indices, energy consumption). These systemic scenarios, called *Reactive city, Thoughtful city, Dynamic city, Green city, Passive city, Nocuous city* and *Business as usual* in this study, start in 2010 and describe the pathway and images for 2040 and 2100.

3.1. Narratives

Only the narratives of the *Reactive city* and *Passive city* scenarios are presented here. The others are available as supplementary material (Supp. Material 3).

3.1.1. The ‘reactive city’ scenario

The economy of Toulouse, which is primarily based on the aerospace sector, performs very well between 2010 and 2040. Therefore, the agglomeration of Toulouse remains an attractive territory where the population increases continuously (+44% of new households compared to 2010). In terms of urban planning, public policies struggle to converge. Consequently, the trend towards urban sprawl continues (91,666 ha of artificialized areas in 2040) in the form of detached houses (83% of the total developed area) and is accompanied by new arterial roads that are quickly clogged. This phenomenon jeopardizes any principle of density and structure around the public transport networks. The preservation of agricultural and natural areas is secondary. In terms of energy, the local policy remains dependent on national trends, which greatly weakens the territory. Energy and environmental concerns are barely present. Regulations and renovation rates progress slowly.

By 2040 the price of oil has increased and the oil shock has strong consequences. A global economic crisis hits all countries that are dependent on a market economy. Conscious of its technological backwardness and its strong dependence on carbon-based energy, the state invests heavily. Regulatory and technological developments are finally underway.

At the level of Toulouse, the aircraft and aerospace industries are hit hard and markedly weakened by the global crisis in the period between 2040 and 2100. Therefore, the territory loses its attractiveness. In parallel, the population falls (−9% from 2070 to 2100) and becomes older and poorer. Local policies nevertheless maintain an economic system that is focused on energy innovation. Faced with scarcity, effective local governance is set up: unity is strength. The aircraft and aerospace industries are stopped, and urban density is enhanced and controlled. Furthermore, Toulouse megalopolis is formed and maintains a hyperpolarization around Toulouse city. Small collective housing units become the dominant urban form (detached houses make up 46% of the total developed area). Likewise, natural and agricultural areas are better protected or restored (only 1472 ha of new developed areas); they help to refresh the city. On the energy side, the economic difficulties push innovation and revise the modes of insulation and consumption.

3.1.2. The ‘passive city’ scenario

This scenario starts similarly to the reactive city scenario but the economy is based on diversification and local policies boost the bio-health and agri-food sectors. The decarbonization of the economy, initiated in 2020, leads to a limited impact of peak oil. Nevertheless, the price of oil continues to increase, at a very fast pace, until 2060. By 2040, policy makers find it necessary to question the current economic system and do not adopt any environmentally virtuous paths.

The economic sectors of Toulouse are not strongly affected as the economy is relatively diversified. The territory remains attractive and the population continues to increase between 2040 and 2100 (+20%). The urban sprawl continues to follow past trends. The ‘Coherent urban development scheme’ fails and local municipalities compete for urban development. Individual houses (81%) progressively spread at the expense of agricultural areas. In parallel, the density of developed areas decreases (−25%). The energy regulations, hardly demanding, evolve very slowly, leading to low levels of innovation and not triggering collective awareness of

