

## **Response to the Referees: "Computing Climate-Smart Urban Land Use with the Integrated Urban Complexity Model (IUCm 1.0)".**

We would like to express our most sincere gratitude towards the referees for their careful reviews of our paper. In this letter we respond to the reviews on a comment-by-comment basis.

### **1<sup>st</sup> ANONYMOUS REFEREE**

#### **First Referee, comment 1**

The motivation of the paper is clearly described, and the overall approach is very clear, interesting and contributes to an important discussion. Some minor points:

Response: we thank you for highlighting the next minor points that will help us to improve the manuscript.

#### **First Referee, comment 2**

Motivation: the overall energy consumption of cities is mentioned, but not the energy consumption of urban mobility - why?

Response: Thank you, we see that we have used different concepts to refer to energy and that this have led to confusions between energy for transportation and overall energy consumption. To avoid this confusion, we modified the text. To clarify the text we now mention "mobility" and the "energy consumption of urban mobility" when elaborating about energy. E.g. the introduction now includes the word "mobility" every time energy is mentioned, and in other sections now the term "urban mobility" is also prevalent, appearing more than 30 times in total.

#### **First Referee, comment 3**

Potential deficits of the methodology could be mentioned more clearly (i.e. that it is yet a very generic model not incorporating local contexts, personal preferences of inhabitants (do they want to live where the model proposes?)),

Response: We are very grateful for pointing out this question; we have introduced these potential deficits in the discussion, which now includes these points reads as follows:

(Text continues pre-existing paragraph). “In any case, the suggested densities should be implemented with the least energy intensive strategy and prioritizing citizen comfort. Both depend upon multiple interrelated factors, other than density, that correspond to lower scale decision levels that are beyond the scope of this study. These multiple factors include building expected lifetime, design, layout, height, shape, materials and type of surface cover, integration with green and blue urban landscapes, orientation and size of the houses, all of which have significant impact both on the embodied and operational energies and on the personal preferences of inhabitants (Seto et al., 2014; Pan, 2014; Kennedy and Buys, 2010).

About the personal preferences of inhabitants, to limit negative externalities of high density, the model includes a limit of 15,000 inhabitants per square kilometer to avoid densities that are expected to create discomfort on urban inhabitants. Still, the local context or the preferences of the population about living in areas of higher density, as suggested by the results of the model, are not considered in the context of the normative results of our model. A possible avenue to consider these would be to discuss with local stakeholder the maximum density and the above factors leading to citizen comfort and livability that could make a difference to the local population. The preferences of stakeholders can be captured by participatory geographical information system (GIS) techniques enabling them to express where and how much the increase of densities should be limited. The underlying reasons of the prospective limitations are specific of every city and its idiosyncrasy: its cultural heritage areas, its history, and other multiple social, economic and environmental features could be sources of preferences for limitations in density and landscape change.”

#### **First Referee, comment 4**

##### **How likely is that the required data can be made available in case of practical application?**

Response: Thanks, this is a very important questions, we found that this is not detailed enough in the methodology section and added information and a new Section “2.2.3. Data for real urban forms and model transferability to other cities” to make clear that a practical application would be

immediately possible for Europe, while in the discussion section we make clear that the next model version would be applicable worldwide. The text including these points now reads as follows:

(Sub-section 2.2.3. Data for real urban forms and model transferability to other cities)

(Text continues pre-existing paragraph). “Because the products used from the Global Human Settlement Layer are freely available for the entire globe, and because there is evidence for the model for Europe, the application to this model to a European city can be done in an immediate basis, by adapting the format of the Global Human Settlement Layer to the requirements of the model. The model can be applied to European cities using the existing evidence as described in Equation (1) at Section 2.2.1. This evidence is implemented in the code available as described in Section 6. The data about flood risks can be obtained from multiple urban and regional data servers about risk management local servers (e.g. the reference of data for the German federal State of Hessen can be found in Section 2.2.4). The data about the spatially explicit population density comes from the Global Human Settlement Layer, the product for 1 km of pixel size is freely available worldwide at <https://ghsl.jrc.ec.europa.eu>.”