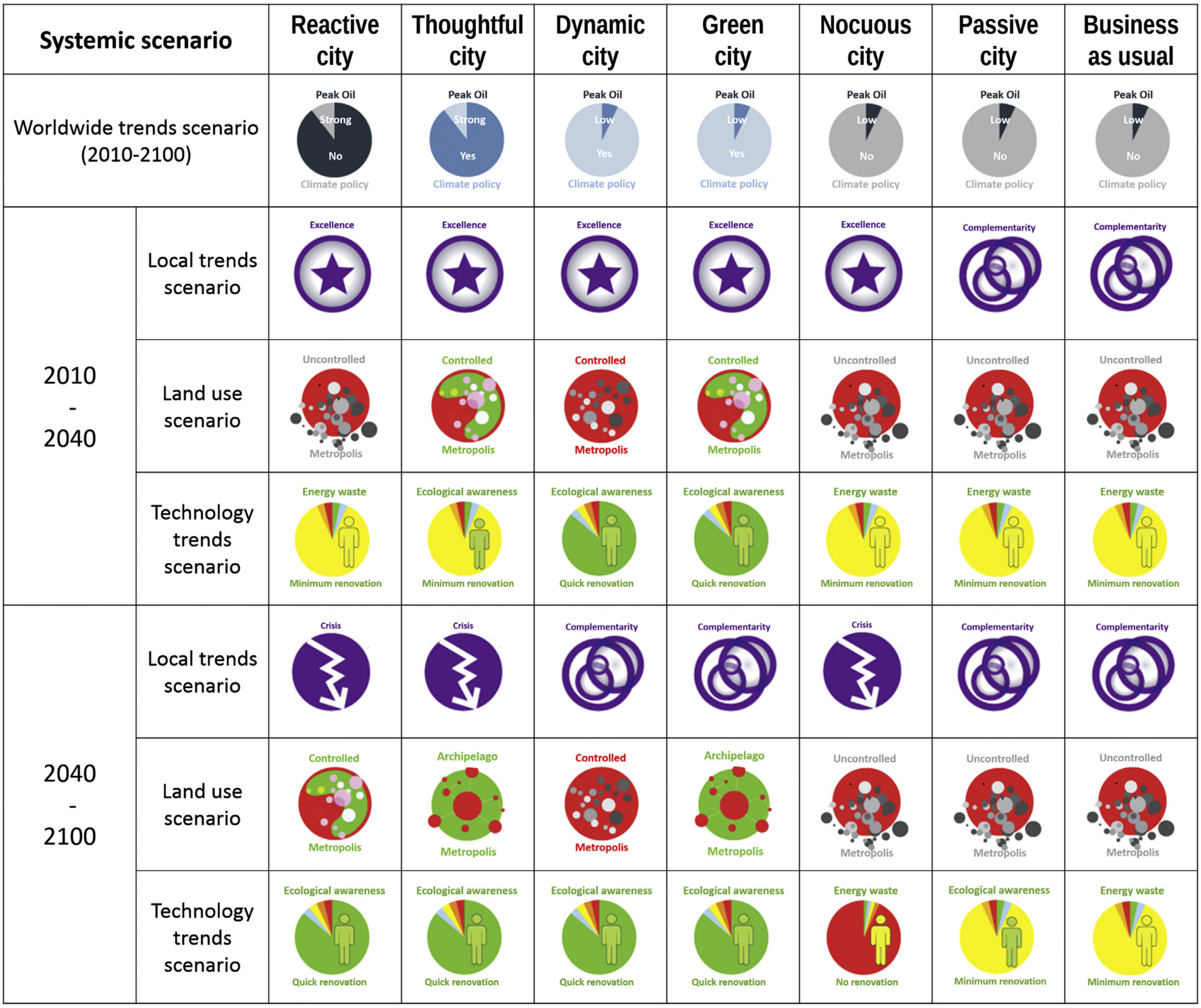

Fig. 2. Overview of the combination of sectorial scenarios to build contrasted systemic scenarios.

policy makers towards energy saving and climate adaptation. Conversely, this contributes to the emergence of a bottom-up environmental awareness from citizens and a willingness to save energy after 2040s. The individual is the catalyst of a culture of innovation that promotes the development of new techniques in new or existing buildings but their penetration and influence on habits is slower than when imposed by regulations.

3.2. Comparison of future urban growth and socio-economic impacts

Once scenarios have been produced, they can be compared through the simulated maps of urban growth, human density and Local Climate Zone (LCZ) (Fig. 3), in order to improve scientific knowledge of the system under study as well as to provide decision makers with not only qualitative but also quantitative information.

One of the ambitions of this methodology was to provide quantified scenarios with possible strong trend breaks. In our case, some of the scenarios presented a strong economic crisis on the territory. This is not only an economic crisis like the Great Depression and the Lost Decade, which were worldwide and lasted 'only' one or two decades. Here, we are able to propose local crisis scenarios that are linked, for example, to the disappearance of an industrial sector in the narrative, which translates into loss of attractiveness of the city inducing a decreasing demography. This has been the case for the car industry in Detroit, USA, since the middle of the 20th century, or the closure of all coal mines in Western Europe in the late 20th century, which induced a large increase in durable unemployment in these cities (i.e. over 50 years).

In our simulations for Toulouse, the population density in the city centre appears to be strongly influenced by the wealth of the city. When the city is wealthy (Dynamic, Green and Passive cities and Business as usual scenarios), the demographic increase maintains a strong need for housing, and population density increases in the city centre. In case of economic crisis (Reactive, Thoughtful, Nocuous city scenarios), the cost of living in the city centre becomes higher than the cost of living in the suburbs and travelling in, and people start to migrate away from the centre (Fig. 3). This is what has been observed in Detroit, USA.

Urban planning policies at the scale of the built-up area have a strong impact on city expansion projections. Without regulation on urban development areas, urban sprawl increases strongly between present and 2100 (respectively +40%, +60% and +92% for the Green, Dynamic, and Passive city/Business as usual scenarios). This is not the case, however, in case of future economic crisis because of the limited number of people moving to the city. By 2100, the Thoughtful, Reactive and Nocuous city scenarios exhibit respectively +26%, +35% and +37% of newly developed areas relative to 2010. On the other hand, some city forms promoted by urban planning are able to curb urban sprawl, as in the dynamic city and green city scenarios where the number of scattered urban plots in the territory is reduced (Fig. 4).

However, compact city forms may (for Reactive and Dynamic city), unexpectedly, increase the distance and duration of commuting in the second half of the 21st century. This can be explained by the fact that strongly controlling the city shape by a large green corridor is efficient as long as rents are affordable inside the green-belt. However, very high rents encourage people to move to the other side. This has already happened in London, and is called the 'leapfrog' effect (Amati and Makoto, 2006; Vyn, 2012).

Another conclusion of the simulation of urban expansion is that inertia is a key parameter in urban planning. For example, the Reactive city scenario lets single houses proliferate and starts an urban planning policy to promote collective buildings only after the 2040 economic crisis. However, this late policy has very little impact because of the very limited increase in the population of the urban area after the crisis. Thus the proportion of single houses increases by 80% between 2010 and 2100. In contrast, the Thoughtful city scenario, which favours small blocks of flats as early as 2010, significantly limits the urban surface occupied by individual houses (only a 40% increase between 2010 and 2100), because the policy is more efficient before the crisis, when the city was still growing fast, than after.

3.3. Impacts on the urban climate

The proposed methodology can also estimate quantitative impacts that are linked not only to the urban characteristics but also to environmental parameters. This is done in a manner ensuring complete consistency between the city expansion and the environmental impact modelling, as both are produced using exactly the same set of scenarios. This section focuses on the impacts of systemic scenarios on temperature fields using the numerical modelling framework (see Masson et al., 2014 for details). Only the impact of urban changes on urban climate is assessed.

The main factor of UHI (urban heat island) generation comes from land artificialization and is due to heat being stored in materials during the day and released during the night, and enhanced by the presence of impervious surfaces and trapped in narrow urban street canyon (Oke, 1982) The set of systemic scenarios foresees strong urban expansion that will tend to increase the UHI intensity. All other things being equal, this trend will be more pronounced for Dynamic, Passive, Nocuous city and Business as usual scenarios, in which the Toulouse urban area continues to grow until 2100 (Fig. 4). The absence of building renovation in the Passive city scenario prevents any measures for adapting buildings, such as reflective paints or insulation on the external side of walls, in order to decrease heat storage during the day. For that reason, even though the population stops increasing in 2050 in this scenario, the urban heat island remains strong.