(Section 4. Discussion)

“This approach has limitations due to the low availability of data and econometric evidence for driving the IUCm 1.0 outside Europe, both on mitigation and on adaptation to climate change (UITP, 2015). Further global evidence should be produced that incorporates either the location of urban services or land use types. Once this evidence is created the model could be available for a practical application in other world regions.”

#### **First Referee, comment 5**

Case study selection: please justify the case-study selection (i.e. why Frankfurt)? Practical reasons, data availability, ... see literature such as Flyvbjerg (2006): Five Misunderstandings About Case Study Research) In this case, I assume practical reasons?

Response: Thanks, we justified it on the basis of being (i) convenient for institutional reasons related to the country of affiliation of the main author, (ii) a large metropolitan area where the size of the pixels of the data of origin (1.000 metres) allow to an interesting analysis, (iii) an area

with an uncomplicated orography that would allow to present clearly the results of the first version of the model, and (iii) and because of Frankfurt is an affluent city, with a higher the likeliness of considering a large scale transformation or growth based on our insights.

The new text added reads as follows:

“The mentioned high density cluster has been selected because of being (i) a large metropolitan area where the size of the pixels of the data of origin (1.000 meters) allow to a meaningful analysis, (ii) an area with an uncomplicated orography that would allow to present clearly the results of the first version of the model, and (iii) because of Frankfurt is an affluent city, with a higher likeliness of considering a large scale transformation or growth based on our insights. Finally (iv), choosing Frankfurt was convenient for institutional reasons related to the country of affiliation of the main author. The second reason (orography) thereby could appear as a confirmation bias (see Flyvbjerg, 2006) but this can safely be negated. The interpretation of the a-priori data would not allow a human to infer the results we present, especially the shape in the formation of hierarchies of densities and the halving of the energy consumption for urban mobility as presented in Section 3”.

#### **First Referee, comment 6**

Reproducibility: discuss where potential data sources for your model exist so that it can be used by cities easily. Where do such data exist hitherto - and where not? Can they be obtained globally by remote sensing in the future?

Response: Thanks, we found it could help the reader to clarify this point together with comment 4 above. Hence the response to comment 4 also takes into account and responds to the suggestions made in this comment.

#### **First Referee, comment 7**

Please perform a more deep reality check of your policy recommendations: can there be a step-wise approach?

Response: Thanks, this will help us to clarify the relation of our results with their usability in a real world policy context, we extended discussions to include this point:

“In a real application of our model for urban growth, the cases so far discussed with policy makers relate to (i) a large number of small areas with opportunities for development and densification spread in a metropolitan area, and (ii) an application to choose between a set of different planning alternatives. In these contexts, what is the meaning of step-by-step model results that provide policy recommendations for urban growth? In the second case just mentioned, what matters would be the result in energy consumption computed by the step I)i)a)(2) of the algorithm in Section 2.2.9. In the first case, which appears to be a topical situation in urban planning, the model would provide density suggestions that would help policy-makers to plan the city for an increased population figure, however, the precise order of the step-wise results would matter much less for the policy-makers than the suggested densities and their location in space.”

### **First Referee, comment 8**

#### **Can you do cost-benefit-analysis to suggest where urban transformation should first take place?**

Response: Thanks, we extended the discussion explaining the opportunities that a cost-benefit-analysis would provide to improve our understanding and the potential barriers faced to quantify the externalities involved. The text added reads as follows:

“A valuable experiment would be a combination of the IUCm results with a cost-benefit analysis. This could then inform policy makers where the suggested transformations of the IUCm should first take place. Additionally, from a scientific point of view, it would highlight the factors controlling the difference between a cost-benefit analysis and a model guided by a goal of resource efficiency. In order to provide this analysis, many of the environmental externalities and multiple factors detailed above in relation to the preferences of citizens would however need to be quantified and their interactions understood, in order to provide a full account of the benefits.”

### **First Referee, comment 9**

If possible, discuss if your results can also hold with new mobility options such as automated shared-vehicles that have different energy consumption levels.