The Dynamic city scenario is characterized by vertical urban forms around squares and public spaces. This architecture exacerbates the urban heat island in summer-time, in particular over the suburbs, which expand strongly. During wintertime, the strongest contrast is observed over the city centre where the urban heat island intensity considerably decreases. This can be explained by the transformation of the old city core (dense, with narrow streets), into spaced out high-rise buildings. Wind penetration is then favoured and can ventilate and cool urban spaces. This, in return, would diminish human thermal comfort, which is quite sensitive to wind (Mayer and Höppe, 1987; Matzarakis et al., 1999).

Scenarios with more vegetation (Reactive, Thoughtful and Green city) produce weaker and less extensive urban heat islands (Bowler et al., 2010; Lambert-Habib et al., 2013).

Finally, the Green city, which expands in an archipelago pattern, produces an urban heat island equivalent in both intensity and extent to those produced by Reactive and Thoughtful city scenarios that are in recession from 2040. Actually, a considerable fraction of new constructions is located in the new polarizing cities, and these constructions do not have an influence over the urban heat island at the city centre.

4. Discussion

4.1. Considerations when using SAS

Linking narratives and numerical models remains a challenging task. In our case study, it relies on a step-by-step approach that, while time consuming, seems particularly suitable for urban planners and modellers (Marchadier et al., 2012). This framework allows for imaginative, flexible scenarios, multiple combinations, long-term simulations, and quantitative impacts that each model, taken separately, would not have been able to address. It clearly belongs to the SAS approach defined by Alcamo (2008). For instance, steps 1, 2 and 3 proposed in this paper can be assimilated to steps 2 and 3 (respectively: “Team proposes goals and outline” and “Panel drafts narrative storylines”) of the SAS approach. Nevertheless, one challenge remains: how to feed models (with quantitative parameters) based on (qualitative) narratives, i.e. how to couple narratives and models? There is no single method for linking narratives and quantitative scenarios (Giaoutzi and Sapio, 2013). Numerous methods exists to convert qualitative information into quantifications: for instance, morphological analysis (Zwicky, 1969), cross-impact analysis (Helmer, 1981), and cross-impact balances (Weimer-Jehle, 2006). Many studies have used semi-quantitative methods to link narratives and models (e.g. EEA, 2007; Kok, 2009; Jetter and Kok, 2014). More recently, the Fuzzy Set Theory (Kok et al., 2014) has allowed qualitative knowledge to be converted into quantitative knowledge in a transparent way. All these methods expand the toolbox of the generic SAS framework (Alcamo, 2008) but they still face the challenge of validating the definition of the weights of the drivers considered by the models and, even more, their evolution into the future (Schweizer and O'Neill, 2014). We did not attempt to solve this problem but worked around it by taking advantage of the principles of the method for defining participatory/qualitative scenarios to guide the quantitative modelling processes which, in return, were helpful to limit the number of drivers to be quantified.

In our study, narratives provide a broad overview and direction of the (un)desirable future to be reached without giving any quantitative information about it. They are structuring elements of the method that help to select the most convenient drivers to translate them into quantitative input for models while choosing or developing the most appropriate model. The iterative process of selecting and quantifying some driving forces, modelling scenarios, and revising storylines was limited by the development of a modelling platform whose architecture was defined according to the linkage between scenario variables and input variables of models on the one hand, and the development of specific models and the modification of existing models on the other hand. The idea was to ensure that models simulated what the scenarios expected. The quantitative definition of the contrasting hypotheses of the listed variables was made on the basis of observed, quantified trends and based on existing sectorial scenario studies.

Several land use modelling frameworks exist (Mas et al., 2014) and have been used for different contexts and scenarios. The choice of a LUCC model has to be adapted regarding the scenarios that define the land demand and LUCC processes or patterns to be accounted for Houet et al. (2010):

- *LUCC processes*. Depending on the spatial resolution and extent, some may be more appropriate than others for simulating existing and possible future land use/land cover changes and processes (e.g. see Houet et al., 2014; for fine scale agricultural landscape, or Clarke et al., 1997; Houet et al., 2016; for urban areas). A comparative study of the models must be conducted (see, for instance, Agarwal et al., 2002; Haase and Shwarz, 2009) and some new model developments should be considered if needed. Moreover, when scenarios expect new LUCC processes, non-stationarity of LUCC drivers or non path-dependency, they may influence the type of models chosen or developed. In some cases, process-based models can be more suitable than optimized or statistical models as defined by Houet et al. (2014) and conversely.
- *Land demand.* Most of the time, the future land demand of scenarios is defined first, either by LUCC models (Mas et al., 2014) or within participatory frameworks (Kok et al., 2014), and then spatially allocated. The use of external models, such as socio-economic models, allows the hypotheses of future evolution of land demand to be strengthened and refined. Sometimes, when the LUCC model is chosen first, it may constrain the definition of scenarios, and the range of possible, contrasting futures.

4.2. Process, product, and learning

The size and composition of the participation group may strongly influence the whole methodological process (Kok et al., 2014), and thus the scenarios and modelling design. However, since the main purpose is to provide the most contrasting futures and to identify the main levers for coping with and adapting to the effects of urban growth and climate changes, which is the more important: the method or the results? If we agree that new methods to link models and scenarios are required, the way this is achieved is crucial information for stakeholders and policy makers. The transparency of the method might be even more important than the precision of the quantitative variables used to improve the credibility of the scenarios. The range of explored futures, accounting for various and contrasting land use strategies and socio-economic contexts, delineate the uncertainty on the ensemble forecast for the future (Trutnevyte et al., 2016; Maier et al., 2016). Because the ensemble uncertainty goes far beyond the inherent uncertainty of one scenario (Houet et al., 2015), i.e. including the parameters used and the model stochasticity for instance, it minimizes the influence and importance of using extremely accurate quantitative parameters (Hawkins and Sutton, 2009). In this case, it provides key insights on how to limit the effect on the UHI according to current urban strategies and climate change assumptions:

- Defining rapidly long term policies to control the urban forms and extent;
- Improving the greenness of future urban forms as well as the urban water storage to irrigate it and thus maintaining and enlightening its efficiency in the future;
- Increasing the energy performance of old buildings using new technologies and
- Encouraging and promoting changes of households' habits in terms of cooling and heating.

It is worthwhile to add participatory workshops at the end of the full process for discussion and the further involvement of urban planners, even if such workshops are not fully required for the production of the scenarios and their quantification. In the project, a one-day meeting for reporting and feedback with the urban planning agency was held, which involved over 100 people, mostly from the municipalities and civil society, completed by a few experts. None of them mentioned any inconsistencies in the narratives. This constituted an important ‘validation’ step that has to be understood as a plausibility vindication of these scenarios (Wiek et al., 2013). The extremely distant temporal horizon of the scenarios (100 years) compared to the usual horizon for urban planning issues, even if disconcerting at first, in fact proved to be very profitable to the discussion for several reasons. From a scientific point of view, it allowed the urban planning levers having influence in the very long term (and their possible unplanned drawbacks) to be identified. This was the case for the green belt strategy for example, which is good for several decades but needs to be revised – and potentially reinforced – to keep its efficiency in the long term. From a political point of view, looking so far ahead breaks the political constraints in the discussion (such as local quarrels between nearby municipalities). The fact of quantifying precisely the consequences of potential and contrasting scenarios allows a very efficient transfer of the information towards the policy makers, providing, of course, that they are included in the narratives (Shakley and Deanwood, 2003). Therefore, from a social point of view, the quantification of the impacts of scenarios, including small-scale drivers (inhabitants), can contribute to collective awareness.