Response: This is a very interesting point, thanks! We discussed the topic from a similar angle but it provides a broader view to include this point as well. We see that in this question, what makes a difference is where the energy is coming from: is it electricity from 100% renewables, or from an energy mix including fossil fuels that produces the emissions somewhere else outside the city and thus contributes to climate change? Since the current situation in most world countries is an energy mix including fossil fuels, we mention both options and discuss the meaning of our results in a 100% renewable scenario from the lens of new mobility options such as automated shared-vehicles. We modified the text to include the suggested point in the discussion:

“We assume that the statistical relationship between urban form and energy consumption for urban mobility holds for the future as well, and to a degree, a change in this relationship could be captured by the probabilistic setup we are using. Because of this assumption, our results should be discussed also from the perspective of a possible future scenario of successful emissions reduction driven by automated shared-vehicles, either fed by an energy mix combining different sources and including fossil fuels, or fed 100% by renewable energies. Currently electricity is supplied by an energy mix combining different sources that includes fossil fuels, so in the case of a 100% renewables, our planning suggestions would still provide useful advice to further reclaim space from private mobility, making that space free for citizen use (Karsten and van Vliet, 2006), whilst reducing other environmental impacts related to the production of renewable energies (Leung and Yang, 2012). Such future scenarios can be conceptualized with smart fees based on the time spent on the road (Raccuja, 2017).”

Because the discussion has been extended, we included two subsections on it to improve its structure, readability, and to make it easy for readers to find the desired information: “4.1. Implications for the Sustainable Development Goals (SDG) of the Agenda 2030” and “4.2. Outlook”.

## 2<sup>nd</sup> ANONYMOUS REFEREE

### Second Referee, comment 1

The manuscript proposes an integrated urban complexity model to assess climate friendly urban forms based on a cellular automata approach. The purpose and content of the paper is presented clear and traceable and deals with the very relevant planning challenge to steer urban regions to a more sustainable development.

Response: Thanks.

### Second Referee, comment 2

Some comments: you are motivation your work with the objective to minimize global carbon emissions. Focus of your model is the energy consumption per inhabitant. I am not sure about the correlation of these two variables in terms of mobility as the kind of energy (electric, direct combustion) strongly depends on the used mode of transport. For example using public transport will definitely have other impacts on CO2 emissions than driving by car. In terms of urban CO2 emissions I would find vehicle miles travelled by car a more meaningful destination variable. You could change that or rewrite your introduction towards energy consumption. You should at least clearly describe how this variable energy (it is coming from the UITP database, right?) was calculated. Are active modes included in this assessment and which values were taken for which mode of transport/ mode of drive?

Response: Thank you, we see that clarifying these points would improve the paper.

We have rewritten the introduction towards energy consumption: every time CO2 emissions are mentioned we included energy consumption; only in two broader instances we left the term “emissions” alone, when referring to the overall research agenda and when referring to urban areas as a whole, besides that every time “emissions” is mentioned in relation to urban mobility in particular, we have alongside included the keyword “energy”.

We also improved the description of the energy variable and inquired more details about it. The variable energy is described in larger detail now in a paragraph as follows:

“The variable energy was obtained by the UITP (Union Internationale des Transports Publics or International Association of Public Transport) in their Mobility in Cities database through consultation with local authorities in each metropolitan area about each type of fuel or electricity consumed per each mobility type, as reported in local statistics in 2001, or by extrapolation of periodic surveys into 2001; the information was provided only for those cities where there was sufficient information.”

We have established contact with the author providing the evidence in this respect, and he gave us account of using another similar dataset (created by Newman & Kenworthy and published in their book “Sustainability and Cities: Overcoming Automobile Dependence” published by Island Press in 1999) and obtaining similar results, thus supporting the reliability of the data in which our study is based (Le Néchet, priv. comm.).

### Second Referee, comment 3

In general: think about your input variables. I would assume that you can achieve better results for the regression if you would include mode sensitive accessibility measures instead of simple average distance between citizens. Also the spatial entropy could be extended towards land-use mix.