The modelling background of the project team probably oriented this research towards selecting only quantifiable variables to feed the modelling platform and using others as contextual variables to justify or explain disruptions in the trends. For instance, no transport model was considered because the project team was not designed for it, although it could have been interesting to incorporate one. The *a priori* development of storylines has strong implications on the use and the development of models and questions the model validation. Model validation may have different meanings and values depending of the chosen approach to combine narratives and models. The ‘model-based’ approach requires a strong calibration phase often considered as the validation step of the model, allowing to simulate past and future trends. But, while exploring the future, it inherently assumes the system under study to be stationary. Once calibrated using land cover maps, LUCC models would be able to simulate trend scenarios, with more or less contrasts in land demand when it can be modified manually (e.g. Mas et al., 2014; Paegelow et al., 2014; Houet et al., 2015). The ‘narrative-based’ approach accepts the model to not be fully calibrated since it is still able to simulate past trends using observed inputs data. But, their capabilities to simulate various LUCC process and land changes have to be demonstrated beforehand (Houet et al., 2016). Indeed, in scenario studies, model validation may be difficult to achieve without complete historical data (Bishop et al., 2007). Shifting the validation standards for LUCC models such as the model calibration for instance, when they are used in a prospective way, may help to combine narratives and models (Houet et al., 2016; van Vliet et al., 2016). The use of spatially explicit

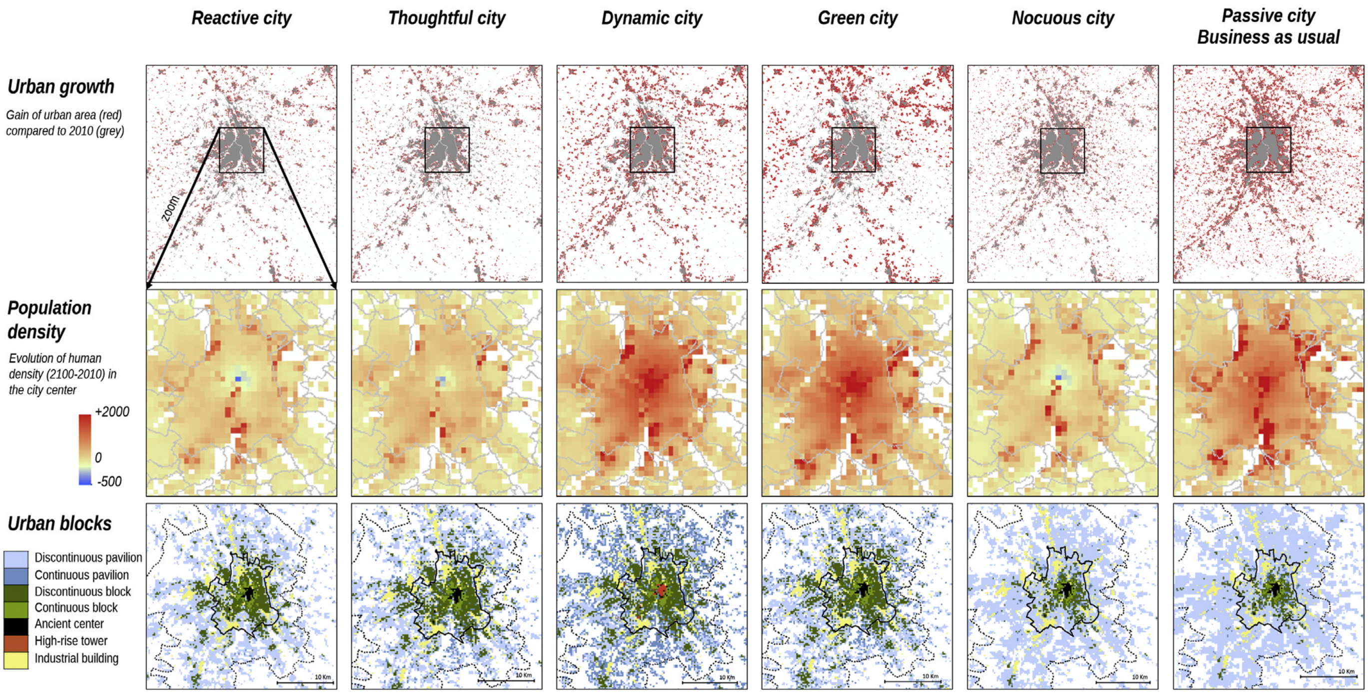

Fig. 3. Simulated spatial outputs of the seven systemic scenarios: urban growth, human density and urban block maps for 2100. Maps were simulated at decadal time steps (not shown here).

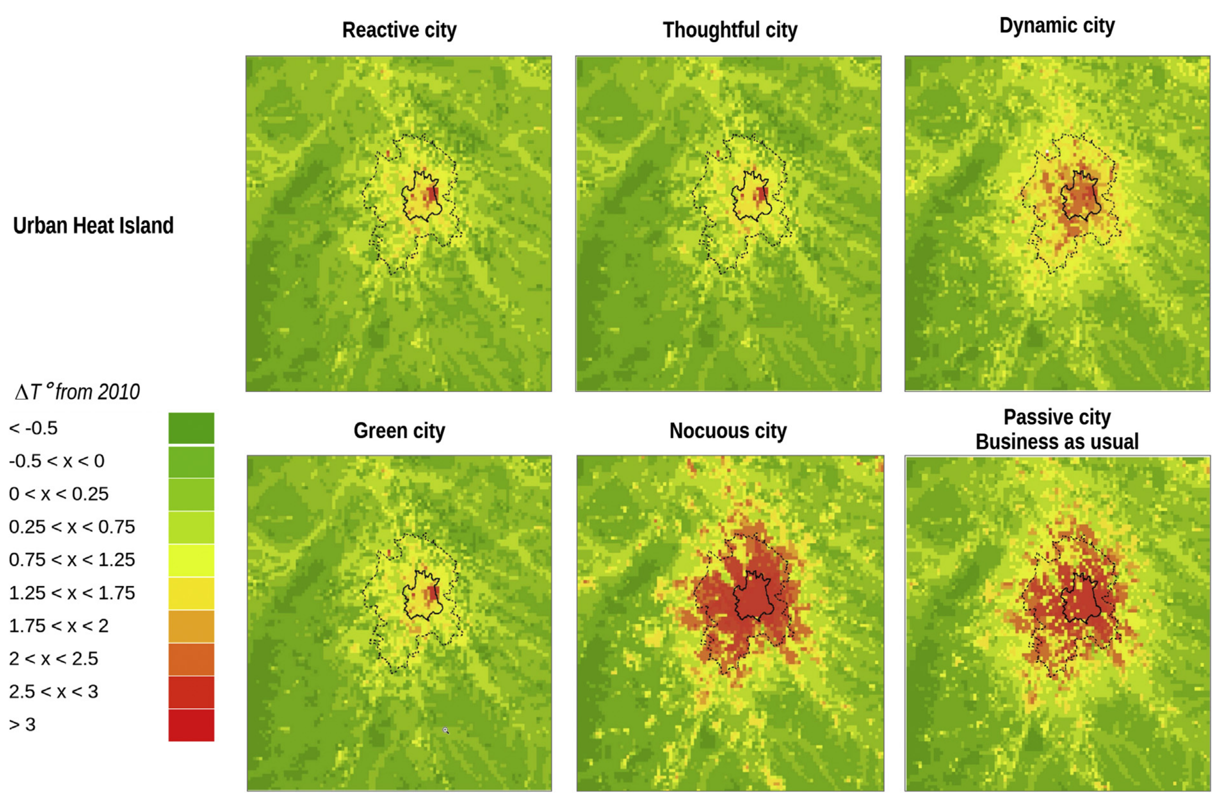

Fig. 4. Simulated UHI maps for the seven systemic scenarios in 2100 – Maps represent the difference (rise/fall) of temperature compared to 2010.

models in prospective modelling may vary regarding the objectives, the spatial scale (extent, resolution) and the time horizon (duration of the scenarios) of the study (Houet, 2015).