Response: Thank you, we find this is an important item in our future agenda and improved the discussion including these points while arguing for future work that would be necessary to improve our model. Now the text in the discussion covering these topics reads:

“Research should follow to improve the detail of the model and of the evidence driving it, mostly studying further detail of infrastructure, accessibility measures and transport systems, land use types and diversity of activities in land use mixes, and the 3-dimensional properties of cities. As mentioned above we plan to include further detail of urban transportation networks and infrastructures by applying a network-based model to urban transportation in urban settlements, a deeper layer of information is planned to include infrastructures and transportation and street networks to improve how the model accounts for accessibility, and to extend the currently used information about population density with data of points of interest and of the location of jobs to proxy land use mixes, and to study the interaction of these factors with energy consumption as

derived from network transit models. About the 3-dimensional properties of urban structures, a most realistic depiction of the urban heat island effect would require coupling with a low spatial resolution urban climate model able to analyse scenarios including 3-dimensional features and building covers, hence we plan a 3-dimensional representation of cities to model land use and building covers and analyse heat-island effect together with a climate model, which would allow us to suggest ventilation corridors and the use of vegetation in urban surfaces to reduce maximum temperatures and deal with an additional climate risks like the urban heat-island effect. These model developments are planned to integrate adaptation and mitigation at lower scales (Li et al., 2016; Koch et al. 2012).

Despite the limitations identified, the methodology that we present goes beyond current exercises on global change in urban areas, like the spatially explicit population scenarios launched consistently with the Shared Socioeconomic Pathways (Jones and O'Neill, 2016). So far these scenarios only consider the concentration of population versus sprawl, and leave out crucial considerations of polycentrism, fractals and complexity in urban forms when providing information about sustainability. Besides, combining both adaptation to and mitigation of climate change in urban plans and policies effectively in a qualitative way (without a quantitative spatially explicit model) has proved to be a challenge leading to conflicting, rather than co-beneficial, outcomes (Hamin and Gurran, 2009). Summarizing, our planning advice is based on significant statistical measures relating the urban form with the energy consumption for urban mobility, and suggests the most efficient way of making urban forms not only more dense, but also less homogeneous and more fractal-like, whilst constrained by climate change related risks.”

#### **Second Referee, comment 4**

Working trips represent the majority of executed trips in urban areas. Therefore the locations of jobs are equally important for the number and length of trips per person as residential locations. Please discuss how this can be incorporated in the planning process/included in the model.

Response: Thanks, we agree this is relevant and discussed the use of the location of jobs in the context of the answer to the above comment (Comment 3), explaining that “As mentioned above we plan to include further detail of urban transportation networks and infrastructures by applying network science to urban transportation in urban settlements, a deeper layer of information is

planned to include infrastructures and transportation and street networks to improve how the model accounts for accessibility, and to extend the currently used data of population density with data of points of interest and of the location of jobs to proxy land use mixes, and to study the interaction of these factors with energy consumption as derived from network transit models”.

### **Second Referee, comment 5**

I would drop the section about absence of existing infrastructure (page 19, 6-13). The optimization you are performing is based on relations between energy consumption and an existing supply of mobility infrastructure and public transport (Le Néchet). That means the optimal urban form you found is only valid if this kind of supply exists.

Response: thanks for this logic argument, we dropped this section as suggested.

### **Second Referee, comment 6**

Extend the section about transferability. Why is it difficult to transfer? Which data is missing? What could you do to overcome transferability issues? As I understood you only need city boundaries, population density and some kind of basic land use. I would say that the main problem is different mobility behavoir/ mobility options.

Response: we created a new Section “2.2.3. Data for real urban forms and model transferability to other cities”, and as mentioned in response to the First Referee’s comment 4, it makes “clear that a practical application would be immediately possible for Europe, while in the discussion section we make clear that the next model version would be applicable worldwide. The text including these points now reads as follows”:

(Text continues pre-existing paragraph). “Because the products used from the Global Human Settlement Layer are freely available for the entire globe, and because there is evidence for the model for Europe, the application to this model to a European city can be done in an immediate basis, by adapting the format of the Global Human Settlement Layer to the requirements of the model. The model can be applied to European cities using the existing evidence as described in Equation (1) at Section 2.2.1. This evidence is implemented in the code available as described in

Section 6. The data about flood risks can be obtained from multiple urban and regional data servers about risk management local servers (e.g. the reference of data for the German federal State of Hessen can be found in Section 2.2.4). The data about the spatially explicit population density comes from the Global Human Settlement Layer, the product for 1 km of pixel size is freely available worldwide at <https://ghsl.jrc.ec.europa.eu>.”

### **Second Referee, comment 7**

Nevertheless, good work!

Response: Thank you for encouraging us.