4.3. Limitations

The generalizability of the proposed methodology to other cities and other landscapes can be questioned. This work, performed from sectors to sub-scenarios and from sub-scenarios to narrative, was helpful to downscale international trends and account for local ones. While multiscale modelling at these scales is too challenging because of all the possible interactions between all the decision levels of this worldwide system, this approach simplifies the modelling and enables quantitative simulations to be performed at fine scales. In other words, narratives outline the system under study and the modelling requirements. This is even more obvious when the long-term future is considered. In the case of studies focusing on urban areas, we assume that all variables are similar for cities of developed countries although their translation into quantified parameters (projections, maps, etc.) may differ with regard to local specificities. For developing countries, we think this framework will have to be slightly adapted by replacing or adding new variables because the urban planning governance/strategies may differ from one country to another, for instance in terms of national policies or socio-cultural habits.

5. Conclusion

The paper presents and describes the development of a six-step approach to improve environmental impact assessment by combining narratives and a modelling framework. Its application on urban growth scenarios and their related impacts on urban heat island show great capabilities for integrating discontinuities (crises) into impact research. Three main approaches for exploring the future can be distinguished: (1) models guide the scenarios that can be built – their limitations and strengths are the context in which scenarios are built; (2) imagining and describing the future, using narratives, is the central goal of the study, and scenarios are valued in their own right without necessarily being associated with a quantitative modelling approach; (3) combining (1) and (2) allows the development of highly imaginative scenarios together with the development of a modelling platform able to use them in a quantitative assessment of the futures they entail. This is the SAS approach to which this study contributes.

Models can and should be further developed when they are not considered fully suitable. In parallel, the quantitative information provided by the quantitative assessment (modelling) is very informative and can capture complex processes that purely imaginative exercises would have difficulties in assessing. Our study helps to demonstrate the generalizability and the interest of coupling narratives and LUCC models for quantitative environmental assessment. Going further, we propose to improve this approach, by identifying a clear 6-step methodology, which involves 4 participatory workshops.

The main interest of this work lies in the step-by-step methodological approach combining the respective advantages of qualitative narratives and quantitative models. It starts, before considering the possible history of the scenarios, with the determination of the relevant drivers in all the sectors pertinent to the system under study. The clue here is to do this without considering, at that stage, the models that will be used afterwards. This guides the following participatory exercises, and constrains the design of the required models and their coupling. It also ensures that all scenarios will provide all the useful contextual and quantitative information for narratives and models. The variables (cf. step 1) are then quantified (step 5) on the basis of observed trends, existing projections, and existing land use management plans. The limitation of the variables that feed the models facilitates the quantification of the narratives. This step-by-step methodology provides a robust, structuring framework for developing narratives, even very contrasting ones, and determining all the input requirements of the models, i.e. contributing more broadly to the SAS approach.

Application of this methodology led to the definition of seven contrasting scenarios of urban growth for the Toulouse urban area (France) in 2100. The simulated maps of urban growth were used as input to a climatic model to assess the impacts of land use strategies and technological and socio-economic trends on the UHI. A comparison of these scenarios and related outputs highlighted some levers to limit the increase of air temperature in the city centre and the suburbs. In summary, rapidly defining the strategies for urban forms, in terms of urban extent and types of urban blocks, is crucial. Other efficient levers are the fraction of vegetation in the urban area, the retrofitting of old buildings to increase their energy performance and changes of households' habits in terms of cooling and heating.

Finally, this study is an original example of the SAS approach applied to an urban area at a fine scale with concern for the links between urban growth and impacts on the urban climate. Its originality may come from the co-design of scenarios and models, which reduces the gap between the narratives and the simulations (Kok et al., 2014). Developments or modifications of models were performed to facilitate their combination with narratives.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2016.09.010.

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